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A decision framework for the management of established biological invasions

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Abstract

In some cases, managing an established invasive species may do more harm to an ecosystem than allowing the invader to persist. Given limited resources available to land managers and the realities of conservation triage, we recognized the need for systematic guidance for management decisions made at the "late end" of the invasion curve. We gathered an interdisciplinary group of experts and practitioners to address the question of "under what circumstances is the active management of an established aquatic invasive species warranted?" Our working group identified three key dimensions to this question: (1) the efficacy of available management options; (2) the net benefits of management actions weighed against the null scenario of no control; and (3) the socio-ecological context that defines management goals, a manager's ability to achieve said goals, and perceptions of management outcomes. These considerations were used to structure a consensus decision tree that supports a multi-criteria approach to decision-making. Our approach promotes interdisciplinarity and systems thinking and emphasizes the need to consider costs and benefits comprehensively, for example by considering the persistence or reversibility of impacts from both the invasive species and from efforts to suppress or eradicate it.

Key words: invasive species, decision framework, systems thinking, management

Introduction

Aquatic invasive species are a leading threat to global biodiversity (Havel et al. 2015, Diaz et al. 2019), and their control remains a key target for the Post-2020 Global Biodiversity Framework, under the Convention on Biological Diversity (Essl et al. 2020). Yet in some instances, management interventions may do more harm to an ecosystem than allowing invasive species to persist (Hobbs et al. 2011; Kopf et al. 2017). Established aquatic invasive species may occasionally provide valuable ecosystem services in addition to their negative effects (e.g., Rogalski and Skelly 2012; Kiviat 2013; Neves et al. 2020).

Few decision support structures are available to help conservation practitioners and habitat managers determine whether an *established* invasion should be controlled or simply monitored on a given land parcel within their jurisdiction. This is particularly challenging for those managing populations "at the late end of the invasion curve," once the species has become established in an ecosystem (Fig. 1A, stage IV). The term *established* generally applies to invasive species capable of reproducing to maintain a self-sustaining population in the invaded region, but as recognized by Kočovský et al. (2018), in practical terms it may be a code word that indicates whether an invasion is deemed manageable or not. As the extent of the invasion increases, the management costs expand while the likelihood of eradication shrinks (Beric and MacIsaac 2015; Green and Grosholz 2021). Management goals may then shift from the finite objective of eradication to sustained efforts towards population suppression, asset protection, and slow-the-spread strategies (Forrest et al. 2009; Larson et al. 2011; Fig. 1). For our purposes, we adopt the pragmatic definition that an invasive species is *established* once eradication is no longer the goal of management efforts (end of stage II in Fig. 1). It does not necessarily follow that eradication is no longer possible, and eradication targets may be readopted because new tools, scientific understanding, resources, or even political will and social license are dynamic (Kočovský et al. 2018).

Given limited resources and the realities of conservation triage (i.e., that limited resources should be allocated to achieve the greatest conservation benefit; sensu Bottrill et al. 2008), we recognized the need for systematic guidance for when resource-intensive and potentially environmentally harmful treatment is warranted. Existing approaches to

Fig. 1. Panel A depicts the classic conception of the invasion curve whereby the population of an invasive species grows at a changing rate through time, influencing management goals and the costs, invasion damage, and public awareness of the invasion. The point at which eradication is no longer the management goal is the juncture at which we consider an invasive species to be established. Importantly, goals are dynamic and new tools, scientific understanding, resourcing, etc. can enable eradication even after a designation as established. Different management actions can alter invasive species growth trends, as depicted in Panel B, such that the pattern of logistic growth to dynamic equilibrium with environmental conditions (B(i)) is not inevitable. This classic conception provides a useful model, but it obscures the feedback between management goals, outcomes, and socioeconomic factors such as resourcing, governance, or public engagement that operate within any socioecological system. This figure was developed for this paper, following the workshop.

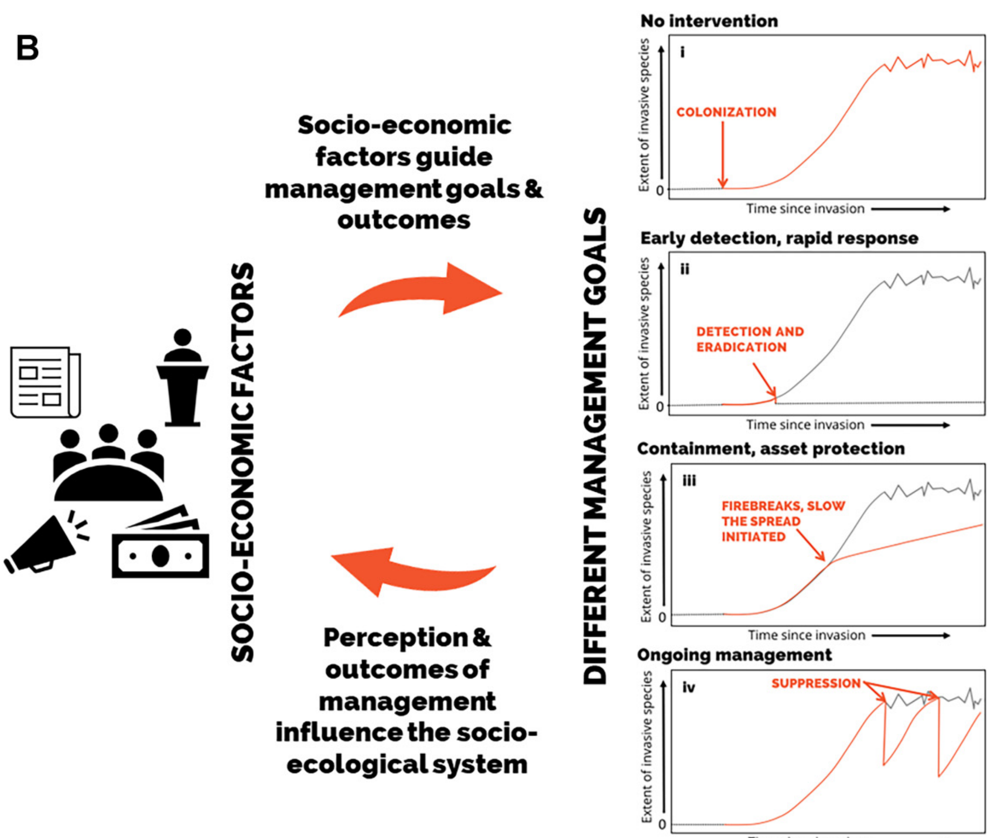
A

CLASSIC STAGES OF INVASION MANAGEMENT

Time since invasion →

Features	I - Prevention	II - Eradication	III - Containment	IV – Long-term Control
Growth	Absent	Isolated patches, rare	Rapid expansion	Reaches equilibrium with available habitat and dynamic conditions for growth
Damages	None	Limited, localized effects	Mounting ecological effects	Sustained ecological impacts, long-term effects manifest, altered ecosystem function
Costs	Monitoring & outreach	Monitoring & treatment or control	Firebreaks, slow the spread programs	Costly ongoing maintenance & suppression efforts
Profile	Unknown outside watch lists	Early warning & experts alert	Rising public awareness	High public awareness & political will to act, but may dwindle
Goals	Prevent colonization	Early detection & rapid response, eradication	Containment, slow the spread, asset protection	Ongoing management, mitigation, adaptation, & triage

B



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support decision-making and inform option prioritization in conservation planning fall short. Cost-benefit analysis, for example, is widely used in the risk assessments of aquatic invasive species (e.g., the global database InvaCost; Leroy et al. 2022). Yet cost-benefit analysis has been criticized as both data-intensive and overly reductionist because it requires monetary values for all costs and benefits when it is recognized that ecological functions and processes are not easily or adequately monetized (Wegner and Pascual 2011; Hirsch Hadorn 2021). Alternative approaches, such as multi-criteria decision analysis (reviewed in Liu et al. 2011), may better integrate non-monetary values and incorporate the multiple dimensions of complex socio-ecological systems (e.g., Saarikoski et al. 2016).

To have general applicability, a decision support framework must be flexible to suit diverse management goals and integrate social and political contexts. In contrast with classic conceptions of biological invasion as a purely biological phenomenon, socio-economic factors, including resource and landscape governance, community engagement, and behavioural psychology, also contribute (Fig. 1), making the problem space multi-layered and multi-scaled (Larson et al. 2011). To address this significant challenge requires "systems thinking" (*sensu* Meadows and Wright 2008), which adopts a holistic view of how the elements of a system interrelate and interact (e.g., Fig. 1B). Given this neglected systems perspective, we formed an expert working group from multiple disciplines to tackle the question of "under what circumstances could we accept and thus adapt to the presence of an invasive species?" An interdisciplinary working group allowed us to think innovatively, incorporating expert elicitation methods to derive an adaptive decision model. Working group members completed two tasks: (1) they developed a framework to support decision-making and (2) they determined under what conditions active management of an established invasive species is warranted to achieve management objectives. To narrow our question further, we focused on aquatic invasive species and applied our expert-derived decision framework to a suite of management scenarios using invasive *Phragmites australis* ssp. *australis* (European common reed) as a case study.

Materials and methods

We brought together a binational, interdisciplinary group of practitioners from academic, government, and non-government organizations to synthesize their knowledge and experience from both the natural and social sciences. Working group members were selected based on their expertise related to invasive species and environmental decision-making, with a conscious effort made to include individuals from various professional, disciplinary contexts and career stages. We did not attempt to engage Tribal or First Nations communities. Thirteen experts from 10 institutions participated in the final working group: (1) the Great Lakes Science Center (U.S. Geological Survey), (2) the Canadian Wildlife Service (Environment and Climate Change Canada), (3) the Great Lakes Commission, (4) the Canadian Food Inspection Agency, (5) the Ontario Ministry of Northern Development, Mining, Natural Resources and Forestry, (6) Ontario Ministry of Environment, Conservation and Parks, (7) the University of Waterloo (Biology Department; School of Environment, Resources, and Sustainability), (8) McGill University (Biology Department), (9) Purdue University (Department of Anthropology), and (10) Ducks Unlimited Canada. Two early-career researchers from the University of Waterloo acted as rapporteurs throughout the workshop.

Working group members were invited to a two-day, "World Café" style workshop (Brown 2010) in Fergus, ON, Canada, in October 2017, an evidence-based format widely adopted to facilitate innovative and collaborative discussion. The workshop began with introductions, setting the context, discussing pre-assigned readings that reviewed pertinent approaches to our research questions (i.e., Martin and Blossey 2013; Gaertner et al. 2016; Lodge et al. 2016; Kopf et al. 2017), and setting the unifying objectives, which were to (1) develop a practical decision framework for whether to manage an invasive species once it has become regionally established and (2) apply this framework to the case of invasive *Phragmites australis* ssp. *australis*. Workshop participants agreed on a definition of "invasive species" as species that are introduced from outside a given geographical region that can create self-sustaining populations in a new environment that may have a detrimental impact on extant ecosystems, similar to the definition of Richardson et al. (2000). The working group acknowledged that not all non-native species are invasive and that even invasive species may provide valuable ecosystem services.

Day One of the workshop consisted of identifying the key dimensions (i.e., characteristics and limitations) of aquatic invasive species and their management. After these dimensions were agreed upon (see Results), working group members were randomly assigned to one of the four groups to develop frameworks for considering these dimensions. Our rationale for assigning members to groups at random was to support our goal of interdisciplinarity without requiring us to label participants as belonging to a single group. Once each sub-group had completed their own draft framework, members gathered to share their results and synthesize an initial consensus framework that integrated aspects of all the four groups.

Day Two began with a brief overview of invasive *P. australis* and its management in North America. *Phragmites australis* ssp. *australis* is a wetland grass that has been considered one of the greatest threats to North American wetlands because, if untreated, it will continue to spread (Catling and Mitrow 2011; Saltonstall and Meyerson 2016; Jung et al. 2017). Despite large annual expenditures on *P. australis* management—for example, the expenditure of $4.5 million USD annually in the USA towards extensive herbicide treatment—the management objectives of *P. australis* eradication and ecosystem services recovery may not be fully achieved (Martin and Blossey 2013; Rohal et al. 2018). Given the expense, the risks to ecosystems and human health associated with herbicide application (e.g., Van Bruggen et al. 2018), and the general failure of management actions to extirpate invasive *P. australis* fully from invaded properties (e.g., Hazelton et al. 2014), it remained unclear how to weigh the risks of intervention vs. non-intervention.

Our working group members were then randomly assigned to four new sub-groups where they reviewed the draft consensus framework developed on Day One. As discussion prompts, sub-groups were given six *P. australis* case scenarios designed by co-authors Rooney, Robichaud, and Larson to represent diverse contexts and management goals (Appendix A). For example, one scenario consisted of managing the linear expansion of *P. australis* along a roadway, a second dealt with small patches of *P. australis* near a busy boat launch, and a third scenario considered managing *P. australis* in areas with species at risk (Appendix A). Rather than report on the outcome of applying the framework to each scenario, the sub-groups used the scenarios as an instrument to test the framework. The discussions sparked by consideration of these scenarios identified strengths in the draft consensus framework, including the structured manner by which the framework encouraged managers to consider the connectivity of their management parcel to other communities and habitats. The sub-groups also identified weaknesses in the draft consensus framework, such as the difficulty of conducting a holistic assessment when it requires weighing financial costs against ecological and social costs that are not easily assigned a monetary value. Further, when a manager is responsible for multiple sites, the draft consensus framework did not provide a means to prioritize among sites.

A whole-group discussion of the six different scenarios revealed the need for formal tools to support the implementation of the framework. Three new breakout sub-groups were created to develop three tools to assess key prerequisites to any management intervention action: (1) assessment of the net negative effects of the invasive alien species at a given site, (2) assessment of the net environmental benefits of the available management activities at a given site for a specified management goal, and (3) assessment of whether the resources and socio-political context were compatible with achieving the site's specified management goal. To address these three prerequisites, working group members self-identified and joined one of the three "tool" groups where they had the most expertise to contribute. The rationale for allowing group members to now self-select for these three new sub-groups was that each sub-group was focused on developing a different tool, and we desired that participants contribute where they had the most interest and expertise. After the sub-group discussions, members reconvened to share the tools developed by their sub-group with all the working group members. By the end of Day Two, members had agreed on a framework with three supporting tools, the workshop coordinators synthesized these results, and members were invited to review and co-author the subsequent manuscript.

Results and discussion

Dimensions

When invasive aquatic species are recognized as having negative impacts on ecosystems where they have colonized or been introduced, our workshop participants agreed that the default assumption is that managers or, more broadly, society should aim to eradicate them (e.g., Aichi Target 9, Convention on Biological Diversity 2011). Yet eradication can be cost-prohibitive, damaging to managed ecosystems, and oftentimes impossible with the available tools and organizational capacity (Hazelton et al. 2014). If eradication is not perceived as achievable and the invasive species is deemed established (Fig. 1), how can land managers decide whether a particular aquatic invasive species warrants active management? Our working group identified three key dimensions to this question: (1) efficacy, (2) the socio-ecological context, and (3) net benefits.

"Efficacy" encompassed aspects of available management options, as some tools or actions might have superior outcomes in terms of both the suppression of the invasive species and the recovery of the ecosystem post-treatment. Workshop members acknowledged that this aspect of efficacy might vary with the geographic extent of invasion, the time frame under consideration, and the accessibility of the site. In evaluating efficacy, workshop members agreed that it is essential to define realistic management goals, which members also acknowledged rarely aspire to eradication when aquatic invasive species have already become established (Fig. 1). For example, a goal to slow invasive species' spread may prioritize resourcing public education, vector management (i.e., regulations and enforcement of clean equipment protocols), and dispersal pathways or suppression of marginal populations. In contrast, the goal of protecting a particular high-value conservation asset, such as a provincial park or critical habitat for a sensitive species at risk, may achieve greater success through routine population suppression within clearly demarcated boundaries.

Secondly, the "socio-ecological context" was recognized by workshop members as influential both in defining management goals and in enabling managers to achieve those goals effectively. Members extended this concept to incorporate multiple factors, including the available capacity in terms of resources, funding, knowledge base, personnel, and complementarity with ongoing management activities. Workshop members recognized that these contextual questions must be continuously addressed in both the immediate term and the long term, as management of established invasions requires sustained effort (Larson et al. 2011), while resource availability can change with political mandates and annual budget processes. As identified by Redpath et al. (2013), the management context for invasive species extends to consider the public support, political will, community engagement, agency niche, and regulatory framework necessary for management success as these factors often influence resourcing decisions. In both the academic literature and in practice, it is well recognized that community engagement is a key component of conservation success (e.g., Stokes et al. 2006; Cooke et al. 2013; Reed et al. 2018). These considerations go beyond "acceptability" analyses of various management strategies and interventions to recognize the multilayered, nuanced, and often-changing relationships between people and invasive species. For Indigenous communities, in particular, the invasive species designation is linked to colonial timelines, the privileging of a settler-colonial idealization of pre-contact areas as natural or pristine wilderness, and a world view premised on the subjugation of nature (Subramaniam 2014). Interventions to eradicate invasive species may have direct, negative impacts on traditional livelihoods or land tenure claims for Indigenous or marginalized groups and may be seen as part of a suite of "top-down, problem-focused land and resource management interventions" that disrupt the complex and dynamic relationships among people and environments (Reo and Ogden 2018).

Workshop members recognized that without this socio-ecological context for success, the risk of failure may be too high. Members emphasized that programmatic failure could carry severe consequences in terms of jeopardizing management agency appetite or the capacity to tackle invasive species in the future or by creating social conflict that could endanger other management goals (Mackenzie and Larson 2010). For example, while community members may understand the impacts of invasive species, their trust and support for management actions can be complicated by distrust of the management agency, personal experience with the invasive species, and confusion over roles, responsibilities, and mandates of government and scientists (Wald et al. 2019). Some working group members acknowledged the vulnerability inherent in invasive species management and that outside factors can hinder progress and result in the loss of community trust and support. Moreover, community perceptions and behaviours are never static; community views of land and resource management interventions may draw from other social or political views and prior experiences, which may not correlate neatly with specific demographic groups (Stinchcomb et al. 2022). Adequate public and stakeholder engagement in invasive species management may lead to more democratic and less conflict-prone interventions (Crowley et al. 2017; Shackleton et al. 2019).

All workshop participants acknowledged that invasive species can exert both desirable and undesirable influences on invaded ecosystems. The "net benefits" dimension entailed considering the costs and benefits of taking a given management action, which members emphasized must be weighed against the null scenario of taking no management action. For example, if the social, environmental, or economic costs of allowing the invasive alien species to spread and establish are very severe—for example, extirpation or extinction of an endangered species—the tolerance for potential environmental damages associated with an effective suppression strategy or the willingness to pay for a costly management action likely would be high. Members sought a comprehensive costs and benefits assessment that would also consider the persistence or reversibility of impacts from the aquatic invasive species and from the treatment of that invasive species. This net benefits assessment also considers that invasive species can contribute valuable ecosystem services (Hershner and Havens 2008) and that their removal can initiate secondary invasions by other non-native species taking advantage of the ecological disturbance (e.g., Pearson et al. 2016; Robichaud and Rooney 2021). Similarly, management actions were recognized as variable not only in their efficacy but also in their environmental and economic costs. For example, the use of chemicals is likely to achieve greater population suppression than mechanical means of controlling invasive plant species in large areas (Beric and MacIsaac 2015). But there are significant risks: chemicals may have non-target effects (e.g., Beaulieu et al. 2021; Beecraft and Rooney 2021) and risk residue accumulation (e.g., Sesin et al. 2021), particularly where established invasive species require repeated treatments. Thus, the costs and benefits analysis should be tailored to the specific management option being considered.

Working group members used these three dimensions—efficacy, socio-ecological context, and net benefits—to structure a draft consensus decision tree that further postulated three key prerequisites for active management of established invasive species, which we pose as questions in Fig. 2.

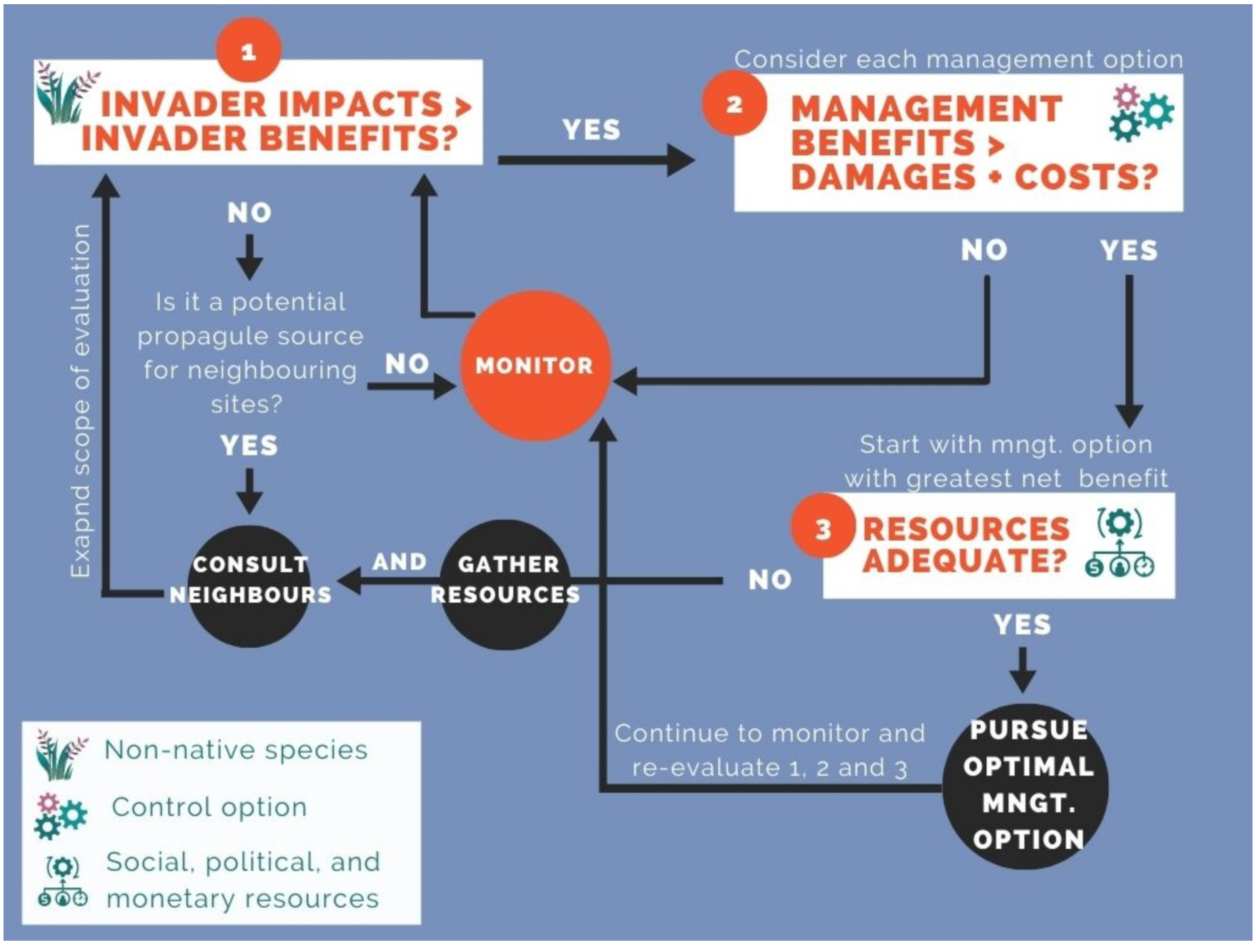
Decision support tools

In the decision tree (Fig. 2, question 1), the effects of the invader on the invaded ecosystem are considered comprehensively, including both negative and positive impacts. To encourage a thorough consideration, the working group members developed a checklist tool (Appendix B). This assessment is scoped to a particular location, given site-specific natural heritage features and landscape context. A manager could consider the available evidence on the effect of the invasive species on a range of environmental (e.g., water quality and floral diversity), economic (e.g., infrastructure maintenance and tourism), and social (e.g., public health and safety and stakeholder interest) factors. The manager could then evaluate whether the net effect of the invasive species on each factor was positive, negative, or neutral given their system knowledge. Factors lacking an adequate basis for assessment could be scored as unknown to highlight knowledge gaps and potential research priorities. The manager could then weigh the prevalence of factors judged to be positive or negative to reach a decision.

Our checklist supports a multi-criteria approach to decision-making (e.g., Liu et al. 2011), with environmental, economic, and social dimensions (Appendix B). We do not provide a prescription for how to weigh positive and negative factors because those choices will depend on specific management goals, management priorities, and the context for managing a given parcel of land. The checklist's purpose is to help managers apply systems thinking to the question of whether to manage an invasive species actively. Individual managers can avail themselves of appropriate rubrics for weighing the relative importance of the factors they list using our checklist. This multi-criteria approach emphasizes an "on the balance" consideration of multiple and disparate criteria by focusing on each factor as net positive, net negative, or neutral rather than attempting to assign commensurable monetary values for factors for which no accepted method of market valuation exists. This emphasis yields a systematic approach to decision-making that evaluates options according to multiple and sometimes conflicting criteria and objectives that managers define a priori.

If the negative environmental, economic, and social effects at the local scale did not outweigh the benefits of the invasion, members agreed that the larger landscape

Fig. 2. Adaptive decision support framework agreed on by members of the working group at the meeting in Fergus. Circles with text indicate actions, and numbered boxes indicate considerations linked to specific decision support tools devised by the working group in breakout sessions. Monitoring plays a central role in the framework, reflecting principles of adaptive management.



context would provide additional insight. If the local parcel of concern could serve as a propagule source to neighbouring lands, then relevant adjacent jurisdictions are consulted and a multi-criteria decision analysis can be repeated between neighbouring landowners or within an integrated land-use management network. If the invasion is not deemed to have a net negative effect on the local or regional system, then members agreed that monitoring could be recommended with periodic re-evaluations of the checklist tool (Appendix B) to engage in adaptive management, whereby a cycle of action, monitoring, analysis, and communication could be repeated to learn about the system being managed (e.g., Núñez-Regueiro et al. 2020).

If the negative environmental, economic, or social effects at the local and(or) landscape scale are deemed to outweigh any benefits of the invasive species, then individual management options are defined and considered in a similar multi-criteria decision analysis (Fig. 2, question 2). This process draws on the dimension of efficacy described above, as the purpose is to identify the optimal management strategy for a given parcel of land among all possible management options.

Working group members defined the net benefits with the following equation:

$$\text{Net benefits}_i = \Delta B_i - \Delta D_i - \Delta C_i$$

In this equation, the net benefits of management strategy "i" (Net benefits$_i$) equal the change in ecological benefits to the invaded ecosystem due to management strategy "i" (ΔB_i), minus the change in damages to the invaded ecosystem imposed by management strategy "i" (ΔD_i) and the change in monetary costs of managing the land if strategy "i" were implemented (ΔC_i). Thus, the management action most effective at suppressing the invasive species population under the current site conditions is not necessarily the optimal choice if it presents a significant risk of non-target effects or imposes unjustified financial costs. While the change in management costs for a given strategy would likely be positive, a strategy could free up resources when compared with the current management approach. Therefore, the formula calls for consideration of the change in management costs rather than the simple cost of each candidate strategy. The challenge is combining the environmental benefits and damages with

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the financial costs of management, as these are not in equivalent units. Manager discretion will be needed to implement this formula, but the explicit representation of changes to environmental benefits, damages, and costs associated with each management strategy could support managers in ranking their options.

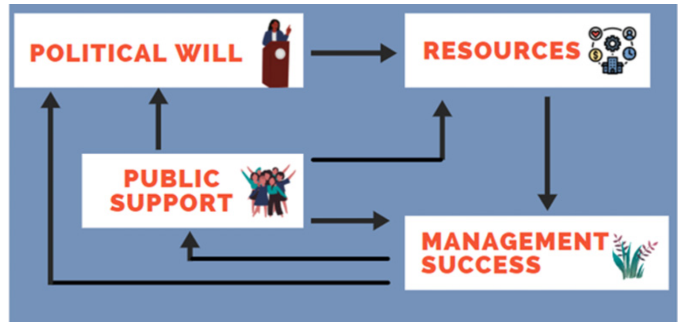
If no available management option has benefits that would outweigh the sum of its damages and costs, then managers could continue to monitor and support research into improved treatment technologies that are either lower cost or that present less risk to the treated ecosystem. If multiple management options exist with positive net benefits, then the option with the greatest net benefit could be favoured, though working group members highlighted that this optimal technique or action may only be undertaken if sufficient resources and socio-political support are in place to have a high probability of success in achieving the management goals for that property (Fig. 2, question 3). Management goals are set by the managers for a given parcel of land and likely reflect the stage of invasion (Fig. 1).

Among the alternative actions, managers are encouraged to consider the "no control" option, thus permitting the invasion to progress. We emphasize that this decision may be, in some cases, an appropriate course of action. "No control" is not necessarily an abdication of responsibility, especially if it is a considered decision, but under the workshop framework it is crucial to recognize that a decision not to control the invasion does not mean that managers are expected to take no action. As emphasized by its centrality in Fig. 2, monitoring is expected to accompany any management action and especially the "no control" action. Monitoring the invasive species may provide an experimental control to learn how an invasion progresses in the absence of active management. These monitoring data can advance our knowledge and be extremely valuable to inform subsequent decision-making. In this way, our decision framework (Fig. 2) lends itself well to an adaptive management framework, whereby the outcome of management decisions feed into future decision-making. For example, we only learned that *Phragmites australis* ssp. *australis* invasion can be benign at early invasion stages by monitoring before acting (Robichaud and Rooney 2017). However, we caution against managers defaulting to monitoring rather than control actions due to a perceived lack of specific, place-based knowledge as this can impede critical action required to save threatened species (e.g., Buxton et al. 2020).

Considerations

When defining the socio-ecological context dimension, members emphasized that aquatic invasive species management can be conflict-prone (e.g., Stokes et al. 2006) and that meaningful, substantive stakeholder engagement and social impact assessment can lead to greater success in achieving management objectives (Crowley et al. 2017). Working group members asserted that the opposite is also true: the loss of political will and public support or the rise of social conflict can ensure management failure through resource reallocation and mandate redirection before eradication is achieved. Support and resources thus form a positive feedback loop (Fig. 3), whereby support is necessary to secure resources for management but is also dependent on successful outcomes and avoidance of non-target effects of management. Under-resourcing the management of an invasive species can lead to failure, which workshop participants noted further erodes support and can lead to continued resource withdrawal.

Fig. 3. The recursive relationship between resource availability (e.g., personnel, funds, time, and knowledge base) and management success is mediated by interrelated elements of political and public support for management. This figure was prepared for the paper after the workshop.



Working group members agreed that a comprehensive assessment of the resources necessary for sustained implementation of a management strategy needs to be considered carefully and that management should commence only once the resources necessary to sustain it are in place. Until then, managers can focus on gathering resources and fostering both the public and political support needed to ensure success (Fig. 2, question 3). Collective action can be a powerful approach to setting the stage for successful management through resource pooling and coordinated efforts (Braun et al. 2016). Managers can consult the agencies or groups charged with the management of neighbouring jurisdictions to build partnerships in support of their optimal management strategy (Fig. 2). To promote a comprehensive assessment of resource needs and socio-political support, the working group members devised a list of questions managers can ask themselves before undertaking their optimal management action (Appendix C).

When active management of an invasive species is deemed necessary, there may be numerous options that vary in effectiveness at suppressing the species, in their potential to damage the treated ecosystem, and in the resources needed to complete the management. We encourage managers to weigh the changes in costs, damages, and benefits comprehensively before selecting the management action that yields the greatest net benefit. Such an analysis may provide insight into whether there is a need for more fundraising, greater engagement with stakeholders, or further research into alternative management approaches.

Where feasible, eradication can be more environmentally and ethically sound than sustained suppression efforts, as eradication may not perpetually usurp management resources or foster reliance on tools like pesticides (Cloute and Veitch 2002). However, ongoing management efforts may be required where eradication is impossible due to widespread establishment and a high potential for reinvasion from neighbouring properties. The resource needs to sustain long-term goals such as asset protection and slowing the spread can be large (Hazelton et al. 2014), yet resource availability can ebb and flow with public and political support (Fig. 3). It is important to consider the long-term sustainability of management interventions to avoid failure resulting from inadequate resources. Managers may work to set aside resources to monitor the effect of the intervention adequately (e.g., both pre- and post-intervention), interpret the monitoring data, and disseminate the data to key stakeholders. If managers have not prepared in these ways, they may risk alienating stakeholders and souring community and political opinion in ways that may jeopardize subsequent control efforts. It is crucial to invest in social impact analysis and engage stakeholders to help nurture the conditions necessary to succeed (Crowley et al. 2017), leading to greater support in the future.

Conclusion

The framework derived by our interdisciplinary working group highlights the challenge and complexity of managing invasive species that are well established and entrenched within a landscape (i.e., late in the invasion curve), when eradication is not perceived as a suitable management goal. Key advantages of our approach include that it engaged experts and practitioners from multiple disciplines and brought them to consensus on a decision support framework that promotes systems thinking.

The importance of systems thinking in decision-making about invasive species management was a consistent message emerging in our working group. Critically, applying a systems lens to the problem of invasive species management requires that decision makers move well beyond cost-benefit analysis, where all factors must be expressed in common monetary units to be incorporated in the decision-making process. Notably, members emphasized that the reversibility or persistence of costs and impacts from either the aquatic invasive species or suppression efforts should also be weighed. More flexible multi-criteria decision-making approaches can enable more holistic assessment of costs and consequences that are not easily assigned a monetary value.

Given the variability in site conditions and management approaches, eradication of non-native *Phragmites* at the landscape scale is very difficult to achieve and(or) may easily be undone by reinvasion from uncontrolled neighbouring populations (Hazelton et al. 2014). Evaluation of the common default position of widespread management is important because alien species, even ones that negatively affect native species and could qualify as "invasive" by our definition, may provide ecological, economic, or social benefits in some contexts. Failing to consider these potential benefits can lead to net ecological degradation and negative social impacts such as increased conflict among stakeholders. Leaving the invasion to progress unchecked also imposes a cost, so it is vital that such cost-consequence accounts consider the change in management costs rather than the simple cost of alternative management strategies.

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The authors declare no competing interests.

Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/facets-2022-0200.

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