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An adaptive management implementation framework for evaluating supplemental sea lamprey (*Petromyzon marinus*) controls in the Laurentian Great Lakes ☆

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ABSTRACT

Invasive sea lamprey (*Petromyzon marinus*) populations in the Laurentian Great Lakes Basin have been suppressed for over 60 years primarily by migration barriers and lamprey-specific pesticides. Improving control outcomes by supplementing barriers and pesticides with additional control strategies has been a long-standing objective of managers and stakeholders, but progress towards this objective has been limited. We developed an adaptive management implementation framework and applied it to this objective. The framework consists of a set of adaptive management implementation goals (develop effective monitoring practices, develop effective participatory process, and conduct management experiments), a set of aspirational targets hypothesized to be related to Sea Lamprey Control Program adaptive capacity (multi-level political and social organization, creation of safe-to-fail decision making arenas, and effective use of multi-criteria decision analysis), and a feedback loop linking adaptive capacity and progress towards adaptive management implementation goals. Progress towards improving sea lamprey control outcomes by integrating supplemental control strategy into the Sea Lamprey Control Program may be possible through adaptive management implementation.

Introduction

Invasive, non-native sea lamprey (*Petromyzon marinus*) populations in the Laurentian Great Lakes Basin are controlled by the Sea Lamprey Control Program (SLCP) coordinated and funded by the Great Lakes Fishery Commission (GLFC; Gaden et al., 2013). Sea lamprey inhabit rivers and streams as larvae, metamorphose from filter-feeding larvae to the juvenile parasitic life stage, and then out-migrate into the Great Lakes to feed on large-bodied fishes for up to 18 months (Applegate, 1950). The SLCP operates on the assumption that sea lamprey inhabiting connected lake basins comprise panmictic populations because there is little evidence that, upon completion of the parasitic life stage, adult sea lamprey preferentially return to natal spawning grounds (Bergstedt and Seelye, 1995; Swink and Johnson, 2014). During their parasitic juvenile stage, sea lamprey can cause high mortality rates on economically and ecologically important fish populations (Smith and Tibbles, 1980). However, the success of the SLCP is demonstrable; the program operates at a cost well below the estimated benefits to Great Lakes fisheries (Irwin et al., 2012) and suppression of sea lamprey populations has allowed for the recovery of some lake trout (*Salvelinus namaycush*) populations (Hansen and Bronte, 2019; Heinrich et al., 2003) and maintenance of many other valuable recreational fisheries (Southwick Associates, 2012).

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The primary management strategies used to control sea lamprey are barriers on Great Lake tributaries that impede sea lamprey migration during spawning periods (Zielinski et al., 2019) and the application of selective pesticides (herein termed lampricides) to sea lamprey larval habitat in tributary systems. While these management strategies have been extremely effective in reducing populations of sea lamprey in the Great Lakes (Robinson et al., 2021), the strategies can be impediments to other natural resource conservation objectives. Barriers to sea lamprey migration limit habitat connectivity for desirable fishes and limit natural reproduction and recovery of valued fish populations (Vélez-Espino et al., 2011); lampricides can result in non-target mortality of desirable fishes and aquatic invertebrates (Boogaard et al., 2003; Dahl and McDonald, 1980; Waller et al., 2003). Additionally, overreliance on lampricide increases the risk that sea lamprey will develop genetic-based resistance to this control strategy and limit future efficacy (Christie et al., 2019; Yin et al., 2021). Consequently, improving sea lamprey control by supplementing barriers and lampricides with additional control strategies has been a long-standing goal of the SLCP (Christie and Goddard, 2003; Lamsa et al., 1980; Siefkes et al., 2021). Applying and evaluating supplemental control strategies using adaptive management could support progress towards this goal.

Adaptive management is an approach to natural resource management that emphasizes accumulation of reliable ecological knowledge and social learning (Holling, 1978; Lee, 1994). A key feature of adaptive management is feedback between learning and decision making (Hughes et al., 2007; Walters, 1986; Williams et al., 2009). This can be represented as a two-phase learning process consisting of an iterative phase, that makes use of monitoring data to make incremental adjustments in decision making, and a set-up phase, that is periodically revisited to institutionalize reframing of decision-making objectives and stakeholder participation (Williams, 2011). However, there are multiple, although somewhat overlapping, approaches to adaptive management (McFadden et al., 2011; Williams, 2011) and related forms of adaptive governance. For example, indigenous natural resource governance systems implement core-tenets recommended by adaptive management (Berkes et al., 2000). Conceptual advances in adaptive governance and adaptive co-management have integrated participatory democracy principles (Cundill and Rodela, 2012) and explored how social-ecological system characteristics may enable social learning and feedback between learning and decision making (Armitage et al., 2008, 2009; Folke et al., 2005; Olsson et al., 2004). Advances in adaptive-governance concepts are useful to consider for adaptive management practitioners because adaptive management and adaptive governance are closely linked. Adaptive governance depends upon feedback loops between decision-making and learning processes created through adaptive management; features of adaptive governance, multi-scale coordination, flexibility, and inclusiveness, may be key to successful adaptive management implementation (Chaffin et al., 2014).

Accumulation of ecological knowledge through adaptive management can be accomplished opportunistically (passive adaptive management) or with a deliberate plan for learning (active adaptive management) that will improve long-term ability to meet natural resource management objectives (Shea et al., 2002). For the latter case, system dynamics are monitored and management strategies are enacted with the intent of learning about how the system behaves. Active adaptive management requires investment in monitoring that results in opportunity costs, as resources used to monitor for learning are not available for implementing management actions. Channeling resources towards monitoring may be most beneficial when collected data effectively reduce uncertainty and reductions in uncertainty lead to improved management decisions (Fenichel and Hansen, 2010). Therefore, a monitoring program guided by tractable questions (e.g., Lindenmayer and Likens, 2009) and linked to management decisions can help ensure gains in long-term ability to inform decision making outweigh the opportunity costs of implementing active adaptive management.

Reviews of adaptive management case studies and practitioner's experience underscore that, although adaptive management offers an intuitive, promising approach to achieving challenging natural resource management objectives, it can be difficult to carry out in practice (Allen and Gunderson, 2011; McLain and Lee, 1996; Walters, 2007). One conceptual misstep is considering adaptive management an apolitical process (Voß and Bornemann, 2011). Decision makers may be reluctant to support adaptive management initiatives when the perceived risk of failure is high. Stakeholders and decision-makers may actively oppose one another, rather than work collaboratively towards common objectives. Given the potential for widely different viewpoints and values among stakeholder groups and decision makers, stakeholder participation and engagement with decision makers early in the adaptive management process is critical for establishing common expectations, acceptance of outcomes, and for identifying and resolving uncertainties that can shift decision making (Allen and Gunderson, 2011; Lee, 1994).

A strategy of supplemental control based on integration and synergy of sea lamprey control tactics targeting adult and out-migrating juveniles with established control tools (lampricide and barriers) may lead to improved sea lamprey control outcomes compared to strategies solely relying on established tools (Siefkes et al., 2021). However, a roadmap for working towards this goal does not exist. Our objective here is to address this deficit by developing an adaptive management implementation framework for invasive sea lamprey control in the Great Lakes and to provide guidance on how to apply this framework towards evaluation of experimental supplemental control interventions.

Adaptive management implementation framework for invasive sea lamprey control

The context for sea lamprey control adaptive management is a biologically invaded social-ecological system, where invasive sea lamprey negatively affect Great Lakes fisheries valued by resource users, control actions mitigate sea lamprey induced damage to fisheries, and non-target effects of control actions can negatively affect other valued resource systems (Fig. 1). The strategic objective of adaptive management implementation is to build towards a SLCP system state with highly developed adaptive capacity in each of the structure, process, and culture domains; thereby, improving long-term ability of the SLCP to achieve desired sea lamprey control outcomes (Fig. 2). Here, SLCP adaptive capacity is defined, following Engle's (2011) treatment of adaptive capacity, as the capacity of the SLCP to remain in or transition towards a desired system state. A feedback loop exists between achievement of adaptive management implementation goals (develop effective monitoring, develop effective participatory processes, and conduct management experiments) and SLCP adaptive capacity (Fig. 2). Increasing SLCP adaptive capacity facilitates achievement of adaptive management implementation goals and progress on adaptive management implementation goals further increases SLCP adaptive capacity. Aspirational targets hypothesized to increase SLCP adaptive capacity are multi-level political and social organization, effective use of multi-criteria decision analysis, and creation of safe-to-fail decision making arenas (Fig. 2).

Social and political organization

The Convention on Great Lakes Fisheries (GLFC, 1954) and the resulting formation of the GLFC to enact the duties of the conven-

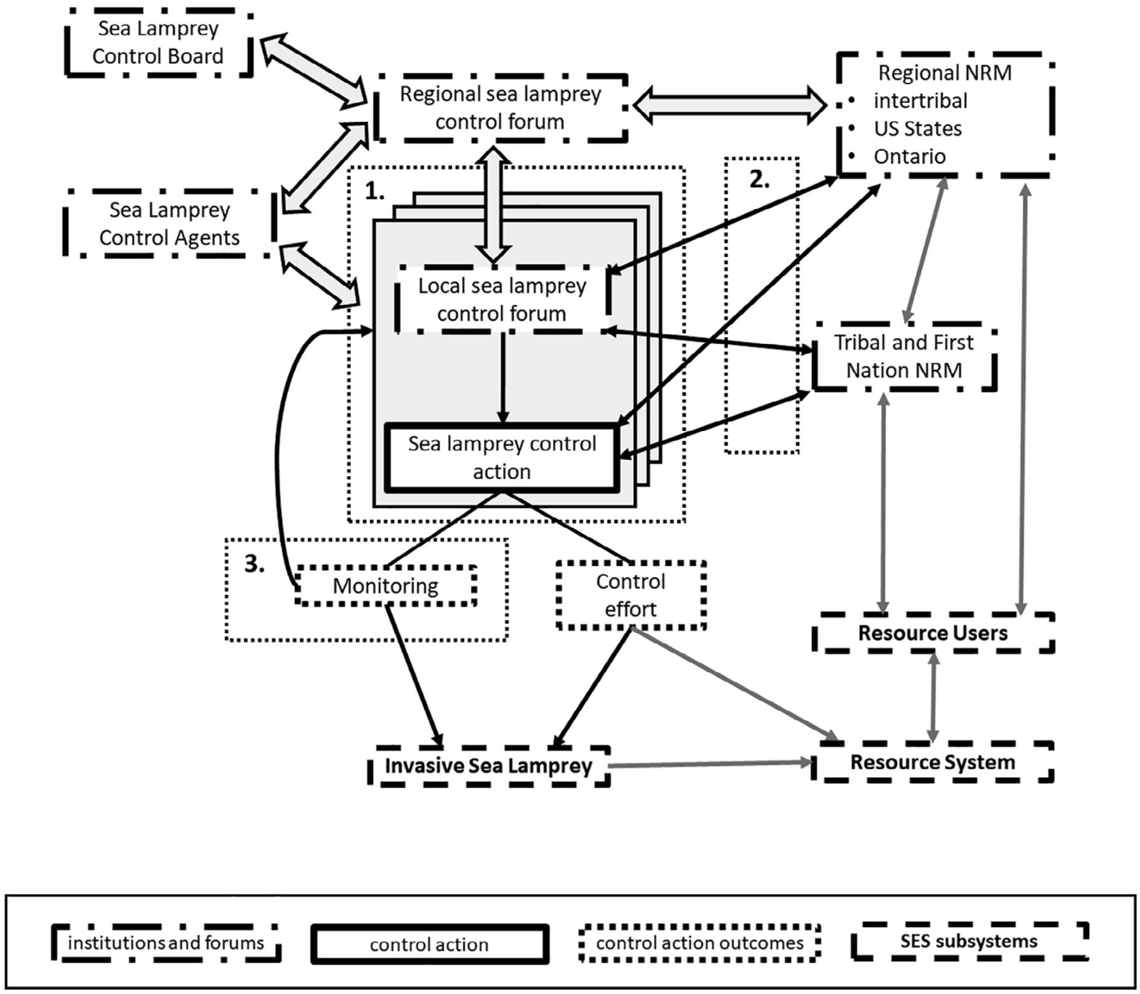

Fig. 1. Conceptual model of multilevel sea lamprey control social and political organization and control actions situated within the Great Lakes social-ecological system (SES) showing interactions among governance institutions (NRM = Natural Resource Managers) and forums, control actions and outcomes, and SES subsystems. Straight block arrows represent linkages currently enabled by the Great Lakes Fishery Commission's fulfillment of the Joint Strategic Plan for Great Lakes Fishery Management, numbered boxes indicate the scope of adaptive management implementation goals developed in the text, and solid grey arrows represent key linkages that are not discussed herein.

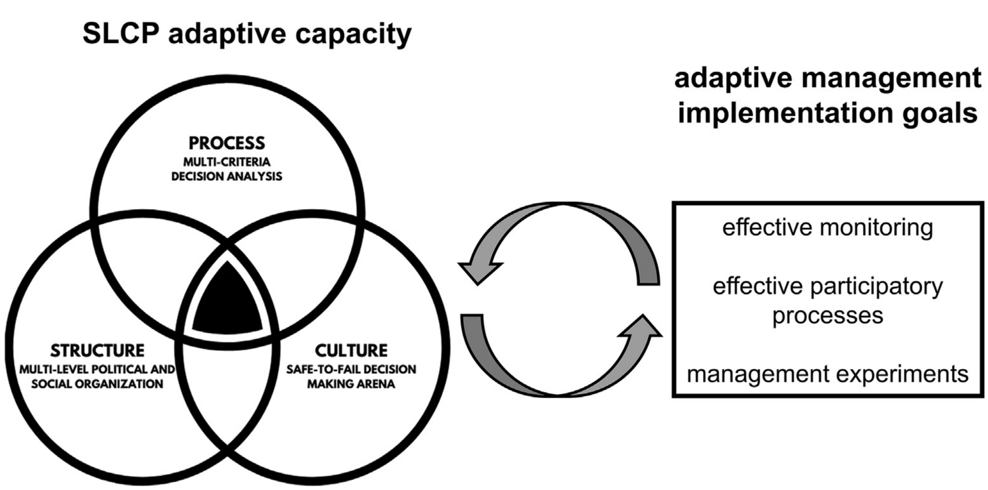

Fig. 2. An adaptive management implementation framework for invasive sea lamprey control in the Great Lakes showing feedback between Sea Lamprey Control Program (SLCP) adaptive capacity and adaptive management implementation goals. Increasing adaptive capacity facilitates achievement of adaptive management implementation goals and progress on adaptive management implementation goals further increases adaptive capacity. Effectively evaluating multi-objective management outcomes using multi-criteria decision analysis, creating safe-to-fail decision making arenas, and multi-level political and social organization are aspirational objectives hypothesized to increase SLCP adaptive capacity. The shaded region, representing highly developed adaptive capacity within process, structure, and culture domains, is the strategic objective for adaptive management implementation.

tion provided the institutional framework for implementing the Great Lakes Basin-wide SLCP. A Sea Lamprey Control Board and representatives from intertribal (1854 Treaty Authority, Chippewa-Ottawa Resource Authority, Great Lakes Indian Fish and Wildlife Commission), US State (Minnesota, Wisconsin, Illinois, Indiana, Michigan, Ohio, Pennsylvania, New York), and the Province of Ontario fisheries management agencies direct sea lamprey control efforts through a set of institutions and processes enabled by the GLFC (Gaden et al., 2013, 2008) for deliberating sea lamprey control options at the regional and basin-wide scale (regional sea lamprey control forum; Fig. 1). Even though lake-wide reductions in parasitic sea lamprey abundance is the aim of control, individual control actions nevertheless occur at river system or reach scales. Sea lamprey control agents (US Fish and Wildlife Service and Fisheries and Oceans Canada) engage with collaborating natural resource management institutions to decide upon suitable control actions at the local scale that maximize reductions in sea lamprey production while minimizing non-target effects on other valued resource systems (local sea lamprey control forum; Fig. 1).

Aspirational targets

We identified *multi-level political and social organization* as a key aspirational target for increasing SLCP adaptive capacity within the structure domain. Other aspirational targets expected to increase SLCP adaptive capacity are directly tied to decision-making and learning processes that fall within the culture and process domains. Specifically, the creation of *safe-to-fail decision making arenas* and the ability to effectively make decisions that consider multiple, possibly competing, management objectives, using *multi-criteria decision analysis* (MCDA). Here, we present these concepts in more detail and highlight linkages with adaptive management implementation.

Multi-level political and social organization

Enacting sea lamprey control as a set of collaborative management experiments at the community scale, with regional forums and institutions enabled by the GLFC facilitating coordination and sharing of knowledge (i.e., acting as a bridging organization; Berkes 2009), may contribute towards successful adaptive management implementation. The hypothesized mechanism is increased ability to address both regional sea lamprey control objectives and goals associated with non-target control effects, which may presently be more localized and tend to occur at the community scale. Organizational schemes containing multiple levels of political and social organization, such as what we propose here, are a characteristic of successfully implemented community-based conservation programs with both local and extra-local objectives (Berkes, 2007). Along with a multilevel organizational scheme, adaptation of multiple evidence-based approaches that foster synergies between diverse knowledge systems enhances collaboration (Mattes and Kitson, 2021; Reid et al., 2021; Tengö et al., 2014). Collaborative approaches to monitoring and natural resource management, compared to centralized approaches, can lead to improved understanding of ecosystems, social learning, and generation of actionable monitoring information (Fernandez-Gimenez et al., 2008).

Safe-to-fail decision making arenas

Within safe-to-fail decision making arenas, both expected and unexpected outcomes of natural resource management actions are tolerated, beneficial learning opportunities are identified and capitalized upon, and risk is managed (Allen and Gunderson, 2011). We further develop this concept based on ideas presented in adaptive management and organizational learning literatures.

Organizational learning studies have explored linkages between experiential learning outcomes and attitudes towards unexpected results of management actions. Organizational work groups hold tacit beliefs about appropriate responses to failure, defined as deviation from expected and desired outcomes, and these beliefs vary substantially among groups (Cannon and Edmondson, 2001). Experiential learning is facilitated by responses to failure that allow for failures to be identified, discussed, and analyzed and ensuing conflicts to be handled productively (Cannon and Edmondson, 2001). Attitudes towards failure and the need to project an image of decisiveness likely explain why program administrators rarely enact organizational experiments, a type of experiential learning (Huber, 1991). Furthermore, responses to failure that only allow for dissemination of findings expected to be viewed favorably can curtail learning from organizational experiments (Huber, 1991).

Safe-to-fail concepts from the adaptive management literature consider the balance of risk and learning opportunity. Here, there is emphasis on developing tools and heuristics that can be used to envision or identify scenarios in which long-term benefits from learning outcomes associated with management experiments are more valuable than losses incurred by the experiment (Walters, 1986). Quantitative methods for evaluating the value of learning in terms of expected improvements to future management outcomes have been developed for diverse management applications (Atkins et al., 2020; Chadès et al., 2017; Groot and Rossing, 2011). The need for tools that discern the value of management experiments implies that not all management experiments are worth the risk or added cost. This idea is made explicit by heuristics presented in Allen and Gunderson (2011) that define the safe operating space for adaptive management as scenarios with high controllability over experimental treatments, high learning potential due to high system uncertainty, and low risk.

Creating safe-to-fail decision making arenas is a multifaceted challenge, but strategies for both enhancing organizational learning by breaking down barriers to critical reflection and creating low-risk, high-reward scenarios for enacting management experiments can offer some guidance. Framing natural resource management and experiential learning as intrinsically connected endeavors may be a simple, yet powerful, approach for creating a culture of learning that is tolerant of unexpected outcomes. This framing, put succinctly by Lee (1994), is to consider that "[management] experiments often bring surprises, but if resource management is recognized to be inherently uncertain, the surprises become opportunities to learn rather than failures to predict". A clear goal of creating an organizational culture with pro-learning attitudes, such as the one articulated by Lee (1994), combined with effective leadership is one strategy shown to be effective at reframing unexpected outcomes as learning opportunities (Cannon and Edmondson, 2001).

An operational strategy for decreasing risk and increasing learning is to construe large-scale management applications as spatial subsets, with each subset providing an opportunity to evaluate a management treatment. This increases learning capacity by increasing statistical power, creating capacity to simultaneously test multiple treatments, and creating capacity to examine relationships with spatial habitat variables (Shea et al., 2002). Spatial subsetting of large-scale management applications is also associated with risk management. Lister (2007) observes that "[experimental] projects should be small enough that if they are not successful, they can fail safely, without endangering an entire community, ecosystem, watershed, or habitat".

In the context of enacting management experiments related to sea lamprey control, a spatial subsetting operational strategy would be to consider stream-scale, rather than lake-basin scale, control applications as experimental units. Conducting experimental control actions at the stream-scale allows for learning opportunities that would not incur substantial risk to Great Lakes fisheries and the ability to consider experimental design with replicates and controls. In comparison, testing novel strategies for controlling sea lamprey at the lake-basin scale or modifying existing control strategies to learn about system dynamics may lead to unacceptable levels of risk for fishery managers and society and diminished learning capacity. However, as sea lamprey production from large individual river systems could have drastic basin-wide effects on sea lamprey populations (Jensen and Jones, 2018), perceived risk by managers is still salient in localized sea lamprey control trials. Collaborative adaptive management implementation leading to deliberation of tradeoffs and synergies between learning opportunities, long-term control outcomes, and short-term risk may lead to acceptance from fishery managers and society of both expected and unexpected outcomes of sea lamprey control management experiments.

Multi-criteria decision analysis

Multi-criteria decision analysis (MCDA) encompasses a collection of formal approaches to decision making in which individuals or groups take into account multiple criteria that have been identified as being important (Belton and Stewart, 2002). Decision makers involved in MCDA can include government officials, subject-matter experts, resource users, and stakeholders (Mendoza and Martins, 2006). MCDA approaches that are capable of decomposing complex problems into component parts though formal decision analysis, facilitating stakeholder participation, consideration of what is valued and by whom, and consideration of both well-defined and wicked uncertainty (Mendoza and Martins, 2006) are well suited to guiding invasive species control actions (Binimelis et al., 2007; Robinson et al., 2021).

Applying MCDA towards ranking multiple supplemental and lampricide sea lamprey control strategies would involve predicting the value of sea lamprey control outcomes and costs of non-target effects. Reliable predictions of costs and benefits requires identification of relevant stakeholder groups and knowledge of the resource systems valued by these stakeholders. Accomplishing these tasks will require multilevel learning (Pahl-Wostl, 2009) supported by effective participatory processes that enable social learning and iterative reframing (Williams 2011) of sea lamprey control MCDA. Furthermore, while existing regional sea lamprey control forums supported by the GLFC (Gaden et al., 2008) are well-suited for deliberating the value of suppressing sea lamprey in the Great Lakes, the ability for decision makers to reliably predict the outcomes of and assign value to individual sea lamprey control actions is presently limited. Implementing effective monitoring practices and experimental management treatments would help address this challenge by building capacity for more reliable prediction of sea lamprey control outcomes through accumulation of ecological knowledge.

Adaptive management implementation goals

The characterization of adaptive management as a learning process emphasizing accumulation of reliable knowledge through ecological monitoring and social learning (Lee, 1994) guided the development of two adaptive management implementation goals in our framework, *develop effective monitoring* and *develop effective participatory processes.* Though adaptive management depends upon social learning, we determined that development of participatory processes, which leads to conditions favorable to social learning, provides a more tangible implementation goal compared to a goal directly related to social learning. The relationship between participation and social learning is such that social learning is supported through stakeholder participatory processes that allow for collaborative sharing of knowledge in a trusting environment (Cundill and Rodela, 2012). Increased ability to learn about system uncertainties by adopting active verses passive adaptive management (Walters, 1986) is the rationale for the goal *conduct management experiments*. A plan for learning guides experimental design of management experiments (Shea et al., 2002). Our initial plan for learning is focused on learning about how supplemental control strategy (Siefkes et al., 2021) could improve long-term sea lamprey control outcomes.

In the following sections of this manuscript, we propose how to work towards these adaptive management implementation goals. We present an initial experimental design and scope for experimental control interventions (Fig. 1, Box 1), guidance for developing participatory processes at the stream scale (Fig. 1, Box 2), and a conceptual model and set of guiding questions for directing effective monitoring practices (Fig. 1, Box 3).

Initial scope and design of experimental control interventions

The initial experimental design and scope we present here was developed by a workgroup composed of sea lamprey control agent staff, with support from GLFC and USGS staff (authors of this manuscript). As an action item originating from interactions between control agents, the Sea Lamprey Control Board, and GLFC secretariat staff, the workgroup developed a research proposal outlining an experimental design that included a description of the experimental control intervention to be tested, a set of candidate systems delineating the scope of the management experiment, and a methodology for assessing the outcomes of experimental control interventions (see *Development of Effective Monitoring Practices*). The GLFC committed funding for this effort over a four-year period in these candidate systems starting in 2020 (Siefkes et al., 2021). Pending evaluation of the success of the initial four-year phase of the program, the GLFC further committed to maintain longer term (i.e., 12 year) continuity of this effort and work towards developing the knowledge, social capital, and policy needed to integrate supplemental control strategies more broadly into the SLCP and increase the effectiveness of invasive sea lamprey control in the Great Lakes (Siefkes et al., 2021). Moving forward, participatory processes that include sea lamprey control agents, researchers, and representatives from cooperating natural resource management institutions will be critical to effective updating of the experimental design and scope of experimental sea lamprey control interventions.

Experimental control interventions

In our design, experimental control interventions comprise lampricide control and supplemental control. A lampricide control intervention consists of lampricide treatment followed by 3 or 4 years with no control intervention (status quo lampricide control). A supplemental control intervention consists of a lampricide treatment combined with supplemental controls followed by 3–6 years of only supplemental controls. Supplemental and lampricide interventions will be alternated within each experimental unit. Tactics targeting adult sea lamprey will be deployed, standalone or in concert, with the goal of reducing reproductive potential by at least 90%, as empirical data suggest that this level of control is feasible (Johnson et al., 2021a,b). The order of treatments will be governed by logistics (planning for maintaining similar staff day requirements across years) and when plans for deploying supplemental controls become finalized for a given experimental unit.

A suite of sea lamprey control tactics targeting the out-migrating juvenile and upstream migrating adult life stages could be included in supplemental control interventions. Specifically, portable traps with electrical (Johnson et al., 2016) or physical leads can capture and remove migrating adults, portable electric barriers can divert migratory adults from spawning and larval-rearing habitat, and sterile-male-release technique can reduce fertility (Bravener and Twohey, 2016). Additionally, the efficacy of trapping or diversion tactics can be improved by applying alarm cue and natural attractants in a push–pull configuration (Hume et al., 2020; Johnson et al., 2019). These individual tactics have tradeoffs related to effectiveness, non-target impacts, and cost, but their integration could yield a viable sea lamprey control strategy capable of supplementing existing control strategies, particularly in systems where existing sea lamprey control strategies incur costly non-target effects or have low control efficacy (Miehls et al., 2021; Siefkes et al., 2021).

Stream selection

Stream selection is critical to the experiment's success. In selecting these candidate streams, the highest priority was given to streams where supplemental sea lamprey controls were most likely to reduce juvenile sea lamprey production. Recent work by Miehls et al. (2021) found that control strategies that reduced reproduction were most likely to reduce production of parasitic juvenile sea lamprey when applied to streams that regularly produce larvae, have lower than average lampricide treatment efficacy, and have low density of adult sea lamprey relative to larval habitat. Of the roughly 75 streams in the Great Lakes that meet those criteria, 13 streams were ranked highly when also considering proximity to field stations, opportunities for collaboration with local agencies and communities, and the ability to quantify larval sea lamprey density with standard electrofishing equipment (Steeves et al., 2003). These 13 candidate streams are geographically located on the south shore of Lake Superior ($n = 4$), northern Lake Michigan ($n = 2$), and northern Lake Huron ($n = 7$) and require regular sea lamprey control effort (Fig. 3). The expected cost to treat these streams is over $1 million USD (treatment occurs about once every 4 years) and, in combination, they can produce over 3 million larval sea lamprey if not treated with lampricide (Table 1). Assuming maximum larval production is achieved in these streams (3 million larvae pre-treatment) and lampricide treatments kill 90% of larvae, 300,000 larvae could survive lampricide treatment in these systems and ultimately contribute to juvenile production. As a single juvenile can destroy 6.8–19.3 kg of fish (Swink, 2003), fishery restoration goals would benefit if supplemental control strategy further reduces juvenile production in candidate streams.

Development of participatory processes

Developing participatory processes that include cooperating natural resource management institutions and sea lamprey control agents at the scale of individual sea lamprey control actions (Fig. 1) may help mobilize both local and expert knowledge from within the SLCP and enable social learning. Participation can be included in all stages of learning processes associated with sea lamprey control (establish context, establish goals and strategies, and implement monitoring and management interventions) and can encompass informal and formal interactions. However, the question posed by Moellenkamp et al. (2010), "who should initiate and convene a participatory process in an already complex system of administrative competencies and power relations?" illustrates the quandary of a fully prescriptive approach towards participatory process development. In their analysis of a participatory process developed for deliberating river connectivity in a sub-basin of the Rhine River of Germany, Moellenkamp et al. (2010) found that, even within formalized legal and administrative structures, effective participatory processes developed in niches enabled by interplay between informal and formal interactions. A simple lesson from their research is to pursue collaborative approaches in both formal decision-making and informal monitoring and control implementation during the adaptive management process. Furthermore, formal and informal participatory processes combined can build both procedural and affinitive trust (Song et al., 2019). Pursuing development of multiple forms of trust may allow for strengths in one type to buffer deficits in the other and increase the likelihood of developing participatory processes supportive of social learning.

Fig. 3. Geographic location of the 13 streams where supplemental sea lamprey controls are likely be tested and evaluated in an adaptive management framework. These streams regularly produce larval sea lamprey, are wadable, near cooperator field offices, and are places where larval production is difficult to control using barriers or lampricides. Furlong Creek is a tributary to the Millecoquins River. Bills Creek is a tributary to the Whitefish River. Bellevue Creek is a tributary to the Goulais River.

Table 1
List of candidate streams delineating the scope of adaptive management implementation that will include experimental applications of supplemental control interventions. Stream characteristics outlined include the average cost for lampricide treatment, average frequency of lampricide treatment, the date of the last lampricide treatment, the maximum estimated number of sea lamprey larvae that could be produced, average adult abundance estimated via trapping, and average stream width. An asterisk indicates that estimates of adult abundance are only available from 2020. NA = not available.

Stream	Treatment Cost US Dollar	Treatment Frequency	Last Treatment	Max Larval Production	Adult Abundance	Average Width
Cranberry River	$70,000	3 years	Sep-2018	600,000	50*	10 m
Potato River	$120,000	3 years	June-2021	150,000	NA	12 m
Traverse River	$75,000	3 years	May-2021	225,000	150*	7 m
Bills Creek	$45,000	3 years	Aug-2018	60,000	NA	6 m
Furlong Creek	$40,000	4 years	Jun-2017	95,000	NA	8 m
Beavertail Creek	$50,000	4 years	Jul-2018	50,000	NA	6 m
Bellevue Creek	$50,000	4 years	Jul-2019	75,000	50*	6 m
Root River	$50,000	4 years	May-2016	150,000	500	10 m
Pigeon River	$200,000	4 years	Sep-2016	350,000	30	12 m
Sturgeon River	$150,000	4 years	Sep-2016	800,000	30	12 m
Maple River	$100,000	4 years	Sep-2016	200,000	30	12 m
Black Mallard River	$70,000	4 years	May-2019	45,000	500	10 m
Long Lake Outlet	$25,000	4 years	Aug-2021	10,000	300	10 m
Tawas Lake Outlet	$50,000	3 years	Aug-2018	275,000	50*	7 m
	$1,095,000			3,085,000		

Establish context

Identifying which stakeholders should be involved in decision making processes for pragmatic or normative reasons and developing an agreed-upon conceptual system model provides context for setting natural resource management goals and strategies (Reed et al., 2006; Stringer et al., 2006). Participatory modeling is a learning process that engages stakeholder knowledge to create a formalized and shared representation of reality (Voinov et al., 2018), which could help engage stakeholders in the process of building conceptual models of ecological and social outcomes for the question at hand. For identifying stakeholders that should be involved in decision-making, an iterative approach starting with dialogue among cooperating natural resource management institutions with jurisdiction over a candidate system for experimental sea lamprey control intervention and sea lamprey control agents may be effective. Cooperating agencies can then identify other pertinent organizations or citizens who may have a stake in local outcomes of sea lamprey control actions.

As learning occurs through the adaptive management process, stakeholder involvement and conceptual models should be revisited to account for changes in objectives. For example, the U.S. Fish and Wildlife Service initiated waterfowl adaptive harvest management (AHM) with the primary goal of setting science-based harvest policies (Nichols et al., 2007). Twenty years after implementation, aspirational AHM objectives had shifted towards the integration of harvest and habitat management (Johnson et al., 2015), representing a large shift in context that would necessitate further deliberation of which stakeholders should be involved in AHM.

Establish goals and strategies

Participatory processes for setting goals associated with sea lamprey control outcomes from a regional fishery management perspective have been clearly established (Gaden et al., 2008). However, decision making processes related to minimizing non-target effects on valued resource systems and creating desirable social outcomes at the local scale are less developed. Including stakeholders in multiple steps of formal decision-making processes, including problem formation, objective setting, development of alternative actions that could be taken, and evaluation of expected consequences and tradeoffs (Robinson and Fuller, 2017) may create greater acceptance of natural resource decisions (Decker et al., 1996) and build trust (Gray et al., 2012).

MCDA is a useful approach for engaging multiple stakeholder groups in goal setting and evaluating alternative invasive species control strategies (Binimelis et al., 2007; Robinson and Fuller, 2017). For example, economic and ecological risks posed by the establishment of grass carp (*Ctenopharyngodon idella*) in Lake Erie necessitated response from regional natural resource managers, but uncertainty in the invasive grass carp population and the possibility of tradeoffs between competing objectives created challenges for deciding how to best respond to the threat (Robinson et al., 2021). MCDA with a focus on inter-agency collaboration was applied to address the challenge. Clearly defining a problem statement (develop a strategy for controlling grass carp in Lake Erie to socially and environmentally acceptable levels) and a set of agreed-upon objectives (fulfill public trust responsibility, minimize management-associated costs, minimize collateral damage) through MCDA provided the basis for assessing tradeoffs between alternate actions. Additionally, iterative feedback between establishing context and establishing goals and strategies was exemplified in the invasive grass carp case study (Robinson et al., 2021); as the problem statement was developed, stakeholders that could be negatively affected by grass carp, contribute to scientific understanding, develop and communicate policies, and could be indirectly affected by policy changes were identified. As sea lamprey control decision makers must also weigh tradeoffs among competing objectives, collaborative MCDA may prove to be a useful tool for enhancing participation.

Implement monitoring and management interventions

Direct involvement of stakeholders in implementing management treatments and monitoring outcomes can be an asset for both collecting data on system response and developing stakeholder buy-in for adaptive management (Aceves-Bueno et al., 2015). A benefit of supplemental control tactics is that the technical overhead needed to deploy them is typically lower than established lampricide control methods (Siefkes et al., 2021). Furthermore, local knowledge relating to biophysical system characteristics, technical expertise from operating other fisheries gears, or both factors could lead to proficiencies that improve control outcomes of supplemental control interventions through collaborative approaches to deployment. Community participation in monitoring efforts is another way to build the monitoring capacity needed for successful adaptive management implementation (Walters, 2007) while fostering opportunities for social learning.

Development of effective monitoring practices

To fully implement and evaluate the outcomes of adaptive management, a model for predicting the effectiveness of management actions under uncertainty, described as hypotheses about the structural uncertainty in the system, is necessary (Walters, 1986). In the case of sea lamprey control, understanding the capacity for different control strategies to reduce the production of parasitic juvenile sea lamprey is a crucial aspect of developing an effective, integrated control program (Hume et al., 2021; Hansen et al., 2016). Therefore, we present a conceptual model of sea lamprey population dynamics and control to identify key uncertainties in the model that, if resolved, would increase capacity for predicting the outcome of sea lamprey control tactics targeting either larval or adult life stages. We developed guiding questions based on the conceptual model to hone our monitoring objectives and facilitate collection of management-relevant monitoring data (Lindenmayer and Likens, 2009).

Conceptual model of supplemental sea lamprey control

The conceptual model is limited to the dynamics of parasitic sea lamprey production conditional on migratory adult sea lamprey entering the system. We do not expect to create large changes in lake-wide sea lamprey population abundance in the initial adaptive management testing phase and the ecological mechanisms driving interannual variability in migratory adult abundance are not well understood. With this high variability and low effect size, reliably documenting the effects of experimental management interventions on subsequent migratory adult abundance is unlikely and, therefore, we do not include this goal in our monitoring efforts. Furthermore, our initial conceptual model does not include hypothesized mechanisms that could influence control-induced mortality rates because our proposed experimental scope only includes candidate systems with relatively low expected lampricide effectiveness and high-potential for control tactics targeting adults and out-migrating juveniles to be successful. Subsequent iterations of the adaptive learning process could expand the scope of the experimental design and monitoring objectives.

The intent of control tactics that limit reproduction by adult sea lamprey or reduce the abundance of sea lamprey larvae is to reduce production of parasitic juvenile sea lamprey (Fig. 4). Comparing the efficacy of these tactics is challenging, however, because habitat characteristics influence population dynamics driving recruitment of age-1 larvae and production of parasitic juveniles from age-1 + larvae. Furthermore, if the density of sea lamprey or native lamprey influence population dynamics (Bowen and Yap, 2018; Murdoch et al., 1992, 1991; Rodriguez-Munoz et al., 2003; Weise and Pajos, 1998; Zerrenner and Marsden, 2006) there will be feedback between control tactics that modify these densities and parasitic juvenile production (Fig. 4). Environmental characteristics of larval sea lamprey habitat also influence population dynamics (Bowen and Yap, 2018; Griffiths et al., 2001; Manion and Hanson, 1980), but are not influenced by the type of control tactic used (Fig. 4).

Guiding questions for collection of monitoring data

Using our conceptual model to frame the relevant states and processes related to sea lamprey population dynamics and control, the key uncertainty we identified is the relationship between habitat characteristics and sea lamprey population dynamics. To direct the adaptive management learning plan, we distilled this into two tractable guiding questions: (1) what habitat characteristics influence sea lamprey recruitment to age-1, and (2) what habitat characteristics influence production of parasitic juveniles from age-1 + larvae? Addressing these questions will provide insight into the relevant habitat characteristics that determine if a system is amenable to control tactics targeting migratory adults, larvae, or both life stages. These questions will be addressed by elucidating what habitat characteristics lead to increased parasitic juvenile production and the relative influence of habitat characteristics that are dependent upon (e.g., sea lamprey and native lamprey density) or independent of (e.g., water temperature, substrate, hydrology) control tactics on sea lamprey population dynamics.

Integrating established and emerging survey methodologies

Established survey methodologies for monitoring sea lamprey combined with rapidly advancing genetic tools offer a promising approach for investigating hypotheses related to how habitat characteristics influence sea lamprey recruitment to age-1 and production of juveniles from age-1 + larvae. The sea lamprey reference genome (Smith et al., 2018, 2013) and panel of single nucleotide polymorphisms (Sard et al., 2020; RAD-capture) allows family groups (pedigrees) of sea lamprey larvae to be reconstructed. Reconstructed pedigrees provide insight into mating systems, stock-recruitment relationships, and larval dispersal (Derosier et al., 2007; Sard et al., 2020), while genetically marking cohorts of known-age larvae could provide insight into survival, growth, and metamorphosis rates. Established back-pack electrofishing survey (Harris et al., 2016; Steeves et al., 2003) and habitat survey (Slade et al., 2003) methods provide estimates of larval densities in a given habitat patch, while upstream migrating adults and

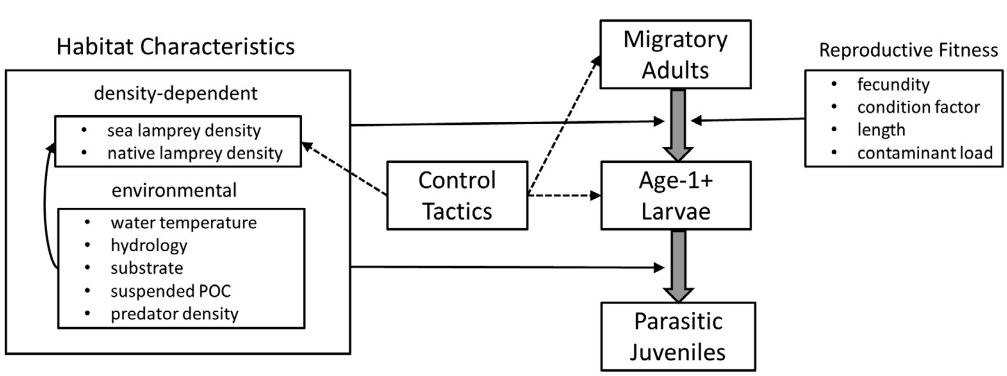

Fig. 4. Conceptual model of sea lamprey population dynamics and control. Habitat characteristics influence sea lamprey population dynamics (grey arrows) and are grouped into density-dependent and environmental characteristics. Biological characteristics of migratory adults drive relative reproductive fitness, which influences recruitment dynamics. Control tactics intended to reduce production of parasitic juveniles either target migratory adults or age-1 + larvae. Feedback occurs among habitat characteristics, as sea lamprey density is influenced by environmental habitat characteristics, and between control tactics and density-dependent habitat characteristics densities.

out-migrating juveniles can be monitored using traps and nets (Mullett et al., 2003; Swink and Johnson, 2014). Using an integrated assessment model to evaluate sea lamprey capture data from established survey approaches targeting multiple life stages, information on the area and distribution of larval and spawning habitat within a given stream, and genetic monitoring data may prove to be an effective way to learn about sea lamprey population dynamics and identify key ecological drivers.

Conclusion

We developed a framework that links adaptive management implementation goals with concepts related to the structure, process, and culture of the SLCP. We hypothesized that multi-level social and political organization, effective use of MCDA, and creation of safe-to-fail decision making arenas may be necessary preconditions for long-term implementation of adaptive management in support of sea lamprey control objectives in the Great Lakes. Furthermore, based on linkages in our framework, advances in long-term SLCP objectives associated with sea lamprey control in the Great Lakes could be realized by conducting experimental supplemental control interventions, developing effective participatory processes, and developing effective monitoring practices. Supplementing barriers and lampricides with additional control strategies, with the aim of increasing control efficiency and reducing non-target effects of control, was the SLCP long-term objective we considered in our discussion of how to work towards adaptive management implementation goals. Large shifts in this objective will require reexamination of experimental design, monitoring practices, and participatory processes. However, given that shifts in adaptive management objectives are expected if adaptive management learning processes are effective, the framework we developed should help support the long-term continuity required for adaptive management by providing a consistent set of goals and a long-term strategic objective for adaptive management implementation efforts supporting the SLCP.

CRediT authorship contribution statement

Sean A. Lewandoski: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization,**Travis O. Brenden:**Conceptualization, Methodology, Writing – review & editing, Supervision,**Michael J. Siefkes:**Conceptualization, Methodology, Writing – review & editing,**Nicholas S. Johnson:**Conceptualization, Methodology, Writing – review & editing, Visualization, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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