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Perspective and Insight

Ten lessons for controlling invasive species: Wisdom from the long-standing sea lamprey control program on the Laurentian Great Lakes

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Abstract

Sea lamprey (*Petromyzon marinus*) control in the Laurentian Great Lakes of North America is among the largest and most successful control programs of an invasive species anywhere on the planet. The effort began more than 75 years ago; it unites multiple nations, states, and provinces with the common goal of controlling this invasive species and protecting a valuable fishery. The science-based control program is administered by the Great Lakes Fishery Commission (GLFC), a body arising from a treaty signed by the United States and Canada. In the present article, we share 10 lessons learned from decades of successful sea lamprey control with the hopes of informing ongoing and future control programs targeting biological invasions. The 10 lessons we identified are to act boldly in times of crisis, to maintain the social license, to invest in capacity building, to break down the silos, to support fundamental science, to diversify your portfolio of control measures, to strive for continuous improvement, to confront the trade-off between information and action, to keep your foot on the gas, and to keep your eyes on the prize. The GLFC has long fostered a framework that uses some military strategy and verbiage that extends across the lessons (e.g., know your enemy). Other lessons are more nascent as the GLFC reenvisions its relationship with Indigenous peoples and governments in a path to reconciliation where two-eyed seeing is being embraced. Through adaptive management, horizon scanning methods, and embracing implementation science, the lessons learned about sea lamprey control will continue to evolve, which is itself a lesson. We submit that the lessons shared in the present article will help guide invasive species control programs spanning taxa, ecosystems, and regions.

Keywords: invasive species, environmental science, conservation

Invasive species represent a major threat to biodiversity (Mack et al. 2000, McGeoch et al. 2010, IPBES 2019) and are considered a key driver of population declines (e.g., Bellard et al. 2016) and even extinctions (Bellard et al. 2021). The impacts of invasions extend beyond individual populations and species, often resulting in dramatic changes in ecosystem structure and function (Crystal-Ornelas and Lockwood 2020). The economic costs of invasive species are immense (Diagne et al. 2021, Ahmed et al. 2023) and eclipse any benefits that invasions may yield (Carneiro et al. 2024). In fact, the effects of biological invasions have manifold impacts on ecosystem services (Vilà and Hulme 2017) extending to human wellbeing and food security (Linders et al. 2020, Rai and Singh 2020). For the aforementioned reasons, there are many efforts to prevent biological invasions (Mack et al. 2000, Keller et al. 2008) ranging from biosecurity initiatives that restrict trade and transfer of invasive species using regulatory mechanisms (for a review, see Lieurance et al. 2023) to educational efforts intended to engage the public in such efforts (for a review, see Haley et al. 2023). Such prevention methods are the obvious first line of defense (Briski et al. 2013) and are often substantially cheaper than postinvasion control (Leung et al. 2002). The management of biological invasions sometimes relies on a rapid response approach, with a focus on eliminating organisms before establishment and, in some cases, the need for comprehensive control programs (Burgeil 2020, Reaser et al. 2020, Herbst et al. 2021).

Despite a focus on prevention, biological invasions do occur, which, in some instances, necessitates invasive species control measures to be used or control programs to be developed (Mack et al. 2000). However, once invasive species become established, control may be challenging or, more often, impossible. For

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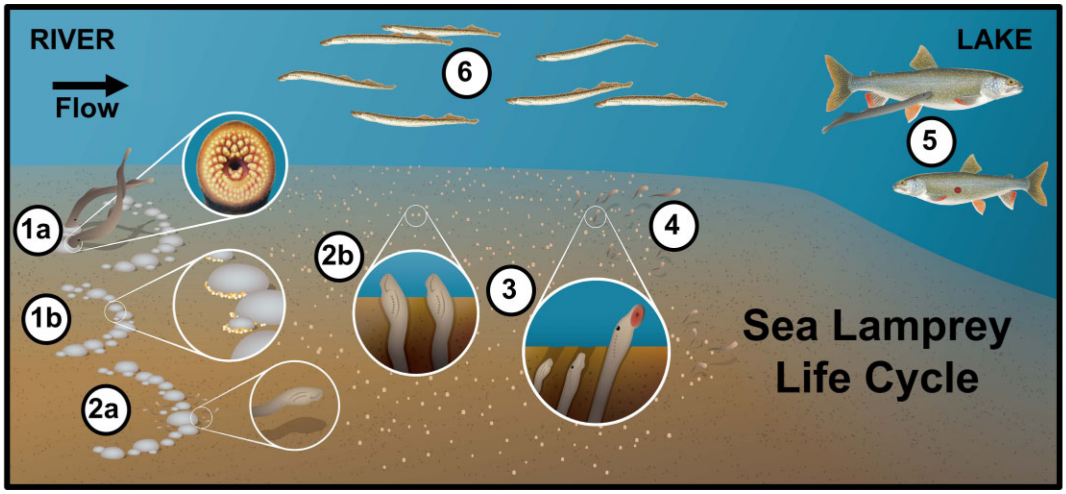

Figure 1. Schematic of the life cycle of sea lamprey. Spawning stage: (1a) Sea lampreys use their sucker mouth to suction onto rocks and make crescent-shaped nests for spawning. (1b) Eggs are deposited in the nests by females while being fertilized by males. Larval stage: (2a) About two weeks after fertilization, larvae hatch from the eggs. Lacking eyes and a sucker mouth, harmless larvae drift downstream and settle into a silt or sand stream bottom. (2b) Larvae live in stream bottoms for 3–10 years depending on conditions. Larvae feed by filtering organic particles, algae, and microscopic organisms from the sediment and water. Metamorphosis: (3) Once large enough, larvae metamorphose, growing sucker mouths, teeth, and eyes. (4) At the completion of metamorphosis, sea lampreys emerge from the stream bottom. Postmetamorphosis: (5) The newly metamorphosed parasitic juveniles migrate downstream into large rivers and lakes where they feed on fish (as parasites) until it is time to spawn. After feeding for 1–1.5 years, the sea lamprey's digestive system shuts down and they become sexually mature. (6) They migrate into streams to spawn and then die, completing the life cycle.

instances where biological invasions create extreme levels of negative impacts on ecosystem services, a coordinated control program may need to be sustained for long periods (Simberloff 2014). In this context, control is defined as efforts intended to reduce the abundance and impacts of a given invader. We intentionally use that term given the inherent challenges with fully eradicating invaders, which may not be needed to reduce impacts to reasonable levels (Bomford and O'Brien 1995). Examples of prominent invasive species control programs can be found around the globe and include the cane toad (*Bufo marinus*) in Australia (Shanmuganathan et al. 2010), the brown tree snake (*Boiga irregularis*) in Guam (Hall 1996), lake charr (trout) *Salvelinus namaycush* in Yellowstone Lake (in the United States; Koel et al. 2020), prickly pear cacti (*Opuntia* spp.) particularly in Australia and South Africa (Humphries et al. 2022), and Asian longhorn beetles (*Anoplophora glabripennis*) in Europe and North America (Haack et al. 2010). Invasive species control programs can be operational for extended periods (i.e., decades) and are often supported by extensive research and monitoring. Although a vast body of research examines the effectiveness of invasive species control initiatives, much of it is focused on the biological aspects (e.g., which removal methods work and in which contexts; for a review, see Metha et al. 2007 and Coleman et al. 2017) but does not consider the institutional and procedural aspects of control programs that underpin the science-based control efforts.

One of the longest-standing control programs for an invasive species is that of sea lamprey (*Petromyzon marinus*; see figure 1 for life cycle) in the Laurentian Great Lakes of North America (see box 1). The Sea Lamprey Control Program is coordinated by the Great Lakes Fishery Commission (GLFC) as part of a treaty signed by Canada and the United States in 1954. Although eradication is currently improbable, control efforts have suppressed sea lamprey populations by about 90% (Siefkes et al. 2021), allowing native fish populations and introduced recreational fishes to thrive (Robinson et al. 2021a, Wingfield et al. 2021).

Given that the sea lamprey control program has deployed control efforts on the Laurentian Great Lakes for more than 65 years (and is therefore one of the longest-running and largest of such programs) and has explored control methods for over 75 years, the program provides a unique opportunity to reflect on successes and failures. In the present article, we present lessons learned over more than a half century of invasive sea lamprey control with the hopes of informing ongoing and future control programs targeting other biological invasions. Billions of dollars have been spent globally on invasive species control measures and programs (Jardine and Sanchirico 2018), reinforcing the need for such reflections. In the present article, we intentionally focus on conceptual aspects related to control program delivery that should be readily transferable to other contexts rather than dwelling on specific control measures. This article is novel in that, to our knowledge, there are few attempts to consider the broader context in which invasive species control programs succeed or fail. Several other synthetic accounts of the sea lamprey control story exist (see Brant 2019, Brant et al. 2019, McLaughlin et al. 2021, Wingfield et al. 2021), but none of these has been framed in terms of transferrable lessons for controlling other invaders. Although we attempt to anchor each of our lessons in empirical literature, the reality is that the majority of these lessons arise from frontline efforts and behind-the-scenes support that collectively enable the sea lamprey control program but have not been well described in the literature. The lessons in the present article are not intended to be prescriptive but rather serve as ideas, inspiration, and candid advice (based on successes and failures) for others working on the control of biological invasions. Similar reflective, lessons-oriented papers related to coordinated invasive species control are lacking (but see Dahlberg et al. 2023 for a more focused retrospective analysis of Dreissenid mussel control efforts in open waters and more general perspectives in Myers et al. 2000, Simberloff 2009, and Phillips et al. 2019 or regional overviews such as Davies et al. 2020). To our knowledge, the present article is unique in its

Box 1. An overview of lamprey control measures.

The present control program has a 65-year history based on sound science, dogged determination, collaborative partnerships, and a little luck. Little was known about sea lamprey when they invaded the Great Lakes, in particular their life history (figure 1). Research and experience revealed that sea lamprey are most effectively controlled in streams, either during their spawning migration as mature adults or during their in-stream residence as larvae. Initial efforts relied on crude electrical barriers to halt migration (figure 2a),

Figure 2. (a) Historical electric barrier used to guide lamprey. (b) TFM treatments occur in lotic systems (e.g., rivers, streams) targeting larval stage lamprey. Photograph: Zak Allen. (c) Granular bayluscide treatments are conducted using boats to target larval lampreys in more lentic (e.g., lake) environments. Photograph: Zak Allen. (d) Low-head barriers are installed on tributaries to prevent upriver migrating lamprey from reaching spawning grounds. Photograph: Ted Lawrence. (e) Traps are used often alongside barriers to capture adult lamprey for assessment and euthanasia. Photograph: Marc Gaden. All of the photos part of the GLFC archive and are used with permission.

but the method was dangerous and nonselective, and ineffective at a control scale (Brant 2019). Through a series of rigorous and persistent tests, researchers found a chemical called 3-trifluoromethyl-4-nitrophenol (TFM), that was selective for lampreys, environmentally benign, and safe for human handling (figure 2b). Although TFM can be toxic to a few nontarget species, such as juvenile lake sturgeon *Acipenser fulvescens* (more than 100 millimeters) and mudpuppy *Necturus maculosus* under certain

(*Continued*)

Box 1. An overview of lamprey control measures.

environmental conditions, it has become the cornerstone of sea lamprey control. A second chemical, 2',5-dichloro-4'-nitrosalicylanilide, or Bayluscide, is used as an additive to enable more judicious use of TFM in large rivers and by itself in lentic areas such as embayments adjacent to river mouths (figure 2c). Barriers to migration, such as purpose-built low-head sea lamprey barriers and dams constructed for other purposes, remain an effective tool to limit sea lamprey distribution and access to spawning habitat (figure 2d; Zielinski et al. 2019). Sea lamprey have infested around 10% of Great Lakes tributaries, and extensive larval assessment operations serve to determine the abundance and distribution of sea lamprey larvae in those tributaries, thereby prioritizing use of limited control resources. Finally, a network of assessment traps deployed in tributaries to intercept migrating adults (figure 2e) provides opportunity to understand relative changes in sea lamprey abundance through time, remove migrating sea lamprey to prevent spawning, and to provide sea lamprey for outreach and ongoing research to advance sea lamprey control techniques. Those aforementioned methods are variously supplemented (see Siefkes et al. 2021) by portable electric barriers, juvenile trapping, sea lamprey sterilization (currently on operational pause), and pheromone or alarm cues (to attract or repel lamprey to improve the effectiveness of other control methods). Sea lamprey control costs roughly US$25 million a year to protect one of the single largest freshwater ecosystems on earth, with a recreational fishery estimated to be worth US$5.1 billion annually (Cornicelli et al., 2022).

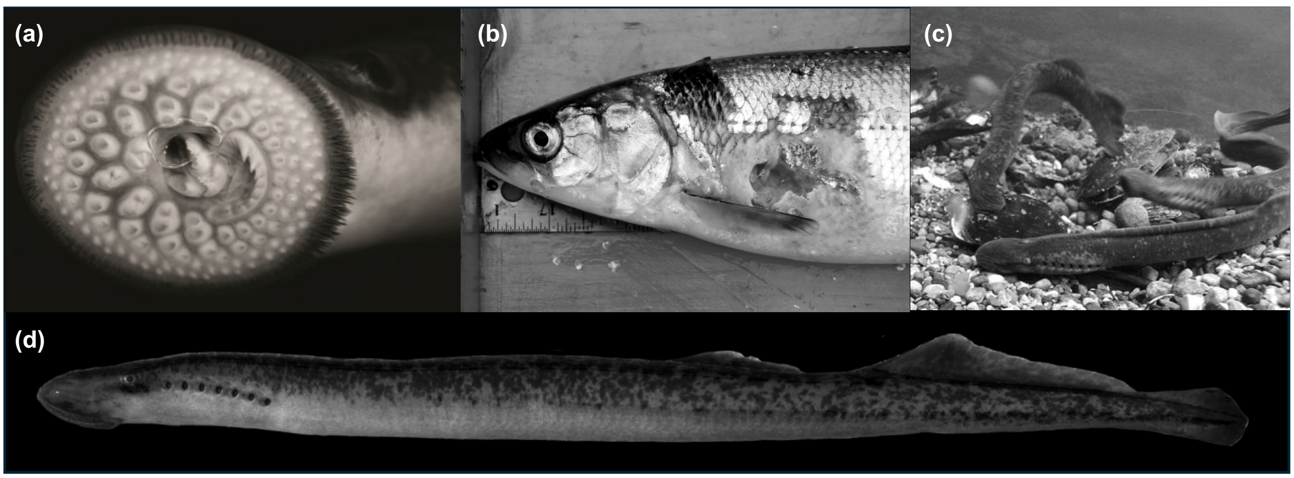

Figure 3. (a) Oral disc of sea lamprey used for attachment to the fish (via keratinized teeth) prior to a rasping tongue being used to feed. (b) Fish with lamprey scar. (c) Lampreys engaging in spawning behavior. (d) Sea lamprey form. Photographs: Andrew Muir.

focus on a coordinated control program targeted toward a single invader.

Ten lessons

The 10 lessons described below were identified through an iterative process where the first step involved building a diverse team. The present coauthors collectively represent scientists (from different disciplines and realms including academia, Indigenous governments, and federal governments), practitioners (including sea lamprey control agents, which we call *control agents*—Fisheries and Oceans Canada and the US Fish and Wildlife Service staff that deliver sea lamprey control on behalf of the GLFC), and GLFC technical, science transfer, policy, and leadership staff. All of the present coauthors have participated in the control program in various ways including through service on various GLFC committees and boards (e.g., the Sea Lamprey Control Board, the Sea Lamprey Research Board). Collectively, the coauthors have more than 275 years of experience with lamprey control. Ideas for lessons were collated, thematized, and where necessary merged or split, to create a final list of 10 lessons. Given the diversity in training, experience, and perspective of our author team, we are confident that the lessons identified in the present article are indeed the key lessons that have emerged from the Sea Lamprey Control Program and are potentially relevant to other control programs.

Act boldly in times of crisis

The control program arose out of crisis. By 1940, when sea lampreys had made it to all five Great Lakes, native piscivorous fishes, such as the lake charr, and their prey were already dramatically reduced in abundance (Muir et al. 2012). Stakeholders and rightsholders, such as commercial fishers, business owners, Indigenous or tribal community members, and recreationalists, witnessed the destruction firsthand when they saw fish with sea lamprey wounds (see figure 3), experienced sharply reduced fish harvest, and as a result of release from predation pressure by lake charr, dealt with beaches littered with dead invasive alewives (*Alosa pseudoharengus*) that had exploded in abundance (Smith 1968, Gaden et al. 2022). The crisis of collapsed fisheries and an unknown invader provided the perfect opportunity to rally jurisdictions and politicians to overcome the impediments to nine previously failed attempts to establish interjurisdictional cooperation in the basin. Failure of individual jurisdictions to control sea lampreys on their own was seized as the fuel for finally establishing cooperative fishery management in the Great Lakes (Gaden et al. 2022). Stakeholders in both Canada and the United States, noting the destruction of valued fisheries, persuaded politicians

Box 2. Two-eyed seeing and sea lamprey control.

Two-eyed seeing, or *etuaptmumk* (a Mi'kmaw word and concept), is learning to see with the strengths of Indigenous ways of knowing together with the strengths of western science, in order to gain a broader perspective for the benefit of all (Bartlett et al. 2012). Although this approach had its beginnings in the health field, it is now being increasingly used in fisheries research, management, and stewardship contexts (Almack et al. 2023, Duncan et al. 2023, Reid et al. 2021). Although one US treaty organization, the Great Lakes Indian Fish and Wildlife Commission (1842 Treaty waters) is represented on the Sea Lamprey Control Board (SLCB; www.glfc.org/sea-lamprey-control-board-task-forces.php), the control program has not yet used two-eyed seeing to guide the decision-making process, a shortcoming considering the many Tribes and First Nations who have inherent rights to the lands and waters of the Great Lakes basin (Mattes and Kitson 2021, Nonkes et al. 2024). However, efforts are underway to better understand Indigenous perspectives of sea lamprey and the control program and to include this previously overlooked source of expertise and wisdom within the sea lamprey research and control programs (Nonkes et al. 2023). Adopting a two-eyed seeing approach is crucial not only in the pursuit of reconciliation but also considering the potential declines in social acceptance of sea lamprey control among Indigenous communities as well as the value added by looking at the issue from a different perspective.

to establish the GLFC by treaty to lead a multinational control effort and, importantly, to fund the operations (Gaden et al. 2022). Applied science to combat the sea lamprey was prioritized and, to this day, effective cross-jurisdiction resource sharing, coordinated by the GLFC, remains critical for the success of the control program (Brant et al. 2019, Gaden et al. 2022). We acknowledge that, during the early phases of an invasion, acting boldly may benefit from being done with expediency in an effort to eradicate an invader before getting to the point where ongoing control is necessary.

Maintain the social license

The control program has been a tremendous success, with sea lamprey populations reduced by at least 90% in most areas of the Great Lakes basin (Siefkes 2017). However, although a wide range of stakeholders and politicians continue to support the control program, the worst effects of invasive sea lamprey haven't been witnessed in 60 years (but see lesson no. 9), so the perceived risk of sea lamprey, and the continuing social acceptance for the control methods are not fully appreciated (Gaden et al. 2021b). The loss of the social license for sea lamprey control could range from limitations on the type of controls that can be used (including challenges with permitting) or, at worst, termination of the control program. The two main techniques for sea lamprey control, pesticides and dams, might not be as socially acceptable as they have been in the past (e.g., pesticides represent addition of chemicals to waters used by people and can result in effects on nontarget species, such as native Unionid mussels, impacts, dams can block native species and cause human safety concerns; Gaden et al. 2021b). Although the GLFC is exploring means of maintaining the social license for sea lamprey control, practitioners must maintain an active effort to provide policymakers and the public with timely, relevant, and factual information about sea lamprey, their effects, and their control. The GLFC and its partners regularly engage with a range of stakeholders, rightsholders, and politicians to keep people informed about the benefits and results of the control program. Likewise, legislative staff from the GLFC work on a regular basis with policymakers and elected officials to demonstrate the importance of invasive species control and to provide data about the economic benefits of sea lamprey control. This communications effort is a two-way street, allowing for the GLFC and its partners to convey the social, ecological, and economic benefits of the control program but also to hear and understand public concerns about the program. Outreach includes near-constant delivery of clear and consistent messaging through social media, web pages, videos, and printed materials, as well as many in-person, interactive venues featuring live lamprey. Another ongoing concern is how changing government policy and funding shortfalls could undermine invasive species control or eradication programs, such as in Australia, where funding cuts could threaten the success of an invasive fire ant (*Solenopsis invicta*) eradication plan (Wylie and Janssen-May 2017). In recognition of the moral and legal imperative to engage Indigenous communities and governments, the GLFC has begun to build better relationships with Indigenous nations and embrace a two-eyed seeing approach (see Reid et al. 2021), which strives for learning to see with the strengths of both Indigenous and Western ways of knowing (box 2; Bartlett et al. 2012). This element of the GLFCs evolution is too novel to consider it a lesson (see box 2 for early learnings), but it underpins the importance of self-reflection and the ability to redress past inadequacies in the delivery of its programs.

Invest in capacity building

Investing in capacity building is critical for the success and longevity of a control program. Capacity building is a process of enhancing the skills of individuals, organizations, and communities, leading to improved program effectiveness, sustainability, and innovation (Eade 2007, Sobeck and Agius 2007, Labin et al. 2012). It also promotes collaboration among management agencies, Indigenous stewards, and researchers, which is vital for mutual learning to inform action (Wiener et al. 2011, Jellinek et al. 2021). Capacity building partnerships capitalize on investments by leveraging multiple resources and enhancing communication leading to collaborative decision-making and better stewardship (Behnken et al. 2016). The GLFC has fostered the training and development of students, early career scientists, and control agents, many of whom have gone on to devote lengthy careers to sea lamprey control in either research or management. It is also important to diversify (Mullin et al. 2021), because diverse teams are better at problem solving (Cheruvelil et al. 2014), ultimately driving positive change and improving control program delivery. To this end, the GLFC is exploring ways to break down barriers to access members of groups that are currently underrepresented in the fisheries field, with an ultimate goal of fostering a more diverse and therefore effective workforce to carry out sea lamprey research and management into the future.

Break down the silos

The control program minimizes siloed thinking by efficiently communicating and coordinating across its own elements and with resource management agencies and science institutions throughout the Great Lakes. Owing to the coordination elements of its mandate, the GLFC serves as a knowledge broker, representing a fundamental central node in the broader Great Lakes environmental governance network (Mulvaney et al. 2015, Song et al. 2019, Song et al. 2020). The control program also adopts and integrates new science and technology through the coproduction and transfer of science to decision-makers (Gaden et al. 2021a and in the present article). Collaboration within the control program is facilitated through the SLCB, which advises the GLFC in implementing control strategies, policies, and programs. The SLCB membership includes representatives from federal, state, provincial, and tribal fishery agencies, along with nongovernmental and academic institutions, and importantly includes both researchers and managers. Coordination with resource management agencies throughout the Great Lakes occurs through GLFC-sponsored lake technical committees (www.glfc.org/joint-strategic-plan-committees.php), of which sea lamprey control agents are invited members on each Great Lake. The SLCB is advised by control program task forces, composed largely of technical folks who advise on the science priorities (Krueger and Marsden 2007). The SLCB research priorities drive the focus of the GLFCs research program. This feedback loop between science and management ensures adherence to the mission. Research proposals are evaluated against the priorities by the Sea Lamprey Research Board (SLRB; https://www.glfc.org/sea-lamprey-research-board.php), which consists of both scientific experts and control agents. Funded research is often coproduced with control program staff (Lewandoski et al. 2021, McLaughlin et al. 2021) and the GLFC sponsors the Science Transfer Board (https://www.glfc.org/science-transfer-board.php), which further facilitates knowledge exchange between scientists and control program staff (Hinderer et al. 2021). Embedding scientists within implementation-focused groups (e.g., the SLCB) and embedding sea lamprey control staff within science-focused programs (e.g., the SLRB) also helps bridge the knowledge–action gap (Nguyen et al. 2017) and promotes evidence-based decision-making resulting in more effective sea lamprey control by providing a direct pipeline for new science into control policies and operating procedures. Therefore, the GLFC has strategically worked to break down the silos through strong communication and establishing and nurturing fora for integration, knowledge sharing, coproduction, and consensus decision-making.

Support fundamental science

Although it is focused on research to augment or improve control methods, the Sea Lamprey Research Program (SLRP) has also played the long game by investing in fundamental science. Fundamental science serves as the foundation for more mission-directed research and may pay unexpected dividends. Sea lamprey pheromone research started in sensory neurobiology in the 1950s and 1960s (see Buchinger et al. 2015); subsequent investments in physiological and behavioral research (e.g., Li et al. 1995, Daghfous et al. 2016), and the identification of the active pheromone components (Li et al. 2018) and their receptors and antagonists (Zhang et al. 2020, Scott et al. 2023) has led to the potential to use pheromones to disrupt sea lamprey migration or spawning. Likewise, a 40-year quest to elucidate the hypothalamic–pituitary system in lampreys, while shedding light on the evolution of this uniquely vertebrate feature, may eventually enable methods to suppress sea lamprey reproduction (Sower 2015, 2018). Similarly, sea lamprey genome sequencing and evolutionary developmental biology studies date back to a long-term interest in this jawless vertebrate as a model to recapitulate the early evolution of vertebrates (York et al. 2019) and the vertebrate genome (Smith et al. 2013, 2018). These genomic resources will enable research into possible genetic control of sea lamprey (Ferreira-Martins et al. 2021). A better understanding the sea lamprey fundamental biology has yet to pay dividends in terms of broadscale control but has laid the groundwork for advancing novel control tools with a different mechanism of action than TFM (Wilkie et al. 2019), advancing selective fish passage whereby sea lampreys are selectively removed from a migrating stream of fishes (Zielinski et al. 2020) and elucidating the mechanism of sex determination and potential gene targets for genetic control (McCauley et al. 2015).

Diversify your portfolio of control measures

The control program adopted an integrated approach to controlling sea lamprey in the 1980s (Sawyer 1980) and has since invested roughly 50% of the annual research budget to developing new control tools (Siefkes et al. 2021). Tactics developed to target the adult stage to reduce reproduction include direct removal of adults in traps with trap encounter rates increased with physical leads and electrical, chemosensory, light, and auditory stimuli (Miehls et al. 2020) and the reduction in spawning success through the release of sterilized males (Johnson et al. 2024) or chemosensory cues that disrupt mate finding (Scott et al. 2023). Tactics have also been developed to remove juvenile sea lamprey during their outmigration from rivers to lakes (i.e., those not killed by lampricide treatment that metamorphose into the harmful parasitic stage). Juvenile sea lamprey encounter rates with traps can be improved using physical diversion, electrical repellents, chemosensory repellents, and lights (Evans et al. 2021). The control program recently reemphasized how new or supplemental control tools can diversity the suite of available tactics and potentially reduce reliance on lampricides (Siefkes et al. 2021), which is needed to prevent or slow the development of pesticide resistance (Dunlop et al. 2018). This renewed supplemental control philosophy is currently being implemented in a framework designed to enhance learning through adaptive management and tailor tactics to align with the environmental and social context (Lewandoski et al. 2021, 2025).

Strive for continuous improvement

Invasive species control requires making decisions in the face of uncertainty (Johnson et al. 2017, Robinson et al. 2021b). Therefore, an adaptive management approach (Walters 1986), in which a reduction in uncertainty leads to refinement of actions and, at times, a complete course change is necessary for success. This requires striving for continuous improvement. Indeed, failure and surprise are expected in adaptive management programs, requiring flexibility to seize them as learning opportunities (Allen and Gunderson 2011). Inspired by the first Sea Lamprey International Symposium (see *Canadian Journal of Fisheries and Aquatic Sciences* vol. 37, issue 11), over the last 45 years, the control program has maintained and enhanced its flexibility in response to learning, as well as a great deal of social and environmental change. This includes learning through experimentation and adaptive management principles but also through failure and surprise (e.g., Sullivan et al. 2021). Some of the first attempts to control sea lamprey did not have the desired or anticipated outcomes, but the flexibility to explore supplemental control options has been effective and has been embraced as part of a new adaptive management program (Lewandoski et al. 2025). Indeed, learning from failure has served several rodent control programs well (Holmes et al. 2015, Samaniego et al. 2021). The coordination of the control program, multiple task forces, the SLRB, and many councils and committees allows for feedback among control actions, monitoring, and targeted research. In addition, the trust built through these long-term collaborations among agencies and between countries, facilitated by the GLFC, over the course of the implementation of sea lamprey control has made this programmatic flexibility possible (van Putten et al. 2022, Muir et al. 2023). Continual control program assessment and associated investments in implementation science (Cooke et al. 2024) allow evidence-informed refinement to occur such that there is opportunity for continuous improvement.

Confront the trade-off between information and action

Since the early stages of sea lamprey control, the control program has relied on lampricides to remove larval sea lampreys before they metamorphose and become parasites. The larval stage typically lasts 3–5 years, but the time to metamorphosis can vary among streams and over time (Brant 2019). In a control program where treatment resources are limited, treating streams with lampricides earlier than necessary (i.e., years before metamorphosis) presents financial and opportunity costs while treating too late allows escapement of large numbers of parasites. The Great Lakes basin is expansive (approximately 240,000 square kilometers) and contains hundreds of spawning streams where sea lampreys flourish, so the GLFC has used larval assessment to prioritize streams for annual treatments. Larval assessment is costly, and there is a trade-off between doing more assessment or allocating resources to treat more streams. Using a field-tested adaptive management approach (Hansen and Jones 2008a) and simulation models (Jones et al. 2009), researchers determined that a less costly and precise assessment approach actually led to better outcomes (i.e., greater suppression for the same cost; Jubar et al. 2021). In addition, control agents realized many streams reliably produced new populations at a predictable time after treatment, leading to the establishment of expert judgment streams requiring even less assessment and gaining further efficiencies. This illustrates the use of a value-of-information approach to guide decision-making, an approach with broad, and underappreciated, salience to fisheries management (Hansen and Jones 2008b).

Keep your foot on the gas

A knowledge of when larvae were likely to metamorphose, and rigorous sea lamprey assessment to prioritize which streams require treatment (Hansen and Jones 2008a), yielded unprecedented success in suppressing sea lamprey in the mid- to late 2000s (Sullivan et al. 2021). However, the need for managers to keep their foot on the gas was made clear during the COVID-19 pandemic of 2020–2022, which demonstrated that even a temporary disruption to the control program could undermine success (Marcy-Quay et al. 2025). The lockdowns and travel restrictions due to COVID-19 in 2020 greatly curtailed sea lamprey assessments and lampricide treatments, with only 26 of 101 scheduled streams undergoing lampricide treatments in 2020 (Burkett et al. 2021). Those reductions resulted in a spike in lamprey abundance and concomitant increase in fish wounding in Lakes Superior and Huron in 2021 compared with 2019 (Marcy-Quay et al. 2025). In 2022, when the bulk of metamorphosed sea lamprey from 2020 had likely matured, the returning adult sea lamprey populations were well above their abundance targets in all five Great Lakes (Marcy-Quay et al. 2025). The cost to the ecosystem was stark; estimates indicated that there were more than 50,000 additional parasitic sea lampreys produced in the five Great Lakes in 2022, amounting to upward of 1,000,000 kilograms of fish killed, based on prior estimates that a single sea lamprey can kill approximately 18 kilograms of fish during its parasitic phase (Swink 2003). It remains to be seen how quickly sea lamprey populations will be brought back under control in coming years, but there is reason for optimism as the control program remains well-funded and normal operations have resumed. The COVID-19 pandemic provides a cautionary case study that invasive species control measures cannot be relaxed, even temporarily, which is salient given changing priorities associated with transitions in leadership, dynamic geopolitical forces, uncertain financial markets, and associated variation in funding for control programs.

Keep your eyes on the prize

Sea lamprey control is a means to a more fundamental set of objectives in the Great Lakes basin, the most notable of which is maintaining sustainable lake charr populations for recreational and commercial fisheries (Gaden et al. 2021b). Over time, these objectives have diversified to include other ecological, economic, and social goals, such as healthy populations of desired species, recreational and commercial user satisfaction, and a lucrative economy. By defining and refining a set of achievable fundamental objectives, the control program remains focused on ultimate needs of the social–ecological system. In addition, these fundamental objectives reach beyond sea lamprey control, providing a basis for other decisions in fisheries management, habitat restoration, and native species restoration that are ongoing in the Great Lakes basin. As a knowledge brokering and boundary organization, the GLFC successfully coordinates sea lamprey control and fishery management across these multiple objectives, jurisdictions, and organizations. Looking to the future, double- and triple-loop learning initiatives might be beneficial if objectives and assumptions need reframing or if the underlying beliefs and values have transformed (Pahl-Wostl 2009), especially in a changing environmental and social climate. Maintaining all eyes on the end objective (i.e., the prize) of healthy sustainable Great Lakes fisheries requires dedicated communications and outreach efforts across multiple jurisdictions and publics and carrying forward institutional knowledge across generations of Great Lakes stewards.

Conclusions

The 10 lessons presented in the present article (figure 4) represent ones that have staying power in that they have been realized repeatedly or continuously over at least the last three decades. There are more lessons that we opted to omit because they were specific to a given project or control measure but less germane to the control program as a whole. We contend that the lessons shared in the present article, in whole or in part, can be applied in diverse contexts that extend well beyond aquatic ecosystems or North America. It is important to emphasize that, since its inception, the control program has been supported by a parallel mission-oriented science program to support management. Recognizing that science can exist in a vacuum, the GLFC has also embraced approaches to connect managers with scientists by embracing coproduction when possible, including managers on grant-making committees, and implementing a science transfer

Figure 4. Summary of the 10 lessons for controlling invasive sea lamprey that are germane to other invasive species control programs. The control program is supported by a science program (which funds research on lamprey biology and control) with a science transfer program serving a key role in knowledge exchange and translation. The GLFC is in the early days of its journey to create space for Indigenous knowledge systems and ways of knowing in the sea lamprey control program.

program to facilitate knowledge exchange among researchers, decision-makers, and sea lamprey control agents (Hinderer et al. 2021). The GLFC has long embraced a framework that uses military strategy and verbiage (and is not alone among invasive species control programs; Janovsky and Larson 2019), extending back to Sun Tzu's centuries-old *The Art of War* (see Tzu 2008) and which extends across the lessons (e.g., know your enemy). Consider thinking about the art of invasive species control. Those historic teachings extend from laying plans to waging war to attack by stratagem. Notably, Tzu stated that "If you know the enemy and know yourself, you need not fear the result of a hundred battles. If you know yourself but not the enemy, for every victory gained you will also suffer a defeat. If you know neither the enemy nor yourself, you will succumb in every battle." In the sea lamprey context, that means know your strengths and weaknesses (both internally and with respect to the target invasive species) and allocate available but limited resources where you can have the most positive influence on the ecosystem (e.g., minimizing the cost per kill or exploiting stereotyped behavioral responses of sea lamprey to traps). We acknowledge that making knowing your enemy a focal point is a challenging task. The GLFC and allied agencies had focused on both knowing their enemy (using science and adaptive management and monitoring) but have also taken the time to understand and build their own capacity and capabilities (recognizing an evolution in thinking). When, at times, actions failed, those failures were not simply dismissed but rather dissected to learn and improve (e.g., Marcy-Quay et al. 2025). We acknowledge that what an invasive species is continues to evolve (recently informed by Indigenous learnings; see Black et al. 2021, Mattes and Kitson 2021, Wehi et al. 2023) such that the military framing may eventually become inappropriate or irrelevant. Whether the control program philosophy is rooted in centuries old military stratagem or a more modern philosophy of caring and sharing, a dedicated control program with dedicated people is critical. To achieve success, such a program needs to be broadly supported, well resourced, coordinated across jurisdictions and integrated across control program elements, knowledge based, diverse, flexible and adaptive, and determined.

Most invasive species control programs do not have the history or resources (control agents, funding, and science) that exist for sea lamprey in the Great Lakes basin. That is more reason to look toward established programs and institutions such as the control program and GLFC for guidance. Most of the lessons shared in the present article can be downscaled or adapted to a more localized or nascent context in that planning for invasive species control is a long-term commitment. As outlined in the present article, through approaches such as adaptive management, horizon scanning methods, and embracing implementation science, the lessons learned about sea lamprey control will continue to evolve, which is itself a lesson. A responsibility to do better and the institutional culture to do so are critical for ensuring that evidence and not emotion guide invasive species control programs. We submit that the lessons shared in the present article will help to guide invasive species control programs spanning taxa, ecosystems, and regions.

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