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Where you trap matters: Implications for integrated sea lamprey management

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A B S T R A C T

Barriers and pesticides have been used in streams to control sea lamprey in the Laurentian Great Lakes for nearly 70 years. Considerable effort has been spent to develop additional control measures, but much less effort has gone toward identifying how or where additional control measures might be cost-effectively integrated into the sea lamprey control program. We use a management strategy evaluation model in Lake Michigan to identify the stream types that would be most suitable for deploying traps to remove adults prior to spawning and estimate the likely impact on adult sea lamprey abundance in subsequent years under several trapping scenarios relative to status quo abundance. The greatest reduction in lake-wide adult sea lamprey abundance predicted by the model resulted when removing adult sea lampreys from streams that are difficult for control program personnel to treat with lampricide because lampricide applications would be required less frequently. Additionally, targeting streams which experience regular sea lamprey recruitment and streams with low adult sea lamprey density should result in reduced lake-wide abundance if trapping costs are relatively low or removal is high. Our results provide direction on where to trap and why, and indicate that trapping may be a valuable part of an integrated sea lamprey control approach advancing the goals of the Great Lakes Fishery Commission.

Introduction

The sea lamprey (*Petromyzon marinus*) was observed in Lake Ontario during the late 1860s (Dymond, 1922), and quickly invaded the remaining Laurentian Great Lakes following expansion of the Welland Canal in 1921 (Eshenroder, 2014). Though a parasite in their native range in the North Atlantic Ocean, sea lampreys proved to be a formidable predator in the Great Lakes (Smith and Tibbles, 1980). The combination of sea lamprey predation and overfishing resulted in collapse of fish stocks across the Great Lakes (Pycha and King, 1975) with devastating effects on the ecosystem and the economy of the region (Smith and Tibbles, 1980). In response, the Great Lakes Fishery Commission (GLFC) was formed in 1955 and tasked with creation and implementation of a Sea Lamprey Control Program (SLCP) to eradicate or minimize sea lamprey populations in the Great Lakes for the protection of the Great Lakes fishery (1955; http://www.glfc.org/pubs/conv.htm).

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Early attempts to control sea lampreys focused on the adult life stage (Applegate, 1950). Barriers that were in place throughout the basin for numerous reasons unrelated to sea lamprey control, proved critical to the SLCP by limiting the area of infestation to a manageable size. The GLFC also deployed an expansive network of mechanical and electrical weirs to block and capture migratory adult sea lampreys in the upper Great Lakes (Lawrie, 1970). However, the need for continuous maintenance throughout each spring trapping season and the risk of damage to equipment during high flows made this effort expensive. Further, evaluation of the effectiveness of control measures targeting adult sea lampreys during the spawning migration may be obscured by the relatively long period (3–7 years; McLain et al., 1965) that larval lampreys reside in streams before migrating downstream and entering the parasitic, juvenile phase.

A selective toxicant targeting larval sea lampreys was needed such as those used for agricultural pest control. After the discovery of the lamprey-specific pesticide TFM (3-trifluoromethyl-4-nitro phenol; Applegate et al., 1961) and the effectiveness of the molluscicide bayluscide (active ingredient niclosamide; Howell et al., 1964), hereafter lampricides, the chemical control program was rapidly implemented in Lake Superior in 1958, Lakes Huron and Michigan in 1960, Lake Ontario in 1971, and Lake Erie by 1986 (Pearce et al., 1980; Sullivan et al., 2003). A successful chemical treatment applied in streams can exterminate multiple year-classes with a single application, whereas successful capture and removal of adult sea lampreys must be conducted annually to achieve the same results. At the time, costs of adult trapping were high and the effectiveness uncertain, therefore, following the advent of TFM adult trapping was largely abandoned, but barriers remained in place to limit the spread of sea lampreys and reduce the area requiring chemical treatment. Relying solely on these two measures of control (barriers and lampricides), the GLFC has maintained adult sea lamprey abundance at 10–30% of the pre-control peak (Lawrie, 1970; Heinrich et al., 2003).

At the first Sea Lamprey International Symposium (SLIS I), an integrated pest management (IPM) approach was suggested for sea lamprey control (Sawyer, 1980; Lamsa et al., 1980), and during the following decade the GLFC adopted an IPM model focused on three critical concepts, (i) control at a level providing an optimum benefit to the fish community, (ii) use of multiple control methods, and (iii) quantitative understanding and systems approaches (Christie and Goddard, 2003). During the 40 years following SLIS I, considerable research has focused on development of control measures to replace or supplement the use of lampricides (http://www.glfc.org/glfc-publications-reports.php), and the removal of adult sea lampreys using traps was highlighted as an alternate control priority in the GLFC's Strategic Vision (GLFC, 2011).

In 2012, the Sea Lamprey Control Board (http://www.glfc.org/sea-lamprey-control-board-task-forces.php) created a Trapping Task Force to, among other objectives, "evaluate the role of trapping adult sea lampreys as an alternative control technique." Most research efforts related to this charge, conducted by SLCP personnel or university scientists, have focused on improving the efficiency of conventional trapping gear, but few projects have explicitly sought to determine how best to implement trapping as a control measure within the SLCP. Velez-Espino et al. (2008) suggested that lake-wide removal of 42–65% of adult females would allow for reduction of lampricide use. In describing the relationship between adult sea lamprey stock and subsequent age-1 larval recruitment, Dawson and Jones (2009) suggested that removal of adult sea lamprey may be most effective for overall reduction in recruitment in streams with low adult density and that adult sea lamprey removal from some streams may be counter-productive. The next step is to identify and evaluate the streams in which trapping would be most beneficial and determine how to incorporate trapping into an already effective program. For example, would trapping be most effective if deployed on streams with large spawning runs to potentially delay lampricide treatments on these streams, or would trapping be more effective if deployed on streams that are difficult to treat with lampricide?

Currently, trapping adult sea lampreys is not considered a control measure, because to date its use has not been demonstrably effective at reducing lake-wide adult sea lamprey abundance, the level at which SLCP metrics operate. Though initially developed as a control measure, the use of trapping migratory adult sea lampreys quickly transitioned to an assessment tool to monitor trends in adult abundance in response to lampricide control (Lawrie, 1970). Since 2015, five to seven trapping sites per lake have been used to index adult sea lamprey abundance, providing an annual measure of overall SLCP success (Adams et al., 2021). Further, multiple process and observation uncertainties obscure the level of adult sea lamprey removal needed to reduce subsequent recruitment. Sea lampreys are highly fecund, so even a few adults can quickly repopulate a river with larvae (Pereira et al., 2017), and a complex pheromone communication system allows adult sea lampreys to find mates even at extremely low abundance when Allee affects might be observed for other species (Buchinger et al., 2015). Additionally, sea lamprey larvae can demonstrate compensatory mechanisms with higher growth and survival rates at lower density (Jones et al., 2003), potentially reducing the effect of adult sea lamprey removal. Recruitment also varies greatly among streams and years, and considerable uncertainty remains regarding the factors driving this variability (Dawson and Jones, 2009); a paucity of stream-specific data currently hampers our ability to determine where adult removal would be most effective. Finally, because the effect of adult removal (reduced adult abundance in subsequent years) is not visible until five to seven years after implementation (i.e. the entire sea lamprey life cycle), stochasticity at every life stage between the point of implementation and the point of evaluation can mask observable effects. Given that the current methods of control have already suppressed the adult sea lamprey population in the Great Lakes by 70–90%, observing the effect of additional control measures can be difficult.

Despite challenges and uncertainty, the SLCP may have reached a point where control options aimed at reducing the abundance or reproductive potential of adult sea lamprey is now appropriate. As the sea lamprey population is reduced, the cost-effectiveness of lampricide applications diminishes (broadcast application requires the same amount of control effort to kill fewer and fewer larvae; Barber and Steeves, 2019), and increases the potential benefits of applying control measures at the adult life stage. Additionally, when density of adults is reduced to low levels the likelihood of large recruitment events is reduced (Dawson and Jones, 2009). Therefore, if trapping can maintain river populations at low density perhaps large pulses of recruitment can be deterred. Thus, trapping for control has the potential to increase the cost-effectiveness of sea lamprey integrated pest management, but the specific conditions necessary for this potential to be realized are not well understood.

The Sea Lamprey Management Strategy Evaluation (SLaMSE) Model was developed to simulate sea lamprey management strategies, recognizing the uncertainties described above, to determine conditions under which alternative strategies might be preferred to the status quo (Jones et al., 2009). The SLaMSE model incorporates uncertainty in: biological processes (recruitment and growth); assessment of larval abundance in streams considered for treatment; and implementation of lampricide control (Jones et al., 2009; Dawson et al., 2016; Electronic Supplemental Material (ESM) Appendix S1). Briefly, the model includes interconnecting biological, observational, and management models, operates at the spatial scale of an entire Great Lake, and forecasts future changes in abundance over a 100-year time horizon. The SLaMSE Model can assess integrated control strategies such as the use of lampricide and adult-targeted control (Dawson, 2007; Dawson et al., 2016). Management Strategy Evaluation (MSE) operating models are widely used to inform policy development for management of industrial commercial fisheries (Butterworth, 2007), but their application to invasive species management has to date been limited to sea lamprey control (Jones et al., 2009).

The SLaMSE Model was modified to determine the combinations of trapping costs and efficacies that would be forecasted to result in a net decrease in lake-wide adult sea lamprey abundance if some control funds were allocated to trapping at the expense of lampricide applications. We focused our simulation analysis on Lake Michigan and compared the performance of trapping strategies that focused on different categories of streams. We hypothesized that the relative benefit of trapping for control would be greatest in streams that tend to attract a low density of adults, streams that exhibit inconsistent recolonization after treatment (designated as "irregular producers"), and streams where lampricide effectiveness is often poor and enough larvae survive to warrant additional treatments during subsequent years (hereafter difficult-to-treat). Difficult-to-treat streams were identified with assistance from SLCP personnel.

Methods

Definition of terms

Clear definitions aid communication within the sea lamprey research and control community as well as with external researchers and managers. Trapping for control seeks to remove adult sea lampreys from individual streams. Therefore, herein we use the term removal rate to describe the proportion of adult sea lampreys removed from a given stream during a single trapping season (Fig. 1). Removal in streams with multiple trapping devices will be dictated by the efficiency with which each device operates as well as programmatic constraints such as intentional release of adults for mark-recapture population estimation. Trap efficiency is simply the proportion of sea lamprey captured by a trap out of all upstream migrating sea lampreys present in the river and is governed by the probabilities that a sea lamprey (1) encounters a trapping device, (2) enters the trapping device, and (3) is retained within the trapping device until removed by SLCP personnel (Bravener and McLaughlin, 2013).

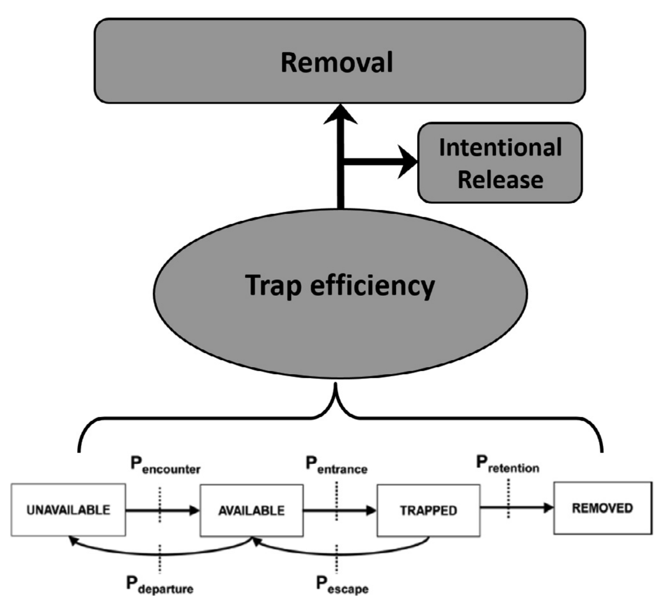

Fig. 1. Trapping efficiency depends on the rates of encounter, entrance, and retention for each trapping device deployed (Bravener and McLaughlin, 2013). Combined trap efficiencies for all trapping devices in a given stream minus losses resulting from intentional release for mark-recapture population estimates will dictate the level of adult sea lamprey removal that occurs each trapping season.

SLaMSE model description

The SLaMSE operating model (Fig. 2) was initially developed to evaluate management measures based on lampricide applications targeting to the larval life stage (Jones et al., 2009) and later updated to simulate measures targeting adult sea lamprey removal by adjusting the presumed (or modeled) number of adult sea lampreys that successfully spawn in a given stream (Dawson et al., 2016). The biological model simulates the sea lamprey life history: adult sea lampreys from the lake habitat are allocated to streams for spawning; these adults produce stream-dwelling larvae according to a Ricker-type stock-recruitment function; the larvae experience growth and mortality before metamorphosing into the juvenile stage and migrating back to the lake. An observation model generates estimates of stream-specific larval abundances intended to reflect measurement uncertainty with existing sampling methods in the Great Lakes; these estimates are used to rank stream segments, called treatment units, for treatment on the basis of cost per expected larva killed in the entire segment. Treatment units are operationally defined as river sections treated with lampricides as a single unit. The number of annually selected treatment units is limited by the total available control budget. The likelihood of a treatment being successful in a particular river was determined by sea lamprey control agents a priori and based on historical treatments. Treatment units selected for lampricide applications experience reductions in larval abundance. The actual proportional reduction in abundance due to a lampricide treatment is calculated as described in ESM Appendix S1. Process uncertainty is also included in the model in the form of a stochastic reproduction function (Dawson and Jones, 2009) and uncertainty in stream-specific larval growth rates. Parameters of the reproduction function were drawn from a Bayesian posterior distribution, as described in ESM Appendix S1. Further details of the model's structure and parameterization can be found in Jones et al. (2009), Dawson et al. (2016), and ESM Appendix S1.

Model calibration and simulations

Prior to evaluating trapping for control, the model was calibrated as described in Jones et al. (2009), using recent control expenditures and recent observed values of adult sea lamprey abundance in Lake Michigan, all provided by the GLFC. A two-year lag between the calculations of calibration target abundance and values of the budget apportioned to sea lamprey control reflects the time lag between a lampricide application and its effect on adult abundance. The model uses the same calibrated control expenditures and adult abundance when forecasting over a 100-year time horizon, and the model is sensitive to larval survival, the parameter adjusted to calibrate the model. We calibrated larval survival using median control expenditures during 2006–2011, excluding 2009 (an enhanced control year for Lake Michigan), and median adult sea lamprey abundance during 2008–2013 (excluding 2011). This resulted in a calibrated larval survival of 0.47802 for a budget of \$2.683 million and a meadian adult sea lamprey abundance of 115,242.

To determine circumstances under which trapping for control might be most effective, we categorized Lake Michigan streams in three ways: regularity of recruitment (regular versus irregular;

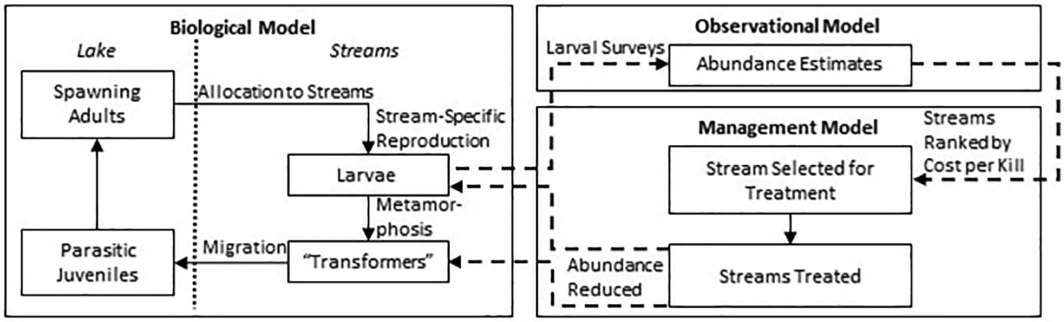

Fig. 2. Conceptual diagram for the sea lamprey MSE model. Solid and dashed lines indicate component linkages within and among the individual biological, observation, and management models, respectively.

for details see Dawson and Jones 2009); historically observed adult densities (greater than versus less than 0.2 adult females per 100 m^2 larval habitat); and ease of lampricide treatment (easy versus difficult-to-treat, as determined by sea lamprey control managers). By considering each of these binary classifications, we evaluated six different scenarios for the selection of trapping locations:

1. Trapping only streams that were designated as regular producers
2. Trapping only streams that were designated as irregular producers
3. Trapping only streams that attracted relatively high densities of adults
4. Trapping only streams that attracted relatively low densities of adults
5. Trapping only streams in which lampricide treatments were designated as easy
6. Trapping only streams in which lampricide treatments were designated difficult-to-treat

We ran each of the six scenarios for actual Lake Michigan tributaries, where streams in each category have different sizes, different lampricide treatment costs, different levels of treatment difficulty, and where the number of streams in each category is not the same (Table 1). For each scenario we simulated a range of trap removal rates (0–80%) across a range of possible annual trapping costs ($0–$11,000) for every stream in the selected category. The cost of trapping was implemented by adding the same fixed cost to every stream that was selected for trapping. Estimates used here could be low because limited cost data exist for efforts to maximize removal of adult sea lamprey. However, for the context of the analysis the range selected provides an understanding of the level of cost-effectiveness necessary to benefit control. Trapping expenditures reduced the funds available in the control budget for lampricide control. The amount of money in the control budget diverted from lampricides to trapping ranged from $0 to $627,000 depending on the scenario being evaluated. In addition, when modeling scenarios that targeted regular and irregular-producing streams we extracted the number of lampricide treatments that occurred when trapping cost was $5500 and removal rates were 0 and 80% to compare the effect of adult sea lamprey removal on lampricide treatment frequency between regular and irregular producers.

Results

Three trapping scenarios (targeting regular-producing, low-density, and difficult-to-treat streams) consistently resulted in predicted lake-wide adult sea lamprey abundances within or below the status quo range of Lake Michigan even at relatively low removal rates (Fig. 3). Trapping all streams classified as difficult-to-treat was identified as the most effective way to incorporate trapping into sea lamprey control operations for Lake Michigan, followed by trapping all regular producing streams, all low-density streams, high-density streams, irregular-producing streams, and easy-to-treat steams (in order of best to worst performance; Fig. 4). For the best scenario (trapping all difficult-to-treat streams), lake-wide abundance could be suppressed to below status quo even if trapping costs per stream were as high as $11,000 with a removal rate of 30%, or with removal rates per stream as low as 10% if costs were maintained below $5500. For the second and third best performing scenarios (regular-producing and low-density), lake-wide sea lamprey abundance could be maintained at or below status quo if removal rates were at least 10%, but stream-specific trapping costs were less than $2750. Conversely, for the worst performing scenario (trapping all easy to treat streams), suppressing lake-wide sea lamprey abundance to less than status quo would require both trapping costs lower than $2750 per stream and high per stream removal rates (>60%).

When cost was fixed at $5500 per stream, increasing trap removal rates from 0 to 80% on regular producing streams resulted in reduced lampricide treatment frequency in these streams (from

Table 1
Tributaries to Lake Michigan were placed in one of four categories based on year to year consistency of sea lamprey production (regular vs irregular) and adult density relative to available larval habitat (high vs low). The average cost of lampricide treatment for the Lake Michigan streams in each category and the percentage of those streams that are identified by control agents as easy or difficult-to-treat with lampricide are also provided.

Stream Type	Stream Count	Average Lampricide Treatment Cost	Lampricide treatment difficulty	
			Easy (%)	Difficult (%)
Regular	29	$219,412	34	66
Irregular	54	$72,376	87	13
High	48	$92,032	77	23
Low	35	$167,249	57	43

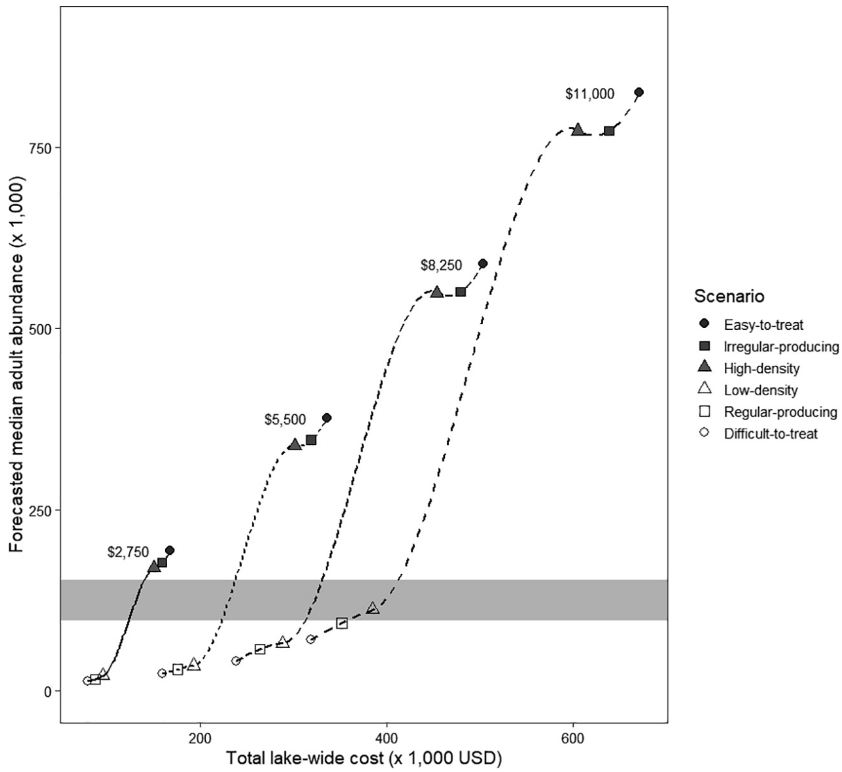

Fig. 3. Forecasted median adult abundances and total lake-wide trapping costs for each scenario at a stream-specific exploitation rate of 30% for four stream-specific costs. Groups of scenarios with a common per-stream trapping cost value ($2750 = solid, $5500 = dotted, $8250 = dashed, $11,000 = long-dash) are connected by black lines representing the x:y pattern they form as modeled using the SLaMSE simulation for the Lake Michigan. Grey shaded area indicates Lake Michigan status quo adult sea lamprey abundance range (100,000–150,000).

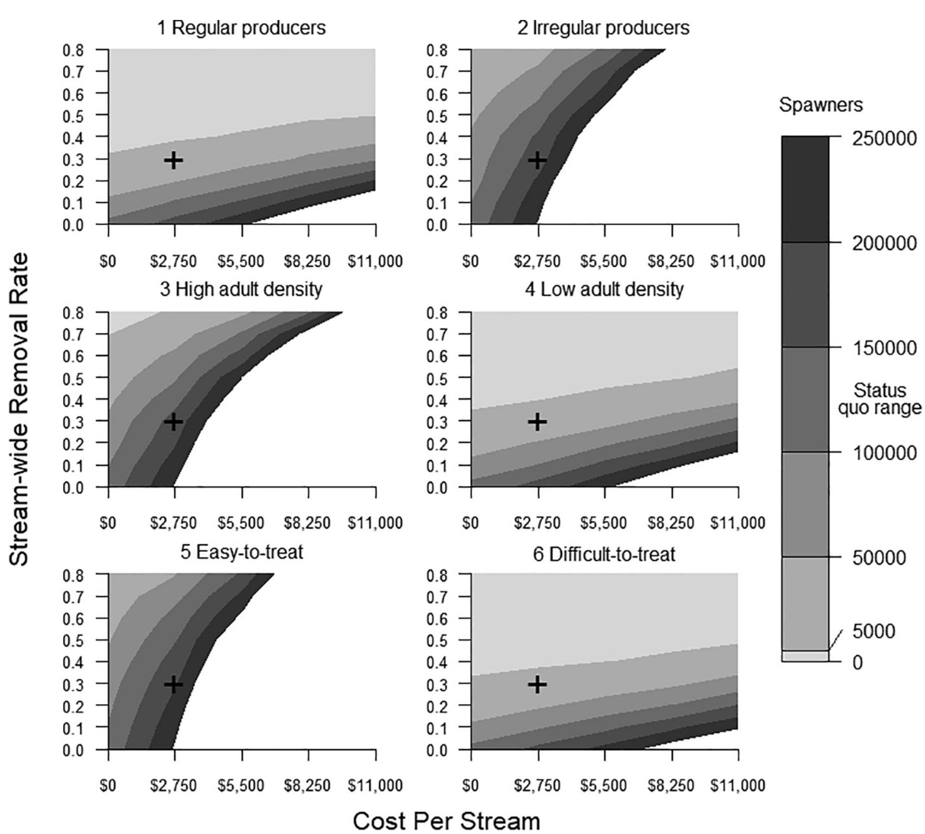

Fig. 4. Contour plots showing forecasted median adult abundance for ranges of trap-specific removal rates and stream-specific trapping costs for Scenarios 1–6 for Lake Michigan. Differently colored contour bands indicate adult sea lamprey abundance, with above status quo adult sea lamprey abundance in the two darkest grays. The cross-hairs indicate a trap-specific removal rate of 0.3 and a cost per stream of $2750 as a reference point for comparison across panels.

∼every 4 years to ∼every 5 years), and increased lampricide treatment frequency in irregular producing streams (from ∼every 8.5 years to ∼every 5.5 years). On average, streams classified as regular producers in Lake Michigan were the largest and most expensive streams to treat. Therefore, increasing time between treatments resulted in savings in treatment costs that could then be re-deployed to other streams. Similarly, increasing trap removal rates from 0 to 80% on irregular producing streams results in reduced treatment frequency in these streams (from ∼every 10 years to ∼every 15 years), and increased lampricide treatment frequency in regular producing streams (from ∼every 4.5 years to ∼every 4 years). Irregular producing streams are, on average, less expensive to treat, so the benefit in terms of re-deployment of control resources is reduced compared to targeting regular-producing streams. Trapping at a fixed cost per stream (Fig. 3) results in a smaller pool of funds available for lampricide treatment when trapping irregular producing streams ($2.39 million) than when trapping regular producing streams ($2.54 million) due to the number of streams in each category (Table 1).

Discussion

The simulation approach used here provides an objective, quantitative basis for determining the conditions under which trapping adult sea lampreys within the framework of the existing lampricide control effort could provide cost-effective, additional suppression of the Lake Michigan lake-wide population by re-directing some lampricide control funds to trapping. This analysis, together with previous applications of the SLaMSE model (Jones et al., 2009, Irwin et al., 2012, Dawson et al., 2016) illustrate the potential utility of MSE operating models to invasive species management issues. Nearly all published examples of MSE applications are focused on developing harvest strategies for exploited fish populations (Punt et al., 2016), but there is no reason why the approach could not have far broader application.

Trapping can be expected to produce the greatest benefits where lampricide treatments are less effective. Thus, reducing the spawning stock in these streams will have a greater relative effect on subsequent recruitment of juvenile sea lampreys than for streams where lampricide treatments reliably reduce larval abundance by more than 90%. In Lake Michigan, the majority of difficult-to-treat streams are large and therefore expensive to treat, and are also typically regular producers. We observed the lampricide treatment frequency of regular producers reduce from ∼25 times per 100 years to ∼8 times per 100 years at trapping removal rates of 0 and 80%, respectively. By increasing the proportion of adults removed in these streams we could reduce the frequency at which these regular producers need to be treated and redirect resources to treat streams elsewhere. Trapping was also observed to have some benefit in streams with low adult density, as removal of adult sea lampreys from these streams is more likely to result in adult abundances below the level associated with a lower likelihood of large recruitment events (<0.2 females/100 m^2, Dawson and Jones, 2009). Especially interesting is that the SLCP reached similar conclusions when defining the target deployment locations for experimental release of sterilized male sea lampreys (Hanson and Manion, 1980). During 1991 through 1996, sterilized male sea lampreys were released into streams that experienced regular recruitment and suffered poor lampricide effectiveness, as these streams were thought to be the primary sources of parasitic juveniles in the lake (Twohey et al., 2003). Those experimental releases were discontinued to redeploy sterilized males into the St. Marys River, a major sea lamprey producer at the time (Schleen et al., 2003), limiting evaluation of the technique and deployment strategy for Lake Superior.

Programmatic, logistical constraints may limit potential benefits of some trapping scenarios. Many of the regular-producing and low-density streams are the largest and most expensive streams to treat with lampricide in the Lake Michigan drainage. The main benefit of trapping on regular producing, low density streams in Lake Michigan appears to result from extending the time between lampricide treatments on these streams; consequently, these scenarios require that the application of lampricide be adaptive and responsive to observed variation in larval densities. However, lampricide treatments for many of these large, regularly producing tributaries have in recent years been determined by a fixed schedule based on historic larval assessment data, thus diminishing the benefit of trapping these systems. However, if lake-wide abundance is reduced as a result of a larval population reduction, as in the scenario of difficult-to-treat streams, trapping could be implemented independently of lampricide application procedures and still provide net benefit to the SLCP.

Accurate stream-specific information will be critical to select candidate streams for trapping efforts. Results here suggest lampricide effectiveness as a primary factor to consider for stream selection, and though we know lampricide effectiveness varies among streams (Bills et al., 2003; Hlina et al., 2017; Tessier et al., 2018; Muhametsafina et al., 2019), determining average values for actual treatment effectiveness has proven difficult (Slade et al., 2006). Further, understanding stream specific larval survival rates will allow better estimation of the value of adult sea lamprey removal as considerable uncertainty remains around growth, survival, and thus stock recruitment. Understanding what drives variability of lampricide treatment effectiveness, larval growth, and survival would allow optimization of lampricide treatment measures and aid in identifying candidate streams for adult removal. In the Great Lakes, lampricide has reduced the lake-wide sea lamprey populations considerably and many streams can be considered low density. There is likely synergy between lampricide and trapping given that lampricide has reduced abundances to the point where trapping even at moderate removal rates can be a viable control tool for the SLCP. Indeed, incorporation of trapping for nuisance insect species when abundances are reduced has been well established in integrated pest management strategies (Mitchell and Hardee, 1974). The next step moving forward should be in stream deployments to ground-truth model predictions of reduced lampricide treatment needs and detailed data collection not only to improve the model accuracy but also to identify the mechanisms that drive variability in recruitment and lampricide effectiveness. This work is on-going with the recent implementation of a Supplemental Control Initiative by the GLFC (Siefkes et al., 2021). Further, our analysis was specific to Lake Michigan and results may vary for other lakes where streams differ in terms of relative size, spawner density, and treatment difficulty.

Finally, understanding and estimating the costs associated with improved trapping will be necessary to ultimately rank trapping for control efforts on a stream-by-stream basis as well as ranking trapping for control against other possible control tools. Cost savings were the major contributing factor in driving down lake-wide abundance for the scenario in which only regular producers were trapped and the scenario in which only streams with low adult densities were trapped because lampricide operations could be spread to more streams. Because few studies have attempted to truly target a river-wide population, limited information is available on the cost of such efforts. The costs modelled here were determined after consultation with SLCP and based on estimates of contract costs to operate the current adult sea lamprey index trap sites. Further complicating the development of cost estimates is the fact that improvements to adult sea lamprey removal rates might require completely new trapping strategies away from barriers or in streams without barriers. Most research has focused on improving capture of migratory adult sea lampreys at existing trap sites, with few studies investigating means to trap migrating sea lampreys away from existing sea lamprey barriers, or if alternate approaches could boost removal rate within a stream. Johnson et al. (2016) provide one recent example of significant removal (>70%) of migratory sea lampreys away from a barrier in two small Great Lakes tributaries (discharge 1–5 cubic meters per second) using an electric lead to guide sea lampreys to a portable trap, where overall costs through the trapping season ranged $5000–$15,000 annually. A second example of trapping efforts on a smaller, difficult-to-treat stream used a less-expensive, low-head weir trap design (~$6000 total) to achieve approximately 60% adult sea lamprey removal (unpublished data). Two of these trap systems deployed in sequence achieved >90% removal (annual cost of $6200). Considerable adult sea lamprey removal was achieved in both cases at costs within the range identified by our modeling effort as beneficial to sea lamprey control in a stream identified as difficult-to-treat. As trapping technology improves, removal rates should increase and therefore make trapping more viable as an integrated control option.

We focused on adult sea lamprey trapping as a potential supplemental control, however trapping is not the only way to reduce the recruitment of juveniles from a given tributary. Any measure that reduces the number or viability of adult sea lampreys (for example sterilized male release or deployment of pheromone communication antagonists) could be evaluated using this MSE approach. Given that staffing cost for daily trap maintenance is the major expense for adult trapping operations, adult control measures that do not require daily maintenance (i.e., sterile male release) could prove more effective and this modeling effort is directly applicable.

Conclusion

The results presented here show that wise selection of streams for trap deployment, can significantly improve the effectiveness of adult sea lamprey control. For 70 years, the program has struggled to incorporate adult control measures. Our model results provide direction on where to trap, specifically streams that are difficult to treat with lampricide, have low density adult sea lamprey populations, and regularly produce juvenile recruits. Selective trapping may provide benefit to an integrated approach and advance both the goals of the Trapping Task Force and the GLFC in general (i.e., integrated control). Three potential trapping strategies were identified as ways to incorporate adult sea lamprey trapping into SLCP operations for a net benefit. The most effective strategy (trapping difficult-to-treat streams) was also the least disruptive in terms of shifting control operations and lampricide application procedures.

Target costs and removal rates are provided to benefit future research on trapping strategies aimed at more cost-effective sea lamprey control and to guide trap development and implementation. The ultimate goal of the SLCP is a cost-effective reduction of sea lamprey entering the Great Lakes, which is currently accomplished with the combination of barriers and lampricides. Inclusion of adult sea lamprey trapping could reduce subsequent lake-wide sea lamprey abundance given the appropriate balance of trapping and lampricide. To test feasibility of these approaches and determine if adult controls are truly biologically relevant will require real world deployments. Deployments can be guided by MSE model results and will in turn provide real-world data to incorporate back into the model and an opportunity for a truly adaptive management approach.

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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Appendix A. Supplementary data

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