

Research Final Report Guidelines

******

Final reporting requirements consist of (1) a project abstract to help the reader quickly ascertain the project’s purpose, including the main results and conclusions, for posting to the Great Lakes Fishery Trust’s (GLFT) public website, (2) a narrative response to the GLFT final report questions, (3) a financial report accompanied by financial documentation verifying expenditures (form and instructions attached), and (4) attachments to include (a) copies of manuscripts accepted or submitted for publication (if applicable) and (b) any other technical reports developed as a result of the grant.

Project ABSTRACT

**Title:** Optimize pheromone application rate to yield large and consistent catches of adult sea lamprey

**Abstract Body:**

Sea lamprey *(Petromyzon marinus)* invaded the upper Great Lakes during the first half of the 20th century and were a primary contributor to catastrophic ecological and economical damage to the Great Lakes fishery. Since the 1960s, sea lamprey populations have been controlled using lampricides to kill larval sea lamprey and dams to block spawning migrations, but new control tactics that are environmental benign are desired. Sea lamprey use pheromones to coordinate migration and spawning and have shown promise for increasing catch of sea lamprey in traps. However, knowledge gaps limiting use of the first fish pheromone biopesticide, 3-keto petromyzonol sulfate (3kPZS), in sea lamprey (*Petromyzon marinus*) control include (1) how much 3kPZS should be applied to traps, (2) what is the expected increase in adult sea lamprey catch, and (3) how do (1) and (2) vary among streams. By conducting 3kPZS dose-response experiments over two years and across six diverse streams and trapping contexts, we conclude that 3kPZS application should be optimized by how much is applied to the trap, not the concentration of 3kPZS when fully mixed with discharge and that 3kPZS would be most effective in wide streams (>30m).  In wide streams, the application of a high 3kPZS dose (50 mg/hour) to the trap increased capture rate by 10-20% because, in general, more sea lamprey entered the trap after encounter.  However, in narrow streams (< 15 m), a high 3kPZS dose generally reduced probabilities of upstream movement, trap encounter, and entrance. Overall, upstream movement, encounter, and capture probabilities were weakly driven by 3kPZS application when compared to other factors such as water temperature, stream width, sea lamprey length, and sex.  Therefore, biological and environmental factors, as well as trap placement and design, will be essential to consider when using 3kPZS-baited traps on wide streams.

Final Narrative Report Guidelines

**Project Title:** Optimize pheromone application rate to yield large and consistent catches of adult sea lamprey

**Grantee Organization:**

U.S. Geological Survey, Great Lakes Science Center, Hammond Bay Biological Station

**Project Team:**

Nicholas S. Johnson1, Sean Lewandoski2, Bethany J. Alger1, Lisa O’Connor3,Gale Bravener4, Peter Hrodey2, Jessica Barber2, Weiming Li5, C. Michael Wagner5, Michael J. Siefkes6

1U. S. Geological Survey, Great Lakes Science Center, Hammond Bay Biological Station, 11188 Ray Road, Millersburg, MI 49759.

2U. S. Fish and Wildlife Service, Marquette Biological Station, 3090 Wright St., Marquette, MI 49855.

3Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences, 1219 Queen Street, East Sault Ste. Marie, ON P6A 2E5.

4Fisheries and Oceans Canada, Sea Lamprey Control Centre, 1219 Queen Street, East Sault Ste. Marie, ON P6A 2E5.

5Department of Fisheries and Wildlife, Michigan State University, Room 13 Natural Resources Building, East Lansing, MI 48824.

6Great Lakes Fishery Commission, 2100 Commonwealth Blvd., Suite 100, Ann Arbor, MI 48105.

**Contact Person:** Nicholas Johnson, U.S. Geological Survey, Great Lakes Science Center, Hammond Bay Biological Station, njohnson@usgs.gov

**Grant Amount:** $164,076 (Match amount $136,300)

**Start and End Dates:** 01/01/2017 to 12/31/2018

**Key Search Words:** sea lamprey, invasive species, trapping, pheromone, catch rate

Background/Overview

1. Briefly summarize the project description as outlined in the original proposal.

The objective was to optimize 3kPZS application rate for use in integrated sea lamprey control by determining if probabilities and timing of trap encounter and entry differ with 3kPZS application rate and stream width. To achieve the objective, 3kPZS dose-response experiments were proposed at sea lamprey traps operated by United States Fish and Wildlife Service (USFWS) in tributaries to Lake Michigan during 2017 and 2018. During each trial, PIT tagged sea lamprey were to be released downstream of traps to quantify tap encounter and entrance rates. Generalized linear mixed models would be used to investigate probabilities of upstream movement to the trapping area, trap encounter, and trap entrance for tagged sea lamprey during the night of release given the 3kPZS dose. The project was to be conducted side-by-side with sea lamprey control agents from USFWS and DFO to facilitate direct science transfer between biologists and researchers.

1. Briefly summarize any significant changes to the work performed in comparison to the originally proposed and funded plan of work. If changes were made, describe how they affected your ability to achieve the intended outcomes for the work.

During Great Lakes Fishery Commission review of the proposal, they suggested we increase the number of study streams and also conduct the experiment in one stream in Ontario. Therefore, the location and number of experimental streams was modified in a way to increase statistical power, which the GLFC provided matching funds for.

Specifically, during 2017, experiments were conducted in the Manistee River, Betsie River, and Carp Lake Outlet as originally proposed. During 2018, experiments were conducted at sea lamprey traps operated by the U.S. Fish and Wildlife Service (USFWS) in the Grand River, Manistee River, Betsie River, Carp Lake Outlet, and Ocqueoc River during April – June 2018. Experiments were also conducted in a trap operated by Fisheries and Oceans Canada (DFO) in the Echo River, Ontario. Below is additional rationale for the changes:

1. Experiments were conducted at the Grand River, Michigan, instead of the St Joe River, Michigan, because sea lamprey trapping on the Grand River was high priority given recent progress toward removing the 6th Street Dam and resorting the rapids. USFWS and USGS activities were highly collaborative at the Grand River. USFWS deployed traps in the fishway and we applied pheromone to increase trap efficiency and improve estimates of sea lamprey abundance. By monitoring movements of PIT-tagged sea lamprey in the fishway, we also confirmed that the fishway was an effective sea lamprey barrier.
2. Experiments occurred over more nights than originally proposed due to efficiencies realized in travel, housing, and in-kind support from the Great Lakes Fishery Commission, USGS, and USFWS. Specifically, at the Grand River, experiments occurred over 21 nights instead of 16. In the Ocqueoc River and Carp Lake Outlet experiments occurred over 22 nights.

The modifications to the proposed approached increased statistical power, improved science transfer from USGS to USFWS and DFO, and allowed research to be conducted in high profile Lake Michigan tributary (Grand River). Overall, the changes reduced focus on Lake Michigan because the Ocqueoc and Echo Rivers are tributaries to Northern Lake Huron.

Outcomes

Please characterize key outcomes of the project related to *knowledge*, *training*, *relationships*, and *practice.* Not all projects will have outcomes of all types.

1. To what extent and how (if at all) did this research project advance scientific knowledge of the issue?

At the broadest sense, we were the first to address the scientific question of how pheromone application to rivers should be normalized across sites that vary in discharge and stream width. This knowledge will benefit other aquatic ecologists testing pheromones to control Asian carps and to restore populations of lake sturgeon, American eel, and sea lamprey where native and is an important scientific advancement for the field of chemical ecology.

In the context of sea lamprey control, the science showed when and where 3kPZS application would result in the greatest increases in trap catch. For example, we found that 3kPZS primarily influences behavior near the trap entrance and in large streams, so the management implication is that 3kPZS will work best on large streams, where many sea lamprey encounter the trap, during nights when sea lamprey are actively migrating and are likely to be in the trapping area. Sea lamprey control agents can use these findings to prescribe when and where 3kPZS should be applied to increase trap catch.

1. To what extent and how (if at all) did this project contribute to the education and advancement of graduate or undergraduate students focused on Great Lakes fishery issues?

Bethany Alger (University of Vermont), Camryn Bullock (University of Michigan), Sofia Fall (University of Michigan), Scott Gifford (Brigham Young University), Autumn Idalski (Michigan State University), and Emma Vieregge (Michigan State University) were undergraduates that directly participated. Beth Alger played a significant role in the planning, field operations, and data analysis and therefore is a co-author of our final report. Sean Lewandoski, a biologist from USFWS helped with the statistical analysis and is planning to start a PhD Program with the Quantitative Fisheries Center at Michigan State University during 2020. Sean is second author on the final report.

1. To what extent and how (if at all) did this work help you or others on your team build new relationships with others in the research or management communities?

The work primarily helped our scientific team build new relationships with the management community. About 15 staff from USFWS sea lamprey control and 5 staff from DFO sea lamprey directly participated in the work by applying pheromone and checking pheromone-baited traps. We also connected with many of the Michigan Department of Natural Resource biologists during the experiment including Mark Tonello (Betsie and Manistee Rivers), Scott Hanshues (Grand River), Tim Cwalinski (Ocqueoc River), and Heather Hettinger (Carp Lake Outlet). Combined, our research team established many new relationships with biologists that control sea lamprey and biologists that desire to balance sea lamprey control (USFWS, DFO) with the need to also promote and pass valued native fishes upstream of sea lamprey barriers (Michigan DNR).

1. To what extent and how (if at all) do the findings have action implications for fishery managers? If the research has direct management implications, do you have any knowledge of use of the findings by managers? If the research does *not* have direct management implications at this stage, to what extent did the research advance the process of identifying management responses to critical issues?

The direct management implication of our research is that 3kPZS should only be used to bait traps on large streams and when the application rate is 50 mg/hour. Given this information, sea lamprey control staff are planning to use this dose of 3kPZS on the Grand River during 2019 to increase catch at the 6th Street Dam and minimize risk of escapement upstream.

1. Considering the above or other factors not listed, what do you consider to be the most important benefits or outcomes of the project?

The key implication of our findings is that although 3kPZS can increase trap catch in large streams by 20%, 3kPZS application to traps should **not** be considered an alternative to lampricide treatment or a sea lamprey barrier. But instead, 3kPZS could be a part of an integrated program as is the model for insect pests. 3kPZS could be a tool that can increase trap capture in some circumstances (like the Grand River) and if when paired with other tools reducing the reproductive potential of sea lamprey populations such as electrical barriers, sterile male release, alarm cues, pheromone antagonists, migratory pheromones, lights on traps, sound, and water velocity, could be an ingredient in a larger recipe that consistently reduces reproduction and larval production. This adult sea lamprey control recipe could then supplement current usage of lampricide and barriers to control sea lamprey and meet ecosystem goals for the Laurentian Great Lakes.

With this key finding in mind, the Great Lakes Fishery Commission charged Dr. Johnson during their December 2018 meeting to develop a team and an adaptive management proposal to test integrated supplemental sea lamprey control tools in up to 8 Great Lakes Tributaries for as many as 15 years. The goal of supplemental controls would be to reduce lampricide treatment frequency, the length of stream treated, and the number of sea lamprey larvae that survive lampricide treatment in streams where biological, physical, or social challenges make lampricide application difficult or less effective. Findings from this research project, will help inform how and when 3kPZS should be used as a supplemental control in this adaptive management experiment.

Related Efforts

1. Was this project a standalone effort, or was there a broader effort beyond the part funded by the GLFT? Have other funders been involved, either during the time of your GLFT grant or subsequently?

The Great Lakes Fishery Commission contributed about $140,000 of in-kind funding that helped provide synthesized 3kPZS, technical staff, vehicles, and fuel. The USFWS and DFO provided in-kind technical support in the form of trap operators and trapping facilities. A much broader effort to develop benign and cheap chemosensory tools (pheromones, alarm cues, and pheromone antagonists) for sea lamprey control has been ongoing by the Great Lakes Fishery Commission since 1998 and will continue for the foreseeable future, especially in the context of the Great Lakes Fishery Commissions new supplemental control initiative.

1. Has there been any spinoff work or follow-up work related to this project? Did this work inspire subsequent, related research involving you or others?

Yes, 3kPZS application will continue on the Grand River and will be funded by the Great Lakes Fishery Commission. The Great Lakes Fishery Commission is supporting a new initiative to test supplemental sea lamprey control tools in several Great Lakes tributaries, one tool of which is likely to be 3kPZS. Dr. Johnson is leading the initiative and developed a team of managers and researchers to begin scoping the proposal during 2019.

Communication/Publication of Findings

1. List publications, presentations, websites, and other forms of formal dissemination of the project deliverables, tools, or results, including those that are *planned* or *in process*.

**Publications:**

Johnson, N.S., Lewandoski, S., Alger, B.J., O’Connor, L.,Bravener, G., Hrodey, P., Barber, J., Li, W., Wagner, C.M., Siefkes, M.J. Behavioral responses of sea lamprey to varying doses of synthesized pheromone in diverse trapping applications. *Canadian Journal of Fisheries and Aquatic Sciences* (To be submitted by April 2019; included as completion report attachment).

Lewandoski, S., Johnson, N.S., Miehls, S., Hrodey, P. Factors influencing catchability of adult sea lamprey in barrier integrated trapping systems. *Journal of Great Lakes Research* (To be submitted as a proceeding from the Third Sea Lamprey International Symposium).

Johnson, N.S., Huerta, B.B., Li, W. Seasonal variation in the concentration of sea lamprey sex pheromones as an indicator of spawning stock size and spawning timing. *Journal of Chemical Ecology* (To be submitted September 1st 2019).

**Presentations:**

Three technical presentations provided updates to the Sea Lamprey Barrier Task Force, Sea Lamprey Trapping Task Force, and Sea Lamprey Control Board.

**Public Engagement:**

Engaging the public before experimentation made it easier to conduct experiments in heavy fished areas like the Grand River Fishway and Tippy Dam. For example, we worked with Mark Tonello of Michigan DNR to get the word out over social media, resulting in two media stories highlighting our work ([Up North Live Story](http://upnorthlive.com/news/local/researchers-seek-new-options-for-lamprey-control-in-michigan)). These media stories made it easier to engage with the public while conducting the experiment. We also received positive press coverage at MLive about our research on the Grand River ([Link to story](http://www.mlive.com/news/grand-rapids/index.ssf/2018/06/researchers_trap_grand_river_l.html)).

1. Please characterize your efforts to share the findings of this research with state, federal, Tribal, and interjurisdictional (e.g., Great Lakes Fishery Commission) agencies charged with management responsibilities for the Great Lakes fishery. If other audiences were priority for this research, please characterize your outreach efforts to those audiences as well. (Please note: You may wish to consult midterm reports in which specific audiences for the findings, and means of outreach to these audiences, were identified.)

We shared findings with federal sea lamprey control agents by having them directly participate in the work and by presenting the findings at technical meetings such as the Barrier Task Force, Trapping Task Force, and Sea Lamprey Control Board. We coordinated research activities with local fish managers from the MDNR. We conducted research on the Betsie River in coordination with the Grand Traverse Band of Ottawa and Chippewa Indians. We plan to work with the Great Lakes Fishery Commission during 2019 to issue a press release about the findings and the supplemental control initiative.

1. Please identify technical reports and materials attached to this report by name and indicate for each whether you are requesting that GLFT restrict access to the materials while you seek publication. (Please note that the maximum amount of time during which GLFT will restrict access to the results of funded research is 18 months, unless notified that more time is needed.)

We request that the GLFT restrict access to our draft manuscript titled, “Behavioral responses of sea lamprey to varying doses of a synthesized pheromone in diverse trapping applications” while we seek publication in the *Canadian Journal of Fisheries and Aquatic Sciences*.

1. Manuscripts. Grantees submitting one or more publications or pending publications in lieu of a standalone technical report must submit a cover memo that confirms that all aspects of the funded research are incorporated in the published work, and in cases of multiple publications, identifies or crosswalks the grant-funded objectives to the published article containing results.
2. Compilation reports. Grantees working on several related subprojects under a single grant may submit a series of subproject reports rather than a single, integrated report. However, grantees must submit a cover sheet or introduction that outlines and crosswalks grant objectives with the location of the results in the compilation document.

Discussion

At the broadest level, the results are generally consistent with previous research and our hypotheses and predictions; 3kPZS increased trap encounter and entrance rates at high doses in wide streams, but did not improve trap capture in narrow streams. We conclude that 3kPZS application should be optimized by the amount applied to the trap, not the concentration of 3kPZS when fully mixed with discharge and that 3kPZS, if used, would be most effective in wide streams (> 50 m).  Overall, the capture, encounter, and upstream movement probabilities were weakly driven by 3kPZS application when compared to other factors such as water temperature, stream width, sea lamprey length, and sex.  Therefore, biological and environmental factors will be very important to consider if using 3kPZS-baited traps on wide streams.

**Upstream movement**

When tested among a diverse suite of traps in different streams, 3kPZS application did not increase upstream sea lamprey movements to within 30 m of the trapping area or consistently increase the speed of these movements, which is not fully consistent with previous research conducted in more controlled circumstances. In a several hundred-meter section of the Ocqueoc River, where no other sea lamprey or their pheromones were present, sexually immature sea lamprey were more likely to move upstream when exposed to 3kPZS 5 x 10-13 M (~1 mg/hour) when water temperatures were less than 15o C (Brant et al. 2015), but not at warmer temperatures. When analyzing upstream movement by sea lamprey we only observed a weak interaction between 3kPZS concentration and water temperature, but nearly all trials in this experiment occurred at water temperatures greater than 15o C. This lack of contrast between very low and very high temperatures may have precluded us from observing the same effect as Brant et al. (2015). In addition, if the behavioral response observed in Brant et al. (2015) was an all or nothing threshold response, 3kPZS naturally produced by other lamprey species (Buchinger et al. 2017) or larval sea lamprey (Buchinger et al. 2013) may have been sufficient for inducing the response during trials when no 3kPZS was applied. In other words, increased concentrations of 3kPZS achieved by applying additional 3kPZS to the trap may drive upstream movement similarly to naturally present 3kPZS concentrations.

Unexpectedly, 3kPZS application resulting in high concentrations of 3kPZS at the release site decreased upstream movement of sea lamprey, especially for males. Motivation for sexually immature males may decrease when 3kPZS concentration is high because very high 3kPZS concentrations could indicate that the male is close to spawning areas; further upstream migration not required and refuge could be sought until sexually mature. Taken together, evidence from this large study showed that addition of 3kPZS did not increase upstream movement from 500 m downstream to within 30 m of the trapping location and could potentially lead to decreased upstream movement when in-stream concentrations are high. Therefore, managers should not expect that 3kPZS will increase upstream movement rates of sexually immature sea lamprey to traps under the trapping conditions experienced here.

**Trap encounter**

3kPZS application rate did not influence the probability of encountering the trap entrance after a sea lamprey moved upstream, but the rate at which a sea lamprey transitioned from within 30 m of the trapping area to the trap entrance did increase in most large rivers. These results are consistent with Brant et al. (2015) in the Ocqueoc River where the probability that sexually immature sea lamprey entered a channel receiving 3kPZS 5 x 10-13 M versus a channel receiving control solvent did not differ. Also, consistent with the present results, a previous experiment at Carp Lake Outlet using the same trap as used in this study, found that movement of sexually immature sea lamprey upstream to the trap entrance did not increase or occur faster when 3kPZS was applied at 2.5 mg/hour (Hume. et al 2015). Application of sea lamprey alarm cue to the side of the stream opposite the trap did reduce the time to locate the trap entrance (Hume et al. 2015). Although the probability of arriving at the trap entrance was not influenced by 3kPZS application, the speed of arrival was shortened in three rivers, including the two widest. When considering our results and previous studies, a possible interpretation of the data is that 3kPZS does not attract sexually immature sea lamprey to the source as it does for ovulated female sea lamprey (Johnson et al. 2009), but instead, when exposed to high doses in large rivers, causes them to increase swimming speed and general search behavior; therefore, less time is required to locate the trap entrance.

**Trap entrance**

The rate of entering the trap after encounter and overall capture probability were only effectively increased by 3kPZS dose in wide streams. This was consistent with our hypothesis that 3kZPS would be more effective in wide streams, but the inability of 3kPZS to positively influence trap entrance in narrow streams at any dose tested was unexpected. In the first management-scale test of 3kPZS at Carp Lake Outlet, video analysis of the trap funnel showed that the likelihood of sea lamprey entering the trap after trap encounter was higher when the trap was 3kPZS-baited (Johnson et al. 2013). Our present results differ from this finding in that sea lamprey remained near the Carp Lake Outlet trap longer as 3kPZS dose increased while the rate of entering the trap decreased, resulting in a negligible effect on overall likelihood of entering the trap. In contrast, sea lamprey became more active near trap entrances as 3kPZS dose increased in wide streams, consistent with an explanation that sea lamprey may be swimming faster and searching more when exposed to 3kPZS.

However, the biological mechanism driving an increase in swimming speed and searching near the 3kPZS in wide streams is not clear. A possible explanation is that sexually immature sea lamprey use 3kPZS as a social cue to coordinate migration (Buchinger et al. 2013 and 2015) and the behavioral response to the cue may differ according to the relative density of adult sea lamprey, the intensity of signal, and size of the river. In our study, sea lamprey abundance in the smallest streams (Carp Lake Outlet; Ocqueoc) was similar to or greater than our largest streams (Manistee, Grand), so the relative density of sea lamprey in the large rivers was much less than the density of sea lamprey in small rivers. In a large stream with relatively few sea lamprey (like the Grand), locating other sea lamprey would be more challenging, so a sudden increase in 3kPZS concentration may indicate lampreys are nearby, trigger faster movement upstream as to not lose the cue within their large spatial environment. In a small stream, where sea lamprey density is high, an increase in 3kPZS implies spawning conspecifics are nearby, but because the spatial scale of the stream is small, the conspecifics are easier to locate, so movement rate may not increase or may even slow down, as observed in this study. In previous management-scale 3kPZS experiments, trap catch increased most in streams with relatively low densities of adult sea lamprey (Johnson et al. 2015), which is consistent with the biological mechanism proposed herein.

In the Grand River, once a sea lamprey arrives at the upstream state, all aspects of the capture process were helped by 3kPZS; sea lamprey approached the trap area more, stayed longer, and entered the trap at a higher rate. This seems like a case for increased movement caused by 3kPZS and directed movement toward the 3kPZS-baited traps. In the Manistee and Betsie rivers movement increased, but more in a non-directed fashion because once sea lamprey were upstream they moved to the trap more, entered the trap at a higher rate, but also left the trap at higher rate. The Grand River traps were located within a fishway. Perhaps 3kPZS works better when used on traps that have a pre-trap setup (fishway); sea lamprey enter a semi enclosed area then move into the trap from there. 3kPZS application to traps in fishways could provide a better signal because it is hydraulically less chaotic. Future work could aim to better understand the biological mechanisms driving the trapping responses observed and how they vary among trap types.

**Other factors influencing probability of trap capture**

Dawson et al. (2017), concluded that environmental factors that could not be manipulated by sea lamprey trappers were stronger drivers of sea lamprey capture probability than factors that could be manipulated (like 3kPZS). Similarly, here, biological and environmental factors like sea lamprey length and water temperature were more likely to influence trapping success than 3kPZS application. To our knowledge, this is the first study demonstrating that longer sea lamprey were more likely to move upstream, encounter, and enter traps than shorter sea lamprey, but similar relationships have been observed in Pacific lamprey as relating to the probability of passage through fishways (Keefer et al. 2009). Consistent with our prediction, sea lamprey had a much lower probability of encountering a trap and doing so repeatedly in wide streams and accordingly, capture probability was lowest among the widest streams. Therefore, biological and environmental factors, as well as trap placement and design, will be essential to consider when using 3kPZS-baited traps on wide streams.

**Caveats**

Results are specific to sexually immature sea lamprey at barrier-integrated traps and should not be used to predict how ovulated female sea lamprey would respond to 3kPZS-baited traps set near spawning areas. 3kPZS induces the strongest responses in ovulated females (Johnson et al. 2009), but that response was not strong enough to lure large numbers of ovulated females into barrier-integrated traps in initial field tests (Johnson et al. 2013) likely because spawning areas may be 100s of meters or kilometers downstream of barriers. Specifically designed traps set on spawning grounds baited with 3kPZS would most likely be useful for exploiting ovulated females, but would require infrastructure and staffing above and beyond the current barrier-integrated trapping network (Wagner and Thomas 2010; Dawson et al. 2016). Results should also not be extrapolated beyond the doses (50 mg/hour) and the sizes of rivers (165 m) tested.

**Management implications**

3kPZS primarily influences behavior near the trap entrance and in large streams, so the management implication is that 3kPZS will work best on large streams, where many sea lamprey encounter the trap, during nights when sea lamprey are actively migrating and are likely to be in the trapping area. Sea lamprey trapping success begins by placing a trap where sea lamprey congregate because a trap’s success is largely driven by the number of sea lamprey that encounter the entrance (Bravener and McLaughlin 2013; Dawson et al. 2017). 3kPZS will not substantially increase trap catch on large streams unless many sea lamprey are encountering the trap. In other words, if the trap is positioned poorly and sea lamprey are unlikely to encounter it, trap catch may only increase by a handful of individuals. 3kPZS application dose across streams should be normalized by how much 3kPZS is being emitted at the trap, not by the molar concentration when fully mixed with stream discharge because 3kPZS generally increases trap capture probability by modifying near source behavioral responses. The dose could be as high as, or higher than, 50 mg of 3kPZS/hour.

The capture of 10-20% more adult sea lamprey in 3kPZS-baited traps will likely not result in meaningful or consistent reductions in the production of sea lamprey larvae and therefore, should not be considered a standalone sea lamprey control tool. Sea lamprey stock recruitment dynamics are largely density independent, so modest reductions in the stock of adults will not be met with consistent modest reductions in the stock of larvae (Dawson and Jones 2009). 3kPZS should not be viewed as a control method that can replace lampricide or barrier usage, nor are pheromones likely going to be a viable control method for other invasive fishes (Sorensen and Johnson 2016), but instead, could be a part of an integrated program as is the model for insect pests (Barzman et al. 2015). 3kPZS could be a tool that can increase trap capture in some circumstances and when paired with tools designed to reduce the reproductive potential of sea lamprey populations such as electrical barriers (Johnson et al. 2016), sterile male release (Bravener and Twohey 2016), alarm cues (Wagner et al. 2011), pheromone antagonists (Raschka et al. 2018), migratory pheromones (Li et al. 2018), lights on traps (Stamplecoskie et al. 2012), sound (Mickle et al. 2018), and water velocity (McAuley 1996), could be an ingredient in a larger recipe that consistently reduces reproduction and larval production. This adult sea lamprey control recipe could then supplement current usage of lampricide and barriers to control sea lamprey and meet ecosystem goals for the Laurentian Great Lakes.