Modeling Sea Lamprey Abundance in Lake Huron After Stopping Lampricide Treatment on Specific Rivers

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Summary

The purpose of this project was to examine how sea lamprey abundance would change in Lake Huron if specific streams in Ontario, Canada we not treated with lampricide. We used a stochastic simulation model (see Jones et al. 2009) to estimate the expected long-term sea lamprey spawner abundance given a set of parameters and a control budget for Lake Huron. To simulate the cessation of lampricide treatment on a stream, we removed each of the streams (and all of its tributaries) individually, to create four river removal scenarios: Garden, Mississagi, Root, and Echo rivers. We also ran a scenario where all four rivers were removed at the same time. Then, for comparison to normal treatment protocols, we ran the model including all streams in the ranking process which selects streams to be treated based on a set control strategy.

We found that when lampricide treatment is stopped on a river that supports spawning sea lamprey habitat, an increase in the number of spawning sea lamprey could be expected. Under normal treatment protocols, there are approximately 145 thousand spawners produced in Lake Huron annually. When lampricide treatment was withheld on the Echo and Root Rivers, the expected number of spawning sea lamprey rose to approximately 150 thousand and 155 thousand, respectively. Expected spawning sea lamprey abundance in Lake Huron rose to approximately 188 thousand when lampricide was withheld on the Garden River. The model estimated that omitting the largest river, Mississagi, from the treatment schedule would cause the expected spawning sea lamprey numbers to increase to approximately 424 thousand if the river was left untreated.

Because sea lamprey abundance is tied to habitat availability and suitability, small streams with less habitat will generally produce fewer parasitic phase sea lamprey and thus fewer spawners to return to the streams. Here we showed that stopping treatment on the smaller streams, Echo and Root, will have much less impact on the mean spawners in the lake than stopping treatment on the Garden or Mississagi rivers. In particular, because the Mississagi River can produce a substantial number of parasitic sea lamprey, not treating it caused a near tripling of spawners in the Lake Huron system. In the absence of feedbacks (e.g., lower survival of parasitic stage sea lamprey or change in their feeding behavior), such an increase would be expected to lead to an approximate tripling of attacks and deaths on the fish host species in Lake Huron (Bence et al., 2003).

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Background

Each year, streams across the Great Lakes are treated with lampricides that target larval populations of the invasive sea lamprey, as part of a bi-national program to control this invasive species and the damage it inflicts on fish that support recreational Indigenous and commercial fisheries. Sea lamprey control efforts have successfully reduced the number of parasitic sea lamprey that prey on large-bodied fish in the lakes, and remains a cornerstone of fishery rehabilitation. Although highly selective, lampricides can also impact other stream-dwelling fishes, particularly those individuals already stressed by disease, reproduction, or degraded water quality. As well, certain species or life stages exhibit sensitivity to lampricides and non-target mortality can be a concern when it involves ecologically important or culturally significant fish species such as lake sturgeon. Exposure to lampricides at concentrations used to control sea lamprey does not present undue risk to human health, according to the U.S. Environmental Protection Agency or Health Canada, however; it is commonly raised as a concern by water users.

The Garden and Mississagi Rivers were last treated in 2014 and 2013 respectively. The Garden River was proposed for treatment in 2016 and 2017 to address a large number of larvae that survived the 2014 treatment, as well as new recruits. Similarly, treatment of the Mississagi River was proposed in 2017 to prevent juveniles from the 2014 larval cohort from escaping to Lake Huron. These treatments were deferred to provide the Garden River and Mississauga First Nations adequate time to review information and material that DFO provided relative to the history of treatment, its role in supporting fish stocks in Lake Huron, and environmental and health impacts related to lampricide exposure. To date, the two First Nations have not supported proposals to treat these two rivers.

Here we model the changes in spawning sea lamprey abundance in response to a cessation of sea lamprey control in the Garden and Mississagi Rivers. We also include the effects on spawner abundance caused by skipping lampricide treatment on the Root and Echo Rivers which serve as the west and east boundaries of the Garden River Reserve because there is concern that the First Nations may not support treatment of these rivers in 2018.

Methods

We used a stochastic simulation model (see Jones et al. 2009) called SLaMSE (Sea Lamprey Management Strategy Evaluation), which estimates sea lamprey spawner abundance given a set of parameters and a control budget. The operating model consists of a biological model representing the full sea lamprey life cycle, and observation model that tracks population assessment, and a management model that evaluates the effects of various control strategies. The biological model represents the larval, transformer, parasitic, and spawning phases of the sea lamprey life cycle (Figure 1).

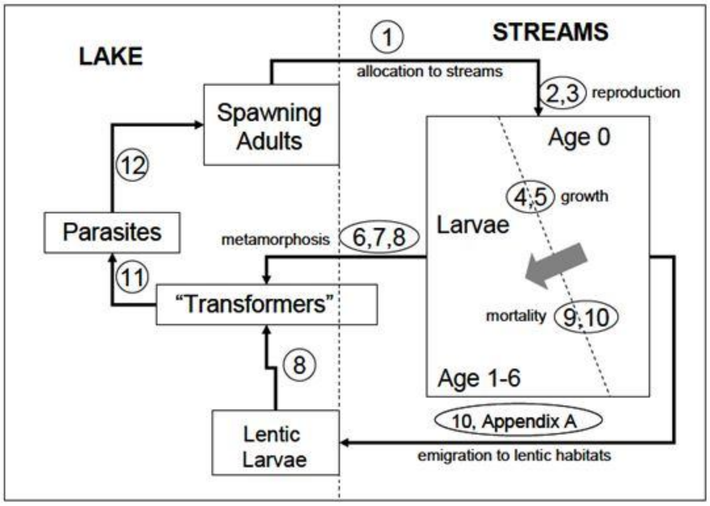

Figure 1 – Biological model flow in SLaMSE model

Spawning-phase individuals are allocated to each stream reach based on stream size and larval abundance. Age-0 recruits are then produced on a stochastic stock-recruitment function from spawning-phase individuals who eventually die. Larval sea lampreys remain in streams for multiple years so the age-structure larval population in each stream is updated annually to account for natural mortality, removals due to lampricide treatment, and losses due to metamorphosis to the parasitic life stage. Any larval sea lamprey that metamorphose but are not removed via control treatments are added to the lake-wide abundance of parasitic sea lamprey. This cohort of parasites becomes the spawning-phase population in the following year after losses due to parasitic-phase natural mortality. Thus, the parasitic phase represents individuals that are leaving streams to migrate to the lakes in search of hosts. During this time, they experience a fixed annual mortality and finally return to the rivers to spawn as adult sea lamprey spawners.

The SLaMSE model is designed to calculate long-term average numbers of sea lamprey. Thus, the model is initially populated just with a specified number of lakewide spawners. Over time in the simulations the streams are populated with age-structured populations of larvae and lake wide numbers of spawners equilibrate to a long term expectation. For our base simulations, our procedure was to run the model for 100 years and use the average number of sea lamprey in the last 10 years of each simulation, averaged over replicate simulations, as an estimate of the expected number of sea lamprey under a given set of conditions.

To simulate the cessation of sea lamprey control on each river, we also employed a new SLaMSE model feature (Jensen 2017) which allows lampricide treatment to be stopped on selected rivers and tributaries. Other model parameters specific to Lake Huron and the St Marys River are the same as those used by Irwin et al. (2012) except for the control budget and target mean abundance of spawning sea lamprey, which were updated to reflect the current time period (Table 1). The control budget is a key number used in all simulations. The target mean abundance is used in calibration simulations to ensure the model under status quo assumptions produces sea lamprey abundance that matches observed values. We used the mean control budget from 2009-2015 ($2,313,034 US) and set the target spawner abundance to the mean from 2011-2017 (142,939 spawners). The spawner abundance was lagged two years from the control budget to account for the delay between treatment and effect on spawner abundance.

Before being used for simulation modeling for evaluating alternative scenarios, as indicated above, the SLaMSE model was calibrated to match target spawner abundance, under the control budget and status quo treatment schedule. During calibration, we considered adjusting survival of larval sea lamprey and a scalar used to determine the movement of age-0 larvae from streams to lentic areas (the outflow scalar). In the end we just adjusted the larval survival value, and left the outflow scalar at its default value. The larval survival value was ultimately set at 0.41, which is reasonably in accord with very limited empirical information. Our standard for successful calibration was to be within 10% of the target and with this survival value, and we ended up within 2% averaged over the last 10 years of the calibration simulations.

Using the calibrated model, we conducted 300 simulations over 100 years for each scenario, starting with the target number of spawners, to allow the system to reach a steady-state level of sea lamprey spawner abundance. Key parameters we used to run the model are shown in Table 1. Each stream also has specific values in the model that define its size, structure, sea lamprey characteristics, and control information (Table 2).

To simulate withholding lampricide treatment on a stream, we removed each of the streams (and all of its tributaries) individually, to create four removal scenarios: Garden, Mississagi, Root, and Echo rivers. We also ran a scenario where all four rivers were removed at the same time. For comparison to normal treatment protocols, we also report results from runs where all streams were subject to treatment. Results from this scenario provide a basis of comparison with the removal scenarios to allow the calculation of relative change in the abundance of sea lamprey parasites and spawners when a stream does not receive lampricide treatment.

Sea lamprey predation on the Great Lakes fish community increases when lampricides are not applied or concentrations are reduced (Smith and Tibbles, 1980). Determining the impact of withholding lampricide on a stream on the fish community is complex and outside the prevue of the SLaMSE model. We provide a rough estimate of lake trout losses per spawning sea lamprey (Bence et al. 2003). This estimate is likely conservative with respect to overall host losses given that fish other than lake trout are attacked (see Results and Discussion).

Results and Discussion

We present the mean sea lamprey spawner abundance and the mean number of parasitic sea lamprey over the last 10 years when the model reaches equilibrium, as indicators of the response to each scenario. Spawners are adult sea lamprey that have spent time in the lake in their parasitic phase. Parasitic sea lamprey are juveniles that haven yet to mature but have migrated to the lake. We apply a fixed annual mortality to the number of parasites (0.75) to determine the number of spawners that return to the tributaries.

The estimated mean number of spawners for each removal scenario increased when lampricide treatments were stopped on specific streams (Table 3), and indicates that lake wide additional resources would need to be invested in lampricide treatments to keep the spawner abundance as low as when the excluded streams were eligible for treatment. A key thing to note is that these simulations assume that the resources that would have been used on the omitted streams are still part of the Lake Huron treatment budget, so the increase in sea lamprey results from a less efficient use of the budget, not from a budget reduction. The number of parasitic sea lamprey in the lake and the number of spawners that would potentially be entering Lake Huron streams varies by river and is affected by the properties of each river system (Table 2), the control budget, and the other streams that could be treated when the removed stream's budget is freed up for treatments (Table 3). Because of the direct relationship between number of spawners and number of parasites, the size of the parasitic lamprey population increases when mean spawners increase.

Stopping sea lamprey control on smaller systems, such as the Root and Echo rivers, impacted the mean spawner abundance significantly less than the larger Garden and Mississagi rivers (Table 3). The small relative change in spawner abundance in the Root (1.06) and the Echo (1.03) rivers indicate that stopping lampricide treatment in these systems has a smaller impact on sea lamprey spawner abundance and thus the number of parasitic sea lamprey entering Lake Huron (Table 3). When lampricide is not applied to the Garden River, there would be approximately a relative increase of 1.29 in the mean spawner abundance (Table 3). A more substantial impact on spawner abundance is seen when lampricide treatment is stopped on the Mississagi River, where an additional 278,000 spawners would be present in Lake Huron, and the mean number of spawners would nearly triple (Table 3) over what would be expected if this stream was not dropped from potential treatment. The biggest impact on mean spawner abundance occurs when lampricide is not applied to all four rivers leading to over 486 thousand spawners estimated to be in the lake (Table 3).

This is an equilibrium-based model and is expected to show the long term average abundance the sea lamprey population will achieve. However, to examine the potential impact of not treating a river with lampricide in the short term, such as during the first 10 years, we reran the model, starting at calibrated spawner numbers, for 10 years. We only withheld lampricide treatment on the largest river, the Mississagi as it is most likely to show short term changes in spawner populations. In the first 10 years we found that there could be a potential to produce 28% more spawners than when all streams are eligible for treatment (as calculated over the same 10 year period, starting from the same conditions). This is a tentative and rough number, in part because the starting population consists not just of the starting input number for lake wide spawner abundance but also numbers for the abundance of each age in each stream. Those stream-specific numbers are not in equilibrium with the status quo (all streams eligible) lampricide treatment schedule. As such, the shorter-term estimate could partly reflect an interaction between initial conditions and the lampricide treatment schedule. An additional issue is that specific predictions for a given year a short period in the future will depend on the actual numbers of sea lamprey present in the starting year, not just the long-term expectations given the current treatment schedule. While the 10 year percent increase estimate is tentative, we do believe it shows that one can expect a substantial increases in lamprey numbers over a 10 year period if the Mississagi River is not eligible for treatment, but that the increase would be much less than what is expected over the long-term. Over many generations, sea lamprey spawning populations continue to expand due to the increased production potential stemming from leaving the Mississagi River out of the treatment schedule, leading to larger increases in the long-term than after 10 years and a bit more than two generations.

Any time lampricide treatment is stopped on a river that supports spawning sea lamprey habitat, an increase in the number of spawning sea lamprey could be expected. The number of additional spawning sea lamprey in Table 3, should not, however, be expected to be exactly additive. That is, the number of spawners added when each individual river is removed does not add to the number of spawners when all four streams are removed. Randomness contributes to the non-additivity. There are numerous places where uncertainty plays a role in this model and thus we ran many simulations of many years to allow the model to come to equilibrium. Additionally, the loss in efficiency due to resources being reallocated to other streams is not generally linear. As more resources are reallocated they become progressively less efficiently used, being directed toward steams ranked lower for treatment. Finally, there are also ecological nonlinear feedbacks. Additional sea lamprey resulting from production in a non-treated stream, often will end up spawning in other streams, and spawning habitat limits production through the stock-recruitment function. The sum of the number of additional spawners, calculated over the four scenarios where one stream was left out at a time was approximately 330 thousand, versus approximately 341 thousand for the scenario when all four streams were simultaneously excluded from treatment (Table 3). The direction of this non-additivity is consistent with what would be expected from resources being less efficiently used when multiple streams are simultaneously excluded.

The model does not track changes in other fish community members but Bence et al. (2003) provide an estimate of 1.32 lake trout lost for every spawning sea lamprey in the lake. Given the number of spawning sea lamprey we project based on this per spawner number (Table 3), lake trout mortality will increase as spawners increase (Figure 2). In small streams, such as the Echo and the Root, estimated numbers of lake trout lost is about 6,700 and 12,000 respectively while the much larger Mississagi River more than doubles (approximately 559 thousand) the lake trout losses compared to the normal treatment protocol (Figure 2, see dashed line for normal protocol). The total number of hosts lost to sea lamprey could well be substantially higher than suggested by these estimates. Bence et al. (2003) reviewed different such estimates, and noted that different calculations led to a substantial range of estimates. The estimate of 1.32 lake trout per spawner was at the lower end. In derivation of this number, the total lake trout deaths was based on statistical catch-at-age estimates of lake trout abundance-at-age, estimates of mean sea lamprey wounds per fish at each age, and an assumed relationship between wounding at per capita lake trout mortality, and the number of spawners was the empirical estimates. Bence et al. also reported numbers of host deaths per feeding sea lamprey based on an assumed seasonal feeding pattern and total number of attacks per sea lamprey (based on how much they need to feed in order to reach the size they do), and lethality of the attacks. The attack lethality was calculated based on survival as related to host size and temperatures synthesized from laboratory experiments (Swink 2003), using specified host sizes and temperature regimes. The range of hosts killed per feeding sea lamprey from these calculations ranged from 4.1 to 9.8, with the lowest number killed when the host size was the largest used (5kg) and the highest number occurring for the smallest host size (1kg), and results were not highly sensitive to temperature. We believe the typical host size is closer to 1kg than 5kg, which although maximizing the number of hosts killed per feeding lamprey, minimizes the biomass killed per feeding lamprey (9.8kg for 1 kg hosts versus 20.3 kg to 22.3 kg for 5 kg hosts depending on temperature regime). SLaMSE assumes that 75% of parasites survive to become spawners. Even assuming that the deaths between the start of the parasitic stage and spawning stages all occur after feeding ceases, it is clear that this latter set of estimates of hosts killed per sea lamprey is substantially higher than 1.32 per spawner. One obvious reason for the differences is that not all sea lamprey attacks are on lake trout. Thus the total number of hosts killed per spawner could be substantially higher than the losses of lake trout we tabulated.

The calculated losses of lake trout (or alternative numerical or biomass losses based on the alternative numbers from Bence at al. (2003) discussed above) assume that the hosts killed per sea lamprey remain constant and do not change as sea lamprey and host abundance change. We do not have the data nor models to dynamically model host-sea lamprey interactions to account for such complexities.

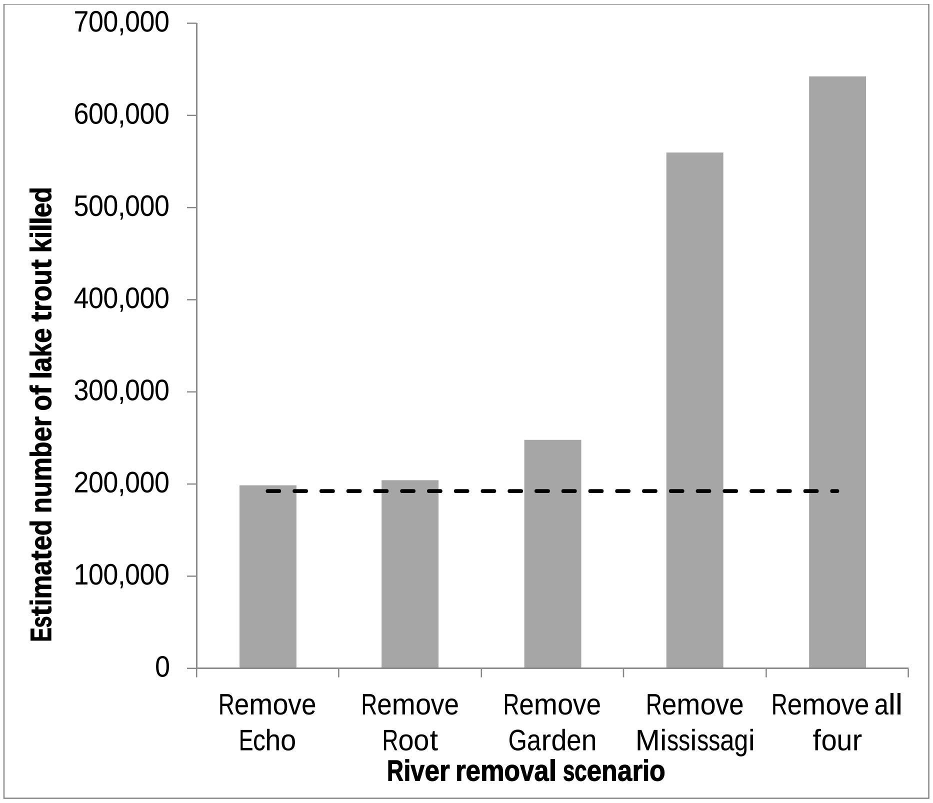

Figure 2 – Estimated number of lake trout that could be killed by sea lamprey in each of the removal scenarios (bars). The dashed line represents the estimated number of lake trout killed when all rivers are being ranked and treated under normal treatment protocols and budget.

Conclusion

Based on the SLaMSE biological model, rivers that are either smaller or provide less sea lamprey spawning habitat will always produce fewer spawners than larger rivers with more sea lamprey habitat. Thus stopping treatment on a small stream will not increase the spawner abundance as much as stopping treatment on a larger stream. Here we showed that stopping lampricide treatment on the Echo and Root rivers (Table 2) will have much less impact on the mean spawners than stopping treatment on the Garden or Mississagi rivers (Table 3) which are substantially larger systems with more sea lamprey habitat. In particular, the size and habitat available in the Mississagi River can support a significant number of spawners and cause a doubling of spawners in the Lake Huron system. In the absence of feedbacks (e.g., lower survival of parasitic stage sea lamprey or change in their feeding behavior), such an increase would be expected to lead to an approximate doubling of attacks and deaths on the fish host species in Lake Huron (Bence et al., 2003).

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Table 1 – Parameters used in the SLAMSE model

Parameter	**Value**	**Source**
Control budget	$2,313,034 US	Mean control budget 2009-2015
Mean spawner abundance	142,939	Mean spawner abundance in Lake Huron between 2011-2017
Larval survival	0.41	Adjusted during calibration to match within 10% of mean spawner abundance between 2011-2017
Calibrated spawner abundance	145,311	Final calibrated value for mean spawners based on larval survival of 0.41
Amount (%) of untreated lentic area	2	Irwin et al. 2012
Lake: Size (ha) of lentic habitat available for treatment	12	Irwin et al. 2012
Lake: Lentic units	1	Irwin et al. 2012
St Marys River: Size (ha) of lentic habitat available for treatment	700	Accounts for St Marys River; Irwin et al. 2012
St Marys River: Lentic units	56	Irwin et al. 2012
Outflow scalar	0.00125	Irwin et al. 2012

Additional model settings used in these simulations:

1. In *Special Options*, click “Apply barrier removal”
2. In *dbStreamTable*, each stream that will stop receiving treatment must have the field “Barrier_TreatmentSwitch” set to 1. All other streams must be set to 0.

Table 2 – Lake Huron stream data used in SLaMSE model.

River	Tributaries (as defined in SLaMSE)	Drainage Area	Default Infested Length	Average Daily Growth	Default Proportion Type1	Default Proportion Type2
Echo	Echo River, Bar Creek and Iron Creek	930	8,424	0.1300	0.075	0.489
Garden	Main	1,019	58,165	0.1500	0.042	0.572
	Tributaries		13,079	0.1500	0.039	0.177
Mississagi	M001	9,271	2,534	0.1700	0.126	0.769
	M002 & M003		27,403	0.1700	0.045	0.725
	Tributaries		7,887	0.1700	0.339	0.370
Root	Main excluding estuary	174	21,859	0.1781	0.007	0.283
	Estuary		1,426	0.1781	0.086	0.877
	Crystal Creek		5,702	0.1800	0.089	0.467
	West Root & Cannon Cr.		13,781	0.1781	0.159	0.194

Other stream data that is the same for all streams listed

Growth parameter ID	9
Annual mortality rate	0.70
Default habitat type 2to1 conversion ratio	0.44
Season days	188
Transformation curve ID	14

Table 3 – Simulation results summarized for the last 10 years in each scenario. The model was calibrated to the estimated spawner abundance between 2011 and 2017 of 142,939 spawners. Our calibrated value, used here to determine additional spawners and relative change, was 145,311. We also present the number of parasites which leave streams as juveniles and enter the lake. Parasites experience fixed annual mortality while in the lake, then transition to the spawner stage as they return to the streams. Uncertainty and the stream ranking process in the SLaMSE model cause differences between the scenarios such that adding the four removal scenarios together will not produce the same results as the Remove All Four scenario.

Scenario	**Number of tributaries not treated**	**Mean Parasites**	**Parasites lost to morality while in lake**	**Mean Spawners in lake**	**Mean spawners under current control**	**Relative change in spawner numbers**	**Increase in number of spawners**
Remove Echo	1	220,691	70,296	150,396	145,311	1.03	5,085
Remove Garden	2	250,888	63,284	187,604	145,311	1.29	42,293
Remove Mississagi	3	562,871	139,218	423,653	145,311	2.92	278,342
Remove Root	4	204,905	50,284	154,620	145,311	1.06	9,310
Remove all four	10	648,779	162,220	486,559	145,311	3.35	341,249