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Research to Guide Use of Barriers, Traps, and Fishways to Control Sea Lamprey

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ABSTRACT. *This paper provides a rigorous and directed research framework for fostering innovations in the design, implementation, and operation of barriers, traps, and fishways used to control the sea lamprey* (Petromyzon marinus) *in the Laurentian Great Lakes. It was developed to support the Great Lakes Fishery Commission's milestone pledging to decrease reliance on chemical lampricides and achieve 50% of sea lamprey suppression through alternative control technologies, including barriers and traps. The paper first substantiates the need to develop a long-term research plan for barriers, traps, and fishways by summarizing (i) current management challenges, (ii) the barrier, trap, and fishway options being used to meet these challenges, and (iii) the key uncertainties in our knowledge regarding these options. The paper then proposes a long-term research strategy that envisions a transition from barriers designed to block the upstream spawning migrations of sea lamprey, to barrier and trap combinations that facilitate physical removal of sea lamprey and, in some cases, passage of non-target fishes, to barrier and trap designs that are specific to sea lamprey, transparent to non-target fishes, and safer for operators. Thirteen research needs are identified to support this strategy along with a general work plan on how they can be achieved. The research needs and work plan highlight the exceptional opportunity to develop the Great Lakes basin as a leading, international research center for fish migration and passage, and the development of environmentally friendly barriers.*

INDEX WORDS: *Barrier, fish migration, fishway, non-target effects, sea lamprey control, trapping.*

INTRODUCTION

This paper provides a rigorous and directed framework for research supporting and fostering innovations in the design, implementation, and operation of barriers, traps, and fishways used to control the sea lamprey (*Petromyzon marinus*) in the Laurentian Great Lakes. The sea lamprey is a predator of large teleost fishes. It invaded the Great Lakes in the 1920s and has strong, negative effects on the native fish community. One of the Great Lakes Fishery Commission's primary responsibilities is to provide a sea lamprey management program that is ecologically and economically sound and socially

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acceptable (Great Lakes Fishery Commission 2001a). In the Commission's vision statement on integrated sea lamprey management for the current decade, milestone 3 pledged to decrease reliance on chemical lampricides and achieve 50% of sea lamprey suppression through alternative control technologies (Great Lakes Fishery Commission 2001a). The milestone will be achieved, in part, through the development and deployment of one new alternative control method, likely exploiting sea lamprey pheromones, by the end of the decade. The science needs for that initiative are developed in Li *et al.* (2007). The milestone will also be achieved, in part, through increased reliance on trapping of migrating sea lampreys in streams and increased deployment of instream barriers that deny migrating sea lampreys access to spawning grounds and facilitate trapping (Great Lakes Fishery Commission 2001a). The science needs for this initiative are developed here.

Traps and barriers have been used to capture sea lampreys and block their movements since the late 1940s (Applegate 1950). Today, trapping is used primarily for assessing abundances of spawning-phase sea lampreys and for providing animals for the sterile-male-release program (Great Lakes Fishery Commission 2001b). Within the Great Lakes, the use of trapping as a control option to directly suppress reproduction has been limited to the St. Marys River. Barriers represent an effective alternative to stream treatment with lampricides. They had a major role in very early efforts to control sea lampreys, but were relegated to a minor role once selective chemical control became available (Hunn and Youngs 1980, Lavis *et al.* 2003). In 1975, the Commission formally recognized a larger role for barriers in controlling sea lampreys and established a barrier program. The Commission currently operates 69 barriers that, collectively, have reduced the amount of primary (Type I) larval rearing habitat accessible to spawning-phase sea lamprey by 15% of the amount available prior to implementation of the barrier program (Burkett *et al.* 2004). The Commission plans to build up to 100 more barriers over the next 20 years. The Commission also monitors *de facto* barriers, owned and operated by other agencies and corporations, that function as sea lamprey barriers (Burkett *et al.* 2004).

This paper first substantiates the need to develop a long-term research plan for barriers, traps, and fishways by summarizing (i) current management challenges, (ii) the barrier, trap, and fishway options being used to meet these challenges, and (iii) the key uncertainties in our knowledge regarding these options. The paper then presents a strong and transparent research strategy and work plan to support the Commission's milestone of increasing sea lamprey suppression with minimal effect on non-target species through the use of barriers, traps, and fishways. The paper concludes by emphasizing how the research strategy and work plan create the opportunity to develop the Great Lakes as a center for research on fish migration and passage, and environmentally friendly barriers. Barriers that restrict the movements of non-native species represent a potentially important tool for reducing the potential population growth rate of invasive species and for protecting and restoring native populations and ecosystems from the negative effects invasive species can cause (Bergstedt and Holmes 1997, Thompson and Rahel 1998, French *et al.* 1999, Maceina *et al.* 1999, Savino *et al.* 2001); however, these barriers remain controversial because of concerns regarding habitat fragmentation and reduced connectivity for non-target species (Jungwirth *et al.* 1998, Graf *et al.* 2002, Graf 2003) and because of limited, broad evaluation of both advantages and disadvantages of barriers and corridors (e.g, Levey *et al.* 2005, Proches *et al.* 2005).

CURRENT MANAGEMENT CHALLENGES

Four key challenges are currently important to the success of using barriers, traps, and fishways as an integral part of a sea lamprey control program that is acceptable ecologically, economically, and socially. They are (i) suppressing sea lamprey reproduction adequately, (ii) minimizing unwanted effects on non-target species, (iii) ensuring the safety of contractors and the public near control structures, and (iv) keeping program costs reasonable. The first three are considered here.

Suppression of sea lamprey reproduction is the foremost challenge; this is the primary purpose for building barriers and traps, and the other management challenges are a consequence of this purpose. At the level of individual streams, properly designed barriers can deny migrating sea lampreys access to spawning habitat (Hunn and Youngs 1980, Lavis *et al.* 2003). Well-designed and operated traps, in combination with barriers or on their own, facilitate removal of pre-spawning animals from the population, thereby eliminating opportunities for blocked animals to spawn below the barrier or in adjacent streams. However, the effectiveness of barriers and traps varies among tributaries and across designs (Lavis *et al.* 2003), and there is still uncertainty regarding standards for what constitute effective barriers and traps. At the population level, assessing the effects of barriers and traps in light of the Commission milestone of achieving a 50% reduction in reproduction through alternative methods remains challenging. Managers and control agents can estimate the percent reduction in larval habitat (Burkett *et al.* 2004), but the actual reproductive suppression achieved is less clear because the production potential of the habitat and the reproductive fate of the animals that are not trapped at barriers are poorly known.

Minimizing effects on non-target species has become an increasingly significant challenge for at least four reasons. First, many stream fishes move more than recognized in the past. The long-distance, cyclic, migratory movements exhibited by large numbers of individuals from populations of taxa such as salmonids and catostomids are well established (Baker 1978, Jungwirth *et al.* 1998, Matthews 1998, Lucas and Baras 2001). However, recent tracking studies, analyses of movement patterns, and comprehensive reviews suggest that many populations or subpopulations of stream fishes move much more often and extensively than appreciated previously (Gowan *et al.* 1994, Gowan and Fausch 1996, Skalski and Gilliam 2000, Lucas and Baras 2001, Rodríguez 2002, Mandrak *et al.* 2003). Second, these movements are an important feature of the life histories of stream fishes, and organisms closely associated with them, such as mussels (Watters 1996). With migratory species, environmental factors restricting movement can eliminate access to critical resources and lead to population declines. Even restricting long distance movements from one population to another, made by few individuals across unsuitable habitats and with substantial risk of failure, can, at least in theory, have significant demographic and genetic consequences (Fausch and Young 1995, Schlosser and Angermeier 1995, Hanski 1999, Rieman and Dunham 2000). Third, concerns regarding restrictions on movement have been reinforced by landscape-level inventories of dams and by scientific evaluations supporting assignments of conservation designations to fishes. Damming is now recognized as one of the most widespread human effects on the environment (Dynesius and Nilsson 1994, Graf *et al.* 2002, Sarakinos and Johnson 2003) and dams and weirs have been specified as a cause for declines of many threatened freshwater fishes throughout the world (Northcote 1998). Fourth, the environmental effects of small dams, like sea lamprey barriers, are just beginning to be assessed rigorously (Helfrich *et al.* 1999, Porto *et al.* 1999, Dodd *et al.* 2003, Tiemann *et al.* 2004) and the societal benefits provided by these structures can be overlooked or underappreciated in these assessments (Graf *et al.* 2002). The growing concern for fish passage presents sea lamprey managers and research scientists with the daunting challenge of designing barriers to selectively block sea lampreys and pass non-target species with minimal effect on fish habitat (e.g., impounding).

Safety has always been an important concern for the Commission; however, its significance has increased with increases in the Commission's barrier inventory. Many barriers and traps are located in streams used for recreational purposes by the public. During the period of sea lamprey migration, contract agents empty traps and fishways daily. Low-head barriers pose a drowning risk when certain conditions of flow and tailrace geometry lead to the creation of a submerged hydraulic jump (vortex) at the base of the barrier (Leutheusser and Birk 1991, Hotchkiss 2001, Leutheusser and Fan 2001). The vortex is created when the nappe of water plunging over the barrier crest hits the bottom of the tailrace, bounces upwards, and rolls back upstream toward the barrier. Submerged vortices pose a drowning risk because the water above them can appear deceivingly calm, the velocities of the upstream current can exceed the capabilities of an Olympic-class swimmer, the plunging nappe can resubmerge a person with considerable force and risk of injury, and the aerated water produces less buoyant force (Hotchkiss 2001).

CURRENT UNDERSTANDING OF BARRIERS, TRAPS, AND FISH PASSAGE DEVICES

The configuration of the control device(s) implemented on any given tributary consists of one to three components: a barrier, a trap, and a fishway. Various design options exist within each component. The fundamental uncertainties for any design configuration are (i) how good is it at blocking or removing sea lampreys? (ii) how good does it have to be to meet the milestone of suppressing sea lamprey reproduction? (iii) how good is it at passing non-target fishes? (iv) how good does it have to be to meet current policy guidelines? and (v) for configurations including a barrier, does the barrier pose an acceptable safety risk? The answers to these questions are interdependent and complex. They require optimizing the effectiveness of potentially incongruent management objectives and discovering new designs that reduce the incongruity between objectives. For example, constructing structures that block sea lamprey completely is relatively straightforward; however, altering a design to facilitate fish passage or minimize impounding of water typically increases the risk of sea lamprey escapement.

Barriers

Presently, the Commission uses three classes of sea lamprey barrier: structures where the crest height is maintained permanently at a constant height relative to the stream bottom (fixed-crest barriers), structures where the crest height or an alternative method of blocking sea lampreys can be adjusted seasonally (seasonal barriers), and hybrids of the two. The class that has been used most extensively and for the longest time is the fixed-crest barrier (Lavis *et al.* 2003). When built properly, these barriers successfully deny sea lampreys access to spawning habitat upstream. However, barriers also differ in their effectiveness at blocking sea lampreys (Lavis *et al.* 2003) and hypotheses for this variation have been developed (McLaughlin *et al.* 2003). Recent examinations of non-target effects have shown that these barriers can alter the composition and abundances of non-target fishes in stream segments above the barrier and restrict the upstream movements of smaller non-jumping species (Porto *et al.* 1999, Dodd *et al.* 2003). They do not alter habitat appreciably, at least on small- to moderate-sized streams (Dodd *et al.* 2003). Current designs of low-head sea lamprey barriers pose a small but significant safety risk (Leutheusser and Birk 1991, Leutheusser and Fan 2001). This risk is not unique to sea lamprey barriers, however. It also exists for the millions of other low-head dams used worldwide for purposes such as water abstraction, erosion and flood control, and micro-hydro generation.

The remaining barrier options include a mix of designs that are, in most cases, newer and studied less well in terms of performance. With some seasonal designs, crest height is increased during the period of sea lamprey migration by adding stop logs or inflating an air bladder to elevate the crest (adjustable-crest barriers). In other designs, movements of all fishes, including sea lamprey, are restricted during the period of sea lamprey migration through seasonal operation of a pulsed DC electrical field (electrical barriers). Hybrid designs include a fixed-crest barrier combined with an electrical field that is activated during peak (high) flows, a fixed-crest barrier combined with stop logs, or a fixed-crest combined with a chute in which flows attain velocities high enough to block sea lamprey migration (McAuley 1996). Uncertainty regarding effectiveness at blocking sea lampreys is greater for these designs than for fixed-crest designs because of their seasonal operation, the possibility of mechanical or electrical failures and, with the exception of electrical barriers, their relatively recent implementation (Lavis *et al.* 2003). The start and duration of operation are primary concerns that depend on our knowledge of the migratory biology of sea lampreys and non-target species. However, the interests of other stakeholder groups can also influence these decisions in ways that increase the risk of sea lamprey escapement. Some of these designs have performed satisfactorily in terms of blocking sea lampreys, such as the inflatable-crest barrier on the Big Carp River (Lake Superior, ON), the electrical barrier on the Pere-Marquette River (Lake Michigan, MI), and the hybrid fixed-crest-electrical barrier on the Ocqueoc River (Lake Huron, MI). The performance of others has been less satisfactory, such as the inflatable-crest barrier on Big Creek, ON (Lake Erie, ON), the electrical barrier on the Jordan River, MI (Lake Michigan, MI), and the former, hybrid fixed-crest/velocity barrier on the McIntyre River (Lake Superior, ON), which was decommissioned in 2005. Overall, these barriers are attractive because they are expected to have smaller effects on non-target species due to their seasonal operation. Their effects have yet to be examined rigorously, but Klinger *et al.* (2003) raised concerns that the period of operation is too long, and that the migration periods of sea lamprey and non-target fishes overlap too much, to allow adequate passage of non-target fishes. In terms of safety, the risk at seasonal barriers with a crest during the period of operation is believed to be comparable to that of a fixed-crest barrier, but it is minimal outside of the period of operation.

Traps

Trap designs can be classified as permanent or portable (Great Lakes Fishery Commission 2001b). Permanent traps are concrete or steel designs, usually square or rectangular, built into a permanent barrier or a trap-and-sort fishway. Some designs trap sea lampreys only, while newer trap-and-sort fishways use a sequence of traps with a decreasing gradation of sizes in funnel openings to trap and, to some degree, passively sort sea lampreys for removal and non-target species for passage. Transportable traps are rectangular sheet mesh cages hung from a structure in a stream during the period of the sea lamprey run and removed afterward.

There is increasing interest in using traps for control purposes, either on their own or in combination with barriers. They physically remove spawning-run sea lampreys from the population and, if capture efficiencies became high enough, they could potentially eliminate the need for barriers and the associated concerns regarding fish passage and safety. Presently, the capture efficiencies of traps are highly variable among streams, and considered too low (23–79%; Great Lakes Fishery Commission 2001b) for control purposes. The capture efficiency needed for control purposes is likely much higher and remains an outstanding question (Jones *et al.* 2003). Capture efficiencies of 95–99% have been achieved for small streams tributary to Lake Champlain (W. Bouffard, U. Vermont, unpubl. data).

Fishways

Fish passage devices can be classified into those where manual sorting is required to pass fishes and those for which manual sorting is not required. Passage devices requiring manual sorting include the new trap-and-sort fishways on Big Carp, Big Creek, Cobourg Brook (Lake Ontario, ON), and the Beaver River (Lake Huron, ON). This class also includes trapping and transporting fishes; an option not used currently within the sea lamprey control program. Passage devices not requiring manual sorting include the jumping pools found at the base of many barriers currently in operation, the former velocity flume on the McIntrye River, and the pool-and-weir fishway operated on the Pere-Marquette River. Other fish passage options, such as Denil fishways, bypass channels, and passive automated sorting devices, have yet to be used by the control program because of the need to separate sea lampreys from non-target fishes. With the exception of the velocity barrier, the fishway options currently in operation appear to provide a low and acceptable risk of escapement by sea lampreys. However, passage of non-target fishes remains a concern. Jumping pools facilitate the passage of jumping species only. The pool-and-weir and vertical slot fishways with manual sorting are used by many more species of fish, but the proportion of non-target fish passed can be low (O'Connor *et al.* 2003). Key sources of uncertainty for fish passage in general include the species and abundances of fishes that need to be passed, placement of the fishway entrance, the quantity and quality of attraction flow required, the timing of operation and frequency of sorting required, and the ergonomics and safety of operation.

RESEARCH STRATEGY

Objective

The principal objective of the research strategy is to **provide the innovation and assessment necessary to improve the efforts of the barrier and trapping program to control sea lampreys, with minimal deleterious effect on non-target fishes and maximal safety for the control agency staff and the public.** This objective will be pursued through a transition from using barriers to deny spawning-phase sea lampreys access to spawning habitat, to using barriers to block and selectively trap sea lampreys, and, ultimately, to the development and deployment of barriers that are transparent to non-target fishes and of novel, barrier-free traps effective enough for control purposes.

This is an ambitious objective that is possibly not achievable in every situation where control efforts are carried out. Nevertheless, the Commission has made and continues to make significant progress toward this end. Early barriers used for sea lamprey control focused on blocking sea lampreys. Today most barriers include built-in traps to remove sea lampreys and, where appropriate, downstream pools designed to assist the passage of jumping fishes. The newest configurations are exploiting seasonal operation of adjustable-crests and electric fields to block sea lampreys, and trap-and-sort fishways to selectively pass non-target fishes. Traps without barriers could provide the next form of improvement if their effectiveness either alone, or combined with other control options such as sterile-male release, can be enhanced adequately, and if they are selective enough to minimize restrictions on the movements of non-target fishes.

Conceptual Development

Two complementary conceptual frameworks were used to identify, organize, and plan specific research needs. The first framework focuses on the innovation needed to broadly assess decisions regarding the implementation of different barrier,

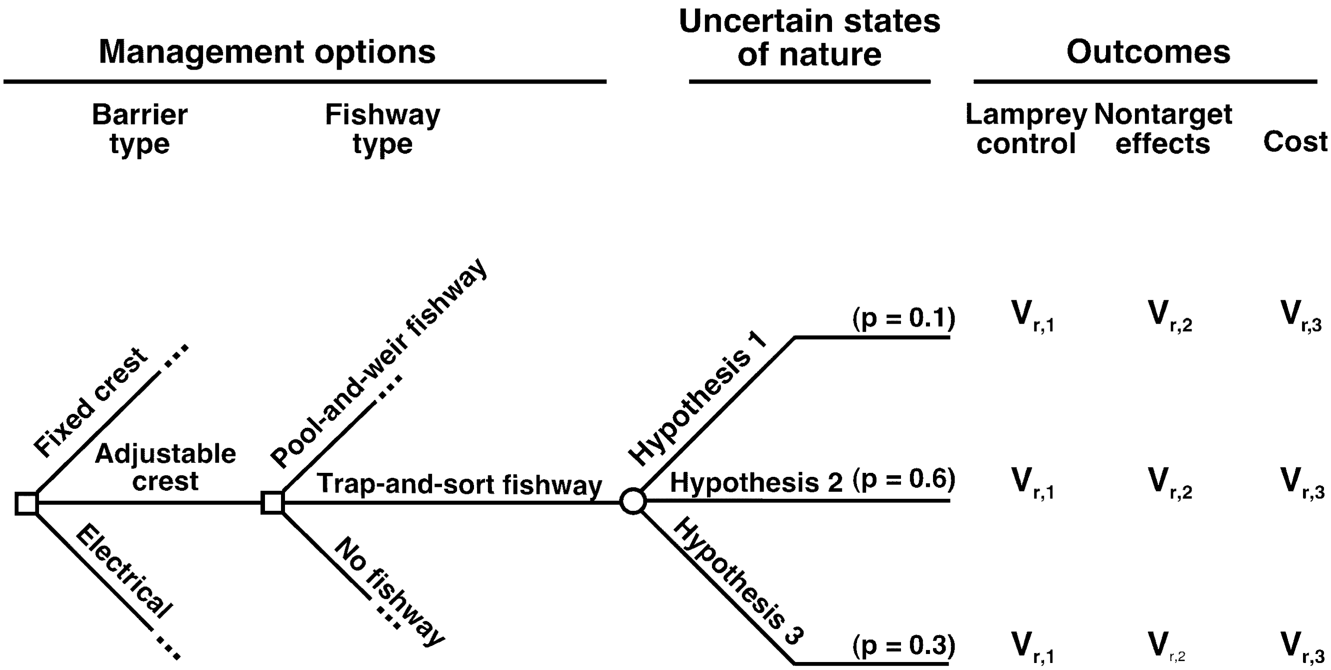

FIG. 1. A generalized decision tree displaying management options (left) and the performance (V's) of each option in terms of meeting management objectives (right). Management options and outcomes are linked by uncertain states of nature (hypotheses) weighted by their probability of being correct (p's). Squares indicate decision nodes and circles uncertainty nodes.

trap, and fishway options in terms of the management objectives identified in policy documents, specifically the suppression of sea lamprey reproduction (Great Lakes Fishery Commission 2001a) and maintenance of biological integrity in the tributaries where the control efforts are carried out (Great Lakes Fishery Commission 2001c). Accordingly, Figure 1 provides an example decision tree displaying three barrier and fishway (management) options on the left and, for each management option, hypothetical performance outcomes (V's) in terms of the management challenges on the right. Management options and outcomes are linked by uncertain states of nature (hypotheses about performance) and each hypothesis is weighted by its estimated probability of being correct (p's). Consideration of management options can lead to the development of new control options and improvements in the potential of existing options. Consideration of management objectives also fosters the development of specific metrics (V's) for the objectives. For sea lamprey, the measure would be the suppression of sea lamprey reproduction above a barrier site (Burkett *et al.* 2004). For non-target species, the measure would be changes in the fish species diversity within the stream (Great Lakes Fishery Commission 2001c). Formal consideration of hypotheses linking the control options to their outcomes provides the basis for developing assessment plans providing the greatest scientific information for a given budget. This framework can also be used to maximize opportunities to learn as new barrier or trap operations are implemented (Parma *et al.* 1998).

The second framework focuses on research explicitly addressing sources of uncertainty identified in Figure 1 and providing the innovation required to develop new management options and improve the performance of existing options (Fig. 2). It considers the challenges faced by a fish moving through a stream and identifies four sequential behavioral components: (i) migration or ranging within a stream, (ii) search for a way around or over any barrier or trap encountered, (iii) passage across, around, or over the barrier or trap, and (iv) fate following passage, where fate can represent survival and reproduction or contribution of the species' normal ecosystem services. These components are

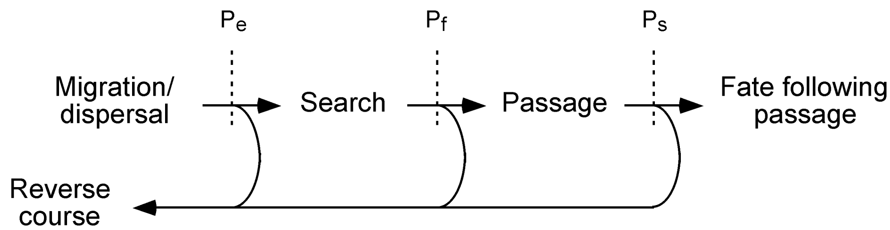

FIG. 2. A conceptual framework for examining the components of fish movement and passage from the perspective of a fish moving through a stream.

separated by three probabilistic events: encountering a potential barrier or trap (P_e), finding a way around it (P_f), and passing successfully (P_s). The fish may also reverse course and head back downstream if it fails to make the transition between two behavioral components in the sequence, i.e., if P_e, P_f, or P_s equals 0. For sea lamprey, the emphasis is on barrier and trap designs that reduce the values of P_f and P_s, while for non-target fishes the emphasis is on maintaining values of P_f and P_s that approximate values observed under natural conditions. The framework can be modified further to accommodate specific questions such as increasing the probability of sea lamprey finding a trap entrance or retaining individuals in a trap following initial capture.

Research Needs

This section identifies and describes 13 key research needs that provide the foundation for a vigorous research agenda focused on sea lamprey barriers, traps, and fishways. The needs were developed by considering the elements of the conceptual frameworks above from the perspectives of blocking or trapping sea lampreys, passing non-target species (upstream and downstream), characterizing the physical environment encountered by the fishes, designing more effective barriers, traps, and fishways, ensuring human safety, and identifying special technological tools needed to expedite the research. The needs have been described specifically enough to ensure the research is pertinent to the barrier and trapping programs, yet open enough to allow investigators to inject highly-desired innovation, scientific rigor, and technical expertise into the planning and execution of the research. Key issues behind many of these needs could be developed and critically examined in a single multi-year research project. The needs are presented in an order corresponding roughly with the sequential components presented in Figure 2. Research needs 1–4 address migration and dispersal. Research need 5 addresses search behavior at barriers, traps, and fishways. Research needs 6–10 address capture or passage at barriers and traps, and corresponding design improvements. Research needs 11–12 address the overall effectiveness of barriers, traps, and fishways. Research need 13 spans across all components of fish movement and passage. Ranking of needs in terms of immediacy is addressed in the Work Plan below.

1. Predicting timing and magnitude of runs for sea lamprey and non-target species—This research priority is vital to the seasonal operation of traps, fishways, and seasonal barriers. Predicting the timing of runs based on environmental cues and historical information is important for optimizing the opening and closing times of seasonal devices. Predicting the magnitude of runs is important for designing the size of traps and fishways, as well as planning their operation. Understanding the overlap between the phenology of sea lamprey migrations and the phenology of migrations exhibited by non-target species is also important for assessing whether seasonally-operated barriers provide adequate opportunity for fish passage outside of the period when sea lampreys are migrating (Klinger *et al.* 2003).

2. Frequency and consequences of early and late season movements by sea lampreys—Control agents have observed sea lampreys moving in streams before and after the normal period of operation for fishways and seasonal barriers. It is presumed that the earlier migrants move back downstream without reproducing, and re-enter the stream later during the normal migratory run, and that late migrants have inadequate time to reproduce successfully. The reproductive fate of these migrants is poorly known and important to effective control given the high fecundity of this species (Jones *et al.* 2003). Examination of the potential for trapping to select for genotypes spawning at the extremes of the usual phenology in spawning times is also needed.

3. Sea lamprey migration and dispersal patterns—Our knowledge of sea lamprey movements within streams and rivers is inadequate. General predictive models of when sea lampreys move, the routes that they take, where they take refuge, as well as how these behaviors are influenced by stream morphology and hydrology could be used to support efforts to optimize the design and placement of traps and improve the attraction and retention of sea lampreys in traps. Such information could be particularly helpful for large systems where it is challenging to trap large portions of the spawning run. How sea lampreys respond after encountering a barrier and their propensity to leave a barrier stream and move to reproduce in adjacent tributaries are also important concerns (Applegate and Smith 1951, Kelso and Gardner 2000).

4. Passage needs for non-target fishes—This research is important to help identify species with special passage needs, to prioritize species for fish passage research, and to guide the design of fishways. There are over 170 fish species in the basin and over 90 of these have been observed in sea lamprey streams and rivers (Mandrak *et al.* 2003). The timing and extent of seasonal movements are poorly known or unknown for most species, with species of economic importance (e.g., salmonids) or species exhibiting strong seasonal runs (e.g., suckers) being exceptional.

5. Behavior of sea lampreys and non-target species at barriers, traps, and fishways—This research is critical to improving our effectiveness at denying sea lamprey passage upstream, improving guidance to traps, improving trap retention, and improving passage of non-target species through fishways. Needed are general models or investigations of how sea lampreys and non-target fishes search for ways around barriers, how the intensity of this behavior changes over the migratory season, the types of behavior exhibited during this search, how search behavior differs between sea lampreys and other non-target species, and how search behavior is influenced by stream morphology, flow, and other physical factors that might facilitate (e.g., attraction flow) or disrupt this behavior (Coutant and Whitney 2000, Goodwin *et al.* 2001, Nestler *et al.* 2002). Identifying non-target species that would normally move upstream, but do not approach barriers or fishways, is an important priority. Also needed are general models or investigations of the role sea lamprey attachment behavior plays in passing barriers, how sea lampreys and non-target species differ in volitional swimming performance, exploitation of hydraulic complexities (Liao *et al.* 2003a, b), and motivation to pass obstacles during the migratory period or in response to the magnitude or nature of the obstacle.

6. Hydraulic, hydrological, and biological criteria for barriers—Existing barriers differ in their effectiveness at blocking sea lampreys (Lavis *et al.* 2003). This variation is likely due to a complex interaction between (i) the biology of sea lampreys (e.g., magnitude and timing of migration, swimming performance), (ii) among stream variation in stream hydrology (e.g., frequency of flooding) and the hydraulic conditions below the barrier, and (iii) variation in barrier design (e.g., crest height, armoring, and lip design). Identifying the characteristics of effective barriers will assist with the design of more effective, new barriers.

7. Attractors and distracters for sea lamprey and non-target species—This research is vital to efforts to attract and retain sea lampreys in traps and to facilitate passage of non-target fishes. Needed under this priority is a clearer understanding of what makes attraction flow attractive to fishes (e.g., velocity, turbulence, pressure waves), other stimuli that could function as attractors (e.g., light, pheromones) or distracters, the senses lampreys and non-target fishes use to detect these attractors and distracters, and the potential to **combine** attractors and distracters (Coutant 1999) in ways that enhance the control of sea lamprey and the passage of non-target fishes.

8. Funnel and trap configurations—A more formal experimental approach to funnel and trap design will help improve our effectiveness at attracting and retaining sea lampreys in traps, as well as attracting and passing non-target fishes. Valuable areas of research include the placement and orientation of these devices within the stream, the placement and configuration of trap and fishway entrances, optimization of the sizes and configurations of traps and fishways in relation to the anticipated sizes of migratory runs and the ergonomics and economics of trap operation, and the maintenance of attraction flows through the development of more effective self-cleaning screens at the upstream intake of traps and fishways.

9. New and improved designs of barriers, traps, and fishways—In addition to improving existing barrier, trap, and fishway technologies, there is the need to develop and explore entirely new designs arising either from experience outside of the basin (e.g., fish wheels) or from the research advances expected from research needs 1–8.

10. Spillway design—Sea lamprey barriers can create complex flow patterns of potential danger to swimmers, canoeists, and kayakers. Consequently, human safety is emerging as a significant concern for barrier placement and design. Barrier designs that minimize the complex vortices below the barrier are achievable (Hotchkiss 2001), but how effective these alternative designs are in terms of blocking sea lampreys or passing jumping fishes needs to be assessed rigorously.

11. Effectiveness of blocking and trapping sea lampreys—This research is needed to critically evaluate our success at blocking and trapping sea lampreys, as well as assess the effectiveness of new barrier and trap designs or features. Research needs include a greater understanding of how effective barriers and traps need to be for successful sea lamprey control, what maximum level of sea lamprey suppression could potentially be achieved through the use of barriers and traps, and whether highly efficient traps could eliminate the need for barriers.

12. Effectiveness of non-target fish passage—This research is needed to critically evaluate our success at passing non-target fishes, as well as assess the effectiveness of new barrier, trap, and fishway designs or features. Research needs include an improved understanding of how effective barriers, traps, and fishways need to be in terms of maintaining species and genetic diversity and maintaining ecosystem services, some minimum understanding of passage rates and these ecological attributes in the absence of barriers (for reference and interpretation), and what minimum amount of passage is "good enough" both ecologically and socially.

13. Traditional and personal knowledge about movements of sea lampreys and non-target species in streams—Field personnel with the contract agents possess a potentially rich source of qualitative observations and information about the behavior of sea lampreys and non-target fishes in the wild. This information has considerable value for guiding research efforts by providing ideas for new research directions, providing guidance on research directions considered less promising based on past experience, and providing information important to management decisions. Unfortunately, much of this knowledge is not formalized in print, can vary among personnel and agencies, and is at risk of being lost as personnel retire.

WORK PLAN

The research program will be executed using the following three-point plan. First, the research will be funded through a competitive-granting process supported by rigorous peer review of grant proposals. This approach has been taken to maximize opportunities for the infusion of novel ideas and to ensure the rigor of the research and the quality of the knowledge it provides. The Commission administers a Sea Lamprey Research Program and investigators interested in submitting proposals are encouraged to visit the program's web pages (http://www.glfc.org/research.asp).

Second, funding opportunities will be open to all members of the scientific community interested in contributing to sea lamprey control through improvements to the design and operation of barriers, traps, and fishways. The Commission and its partner agencies have access to considerable science capacity. Nevertheless, these agencies also recognize the significant challenge presented by the research agenda and the important synergistic role new investigators can provide as sources of energy, novel ideas, and unique expertise.

Third, each year, guidance in the form of emerging research priorities will be provided to potential investigators by the Sea Lamprey Barrier Task Force and the Reproduction Reduction Task Force prior to the deadline for submission of pre-proposals. While applicants may submit proposals addressing any of the research needs, this process will help applicants maximize their opportunity to contribute to the research program. It will further provide the flexibility to update the prioritization of individual research needs in light of past funding decisions, new exciting research developments, and emerging challenges.

Scientific integration, application of new technologies, collaboration with control agents, and communication within and between the scientific and management communities are additional ingredients vital to the success of the research program. Integration is needed across several conceptual axes. The research program is inherently interdisciplinary. Productive and early exchange and application of ideas from civil engineering, fish physiology and ecology, conservation biology, and resource management are critical to the program's success. The research plan requires striking the right complementary balance between field and laboratory research and the corresponding differences in spatial and temporal scales at which they are conducted and the level of experimental control they offer. Field studies are needed to define key research challenges, provide the raw material for innovative solutions, and field-test innovations developed and tested in the laboratory. Laboratory experiments are needed to refine and test mechanistic hypotheses with greater experimental control and quantitative rigor, and to experimentally assess opportunities to exploit these mechanisms in ways that meet the research needs. The research also requires striking the right balance between rigorous description and hypothesis testing. The latter is highly prized and generally preferred. Nevertheless, the plan recognizes that our knowledge regarding many of the research needs is scant and that rigorous, descriptive, quantitative studies can play justifiable and important scientific roles in developing or selecting the appropriate theoretical framework (Ford 2000) and defining initial conditions prior to experimentation (Hairston 1989).

Exploitation and development of new and existing technologies will be an integral part of achieving the research needs. Innovation requires creative ideas, but it also requires the appropriate application of tools to the see new ideas through to application. Equipment for fish tracking, such as biotelemetry and underwater video (Haro and Kynard 1997, Almeida *et al.* 2002), and equipment for flow characterization, such acoustic Doppler velocity meters and three-dimensional models of flow (Lai *et al.* 2003, Mahesh *et al.* 2004), will be required to extend practical limits on the observation and characterization of fish behavior and water flows in the proximity of barriers, traps, and fishways, and thus to provide information germane to developing more fish-friendly devices. Detailed experimental studies may require dedicated sites or facilities similar to those at other centers of fish passage research, such as the Bonneville Laboratory (Columbia River), the Conte Anadromous Fish Laboratory, MA, and the Tracy Fish Collection Facility, CA. Technological advances will also be considered for incorporation into the design of barriers and traps, as seen with velocity and seasonal barriers and the growing potential in pheromones (Li *et al.* 2002, Johnson *et al.* 2005, Wagner *et al.* 2006), and into new barrier designs including dedicated fish passage devices. Technologies reducing the need to manually sort sea lamprey from non-target fishes are also highly desirable.

Collaboration among researchers and control agents has been a highly-productive feature of past research successes and is strongly encouraged in new projects. Control agents contribute valuably to scientific advancement by evaluating research ideas, providing guidance during project planning, facilitating assess to critical field and laboratory resources, expertise, and infrastructure, and sometimes participating directly in the research projects.

Communication is essential to increase the visibility and transparency of the research program in ways that attract talented investigators and maximize the impact that research advances from the program have in the scientific and management communities. To this end the Commission encourages data sharing among researchers and networking and outreach through attendance at workshops and scientific conferences. In addition, it strongly encourages and supports the publication of research advances in peer-reviewed journals.

PROSPECTIVE

The opportunities presented by the barrier research program are exciting, unique, of broad potential interest, and likely to cultivate the Great Lakes basin as an international research center for fish migration and passage, and the development of environmentally friendly barriers. The opportunities are exciting because of the dynamic interplay between science and management. Management decisions regarding barriers, traps, and fishways provide rich prospects for making theoretical and empirical advances to the fields of animal behavior and physiology, stream ecology, fisheries science, conservation biology, and civil engineering. At the same time, these advances will benefit society by helping natural resource managers make better decisions regarding the control of sea lampreys, the broad and appropriate use of man-made structures in streams, and the conservation of stream fishes and the habitats in which they live. The opportunities are unique because the research advances can be made on a geographic scale and with a level of replication that is unrivalled by most other aquatic systems, owing to the size of the Great Lakes basin and of the barrier program. The opportunities are of broad interest conceptually and geographically. They are attractive conceptually because of the integrated nature of the research priorities and the increasingly recognized need to address complex environmental problems at different levels of biological organization and on varying spatial and temporal scales (Michener *et al.* 2001, Kostoff 2002). In the case of sea lamprey, the advances will be attractive to scientists in other geographical regions because advances made in blocking the migration of sea lamprey within the Great Lakes basin are relevant to parallel, but opposing rehabilitation efforts involving passage of sea lamprey species over dams in their native ranges in eastern and western North America, and in Europe (Haro and Kynard 1997, Almeida *et al.* 2002, Moser *et al.* 2002a, Moser *et al.* 2002b). In the case of non-target fishes, the advances will be attractive elsewhere because of the rich diversity of tributary types found in the Great Lakes basin, the rich diversity of fishes inhabiting these tributaries, and the large proportion of these species with geographic ranges extending throughout eastern and central North America. Viewing the barrier research program as a vehicle to develop the Great Lakes as a potential research center for fish migration and passage is an ambitious, challenging vision. However, it recognizes the scientific and management advances that can be achieved, with significant benefit to society, through the careful planning and execution of the research, the shared and coordinated commitment among management agencies, and the active participation of the scientific community.

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