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Sea Lamprey International Symposium (SLIS II): Advances in the Integrated Management of Sea Lamprey in the Great Lakes

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ABSTRACT. *This paper provides a brief history of sea lamprey* (Petromyzon marinus) *control in the Great Lakes and introduces the second Sea Lamprey International Symposium (SLIS II). SLIS II was held during August 2000 to synthesize advances in sea lamprey management during the two decades since the first Sea Lamprey International Symposium (SLIS I) in 1979. SLIS I was convened by the Great Lakes Fishery Commission (the commission) to reflect on the effects of the first 20 years of sea lamprey control. Recommendations from SLIS I guided advances in the sea lamprey control program that are reported in this volume, including: improvements in chemical control methods; refinements in monitoring of the effectiveness of alternative methods; evaluations of changes in stream production; the search for natural controls; improvements in the understanding of sea lamprey population regulation; better estimation of alternative sources of sea lamprey; and improved understanding of the damage caused by sea lampreys. The most significant development emerging from SLIS I was the policy of Integrated Management of Sea Lamprey (IMSL) that was ultimately adopted by the commission in its Strategic Vision. IMSL was organized around the concepts of Integrated Pest Management (IPM) including: defining targets for control that optimize benefits; application of alternative techniques; and use of quantitative methods and systems approaches. Decision support tools have been developed to aid tactical control planning and to estimate strategic targets for sea lamprey management. The science reported in this volume points the way toward further improvements in the effectiveness and efficiency of sea lamprey management in the Great Lakes.*

INDEX WORDS: *Sea Lamprey International Symposium (SLIS II), SLIS I, Integrated Management of Sea Lamprey (IMSL), sea lamprey control.*

INTRODUCTION

The second Sea Lamprey International Symposium (SLIS II) was held on 14 to 18 August 2000, at Lake Superior State University in Sault Ste. Marie, Michigan. This symposium took place 21 years after the first Sea Lamprey International Symposium (SLIS I), which was held during 1979, two decades after the beginning of stream treatments with lampricides and successful suppression of sea lampreys (*Petromyzon marinus*) in the Great Lakes (Smith 1980). To introduce this symposium, this paper briefly reviews the history of the sea lamprey in the Great Lakes, the establishment of the Great Lakes Fishery Commission (the commission), and the institutions and programs that it developed to deliver sea lamprey control. The paper describes the first Sea Lamprey International Symposium and connects the recommendations and questions that emerged from that symposium to the papers presented in this volume. The paper also outlines the development of integrated management of sea lamprey (IMSL) as the framework that emerged from SLIS I and its role in providing direction for the program.

THE HISTORY OF INVASION

The first authenticated record of a sea lamprey in the Great Lakes was in May 1835, when Charles Fothergill discovered a breeding population of sea lampreys in Duffins Creek, a Canadian tributary to Lake Ontario (Lark 1973, Smith 1995). It is generally believed that sea lampreys invaded Lake On-

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tario from the Atlantic Ocean through the Erie Canal; likely from the Mohawk-Hudson River drainage (Mandrak and Crossman 1992, Smith 1995) as Lake Ontario lampreys are genetically linked to the sea lampreys in the Finger Lakes (Broussard *et al.* 1981). It is improbable that sea lampreys entered Lake Ontario via the St. Lawrence River, as ammocoetes (larvae) have not been found in the upper St. Lawrence River from Lake Ontario to the Quebec border (Pearce *et al.* 1980). By the late 1800s, sea lamprey wounds were common on lake trout (*Salvelinus namaycush*) in Lake Ontario (Dymond *et al.* 1929, Christie 1973), although sea lamprey attacks were not discussed as a possible cause of fish mortality in Lake Ontario between 1850 and 1890 (Smith 1892).

The first sea lamprey was captured in Lake Erie in 1921, entering through the Welland Canal following the unidirectional flow created with the 1919 deepening of the canal (Eshenroder and Burnham-Curtis 1999). Sea lampreys spread quickly through the Great Lakes after successfully passing the barrier posed by Niagara Falls. The first spawning run was detected in Lake Erie during 1932 (Hubbs and Pope 1937). Sea lampreys established themselves rapidly in the upper Great Lakes, being found in Lake St Clair in 1934, Lake Michigan in 1936, Lake Huron in 1937, and Lake Superior as early as 1938 (Trautman 1949, Smith and Tibbles 1980). Once through Lake Erie, the large size of the upper lakes appears to have offered little impediment to the spread of sea lampreys.

In the upper Great Lakes, a series of significant biological changes occurred following the invasion by sea lampreys (Smith 1971). These impacts of sea lamprey predation are well documented in the case histories of each lake included in this volume (Heinrich *et al.* 2003, Larsen *et al.* 2003, Lavis *et al*. 2003a, Morse *et al.* 2003, Sullivan *et al.* 2003)

THE HISTORY OF INSTITUTIONS

Fisheries management agencies in both Canada and the United States initiated several cooperative programs in response to the collapse of Great Lakes fish populations resulting from the invasion of the sea lampreys. The Great Lakes Sea Lamprey Committee was established in 1946 to cooperatively investigate the life history of sea lampreys, sea lamprey distribution, and the extent of destruction (Applegate 1950). The United States Fish and Wildlife Service established a field station at Hammond Bay, Michigan in northern Lake Huron in 1950, to develop control measures for sea lampreys. In 1952, the Great Lakes Lake Trout Committee combined with the Great Lakes Sea Lamprey Committee to form the Great Lakes Lake Trout and Sea Lamprey Committee (Smith *et al.* 1974). This committee was renamed in 1953 and became the Great Lakes Fishery Committee. These committees were comprised of representatives of the United States Fish and Wildlife Service, the Ontario Department of Lands and Forests, and each state bordering on the Great Lakes. Also in 1953, to investigate the sea lamprey problem in the Canadian waters of the Great Lakes, the Canadian Department of Fisheries and the Ontario Department of Lands and Forests created the Federal-Provincial Fisheries Research Center, in London, Ontario.

The eight states bordering the Great Lakes and the province of Ontario had the primary fisheries management and regulatory responsibility in the Great Lakes (Dochoda and Koonce 1994). There had been several unsuccessful attempts between Canada and the United States to establish an international entity to develop cooperative mechanisms, because of opposition to the transfer of any authority from the regulatory agencies (Fetterolf 1980). The spectre of the sea lamprey, however, was the catalyst sufficient to overcome this opposition and on 10 September 1954 the *Convention on Great Lakes Fisheries* (the Convention) was signed by Canada and the United States, establishing the Great Lakes Fishery Commission (GLFC 1955). The Convention was ratified in the United States on 6 June 1955 and in Canada on 6 October 1955. Both countries passed enabling legislation, the *Great Lakes Fisheries Convention Act* in Canada and the *Great Lakes Fisheries Act* in the United States, to allow for implementation of the treaty. This bilateral agreement affirmed the need for the two nations to collaborate on the protection and the perpetuation of Great Lakes fisheries resources. The Convention mandated the Great Lakes Fishery Commission "To formulate and implement a comprehensive program for the purpose of eradicating or minimizing the sea lamprey populations" (GLFC 1955) in the Great Lakes, as well as to formulate, coordinate, and undertake a research program focusing on fish stocks of common concern. The commission has worked toward its mandate by delivering the sea lamprey program, conducting fishery research, and providing support for joint fisheries management on the Great Lakes (GLFC 1998).

As recommended in Article VI of the Convention, the commission contracted the United States Fish and Wildlife Service (Marquette, Michigan field headquarters) to undertake sea lamprey control in the United States and the Fisheries Research Board of Canada, (headquarters in London, Ontario) to undertake sea lamprey control in Canada. In 1966, the Canadian Department of Fisheries and Oceans established the Sea Lamprey Control Centre in Sault Ste. Marie, Ontario and assumed the responsibility for sea lamprey control in Canada.

The commission established advisory committees to provide technical input to its policy and management decisions about sea lamprey control. From the beginning of the program through the 1980s, a subcommittee of members of the commission met with the control and research agents once a year to gather recommendations on the program budgets and direction. During the late 1980s, this structure was expanded to get input to better integrate sea lamprey control and fishery management interests. The new structure emerged from a series of reviews and workshops during the 1980s, with the purpose of linking the objectives for sea lamprey control to those established by the fishery management agencies for the fish communities in the lakes (Koonce *et al.* 1982, Spangler and Jacobson 1985).

The new structure, called the Sea Lamprey Integration Committee (SLIC), had a membership that included fishery managers, sea lamprey control agents, Great Lakes ecologists, and experts in integrated pest management. Technical subcommittees were established to provide detail on the sterile-male technique, barriers, adult and larval assessment, lampricide control, and the St. Marys River control programs. These subcommittees included members from the fisheries agencies and other relevant experts. The resulting advisory structure, which is in place today, successfully supports the commission's decision-making with recommendations that integrate input from fishery managers and biologists outside the program with all levels of technical and management staff within the sea lamprey control program.

THE HISTORY OF CONTROL

The initial control effort focused on mechanical and electrical barriers erected in streams to deny adult sea lampreys access to the spawning areas in the streams. From the late 1940s to 1960, 162 electromechanical barriers were installed in Lake Superior and Lake Michigan. Although these barriers killed many spawning sea lampreys and provided useful assessment data about the status of sea lamprey populations, they were not thought to have been an effective control technique (Smith and Tibbles 1980). The numbers of migrating adult sea lampreys captured at these barriers had not declined by 1960.

Applegate (1950) completed the study of the life cycle of the sea lamprey and determined that the stream-dwelling non-parasitic ammocoetes were the most vulnerable stage for control, as they are relatively sedentary and several generations are in the stream concurrently. More than 6,000 chemicals were evaluated at the USFWS Hammond Bay Biological Station to discover a chemical that had different toxic effects on larval sea lampreys and fishes. Although a total of 10 halogenated mononitrophenols were found to be more toxic to larval sea lampreys than other aquatic organisms, 3-trifluoromethyl-4-nitrophenol (TFM) was chosen as a selective lampricide for stream treatments, because of its ease of handling in the field, its effectiveness at low concentrations, and relatively lower cost (Applegate *et al.* 1961). During 1963, a second compound, the molluscicide Bayer 73 (5,2′-dichloro-4′-nitrosalicylanilide), was discovered to be toxic to larval sea lamprey (Howell *et al.* 1964). This second lampricide could be used either in combination with TFM, increasing the lethal effectiveness on larval sea lampreys without reducing selectivity, or applied separately, coated on sand grains, directly to the bottom of slower-flowing waters

The first application of the chemical TFM took place on 14 May 1958 in the Mosquito River on the U.S. side of Lake Superior (Applegate *et al.* 1961). In the 1960s, chemical treatments were undertaken in Lake Michigan and Lake Huron and were initiated in Lake Ontario in 1972 and Lake Erie in 1986 (Pearce *et al.* 1980, Cornelius *et al.* 1995). In 1973, the Canadian Department of Fisheries and Oceans accepted the responsibility to treat all the tributaries in Lake Ontario, including those in the state of New York. Chemical control was very successful and had reduced the catches of spawning sea lampreys in Lake Superior by 92% by 1978 (Smith and Tibbles 1980). In addition, chemical treatment eliminated the spawning runs in many smaller streams, but the larger tributaries required ongoing treatment.

SEA LAMPREY INTERNATIONAL SYMPOSIUM (SLIS I) —1979—DIRECTION FOR THE NEXT TWO DECADES

The first Sea Lamprey International Symposium was the fifth in a series of symposia sponsored by the Great Lakes Fishery Commission that now number twelve. Beginning in 1971, the commission sponsored these symposia to assemble science critical to the management of the Great Lakes and they proved to be successful vehicles for tackling large-scale challenges (e.g., Loftus and Regier 1972, Colby 1977, Spangler *et al.* 1987). These symposia followed an interactive workshop format in which information, ideas, and models were exchanged. SLIS I followed this model and was held during the summer of 1979 at Northern Michigan University in Marquette, Michigan. The 84 participants included scientists from around the world and experts from within the commission's control agent and research staff (Smith 1980).

SLIS I was held during a time of new optimism about the future of fishery resources of the Great Lakes. There was recognition that effective sea lamprey control was critical to this rehabilitation. As a direct result of the success of sea lamprey control, large stocking programs for salmonines were undertaken in all of the lakes. The native lake trout, extirpated from most of the lakes, was showing the first significant signs of recovery in Lake Superior (Hansen *et al.* 1995). Because of the reduced sea lamprey predation, stocked fish were surviving until adulthood and formed the basis of rekindled tribal, recreational, and commercial fisheries, as well as providing the spawning adults requisite to re-establish self-sustaining fish populations.

The assembly of information during SLIS I provided clear evidence of the initial effectiveness of lampricide controls and the resulting response among key fish species (Pearce *et al.* 1980, Smith and Tibbles 1980, Walters *et al.* 1980a). The symposium integrated the understanding of basic sea lamprey biology and ecology in the Great Lakes with input from sea lamprey experts from around the world. The findings from assessments during the first two decades of control were used to critically evaluate success. As described in detail below, SLIS I led to the development and application of quantitative performance measures to direct sea lamprey control. The synthesis of fishery and sea lamprey management with emerging understanding in agricultural pest control led to the evolution of the commission's strategy of Integrated Management of Sea Lamprey (IMSL) (Sawyer 1980, Davis *et al.* 1982, GLFC 1992, GLFC 2001).

SLIS I provided direction on how to improve sea lamprey control and Great Lakes fishery management (Walters *et al.* 1980b). During the two decades that followed SLIS I, the implementation of these recommendations has dramatically changed the program. SLIS II was convened 21 years later to reflect on these changes. The recommendations from SLIS I are described below, followed by a brief summary of progress and reference to other papers in this volume where further details are provided.

1. Take steps to improve the chemical treatment program

Through research and assessment, the commission has improved all aspects of chemical control including: efficiency of lampricide application; information supporting environmental safety; and selection of streams for treatment. Much effort has gone into refining the concentration of lampricides applied to streams (Bills *et al.* 2003, Brege *et al.* 2003, Johnson and Stephens 2003, Scholefield *et al.* 2003). These efforts have been remarkably successful in reducing the amount of lampricides applied. From their original discovery, lampricides have continued to undergo extensive testing to ensure environmental safety (Meyer and Schnick 1980, Boogaard *et al.* 2003, Waller *et al.* 2003, Weisser *et al.* 2003). During the 1990s, under a U.S. Environmental Protection Agency mandated reregistration program, the commission invested more than $5 million to study the environmental fate and toxicity of the two lampricides, TFM and Bayluscide (Dawson 2003, Hubert 2003). These studies confirmed the findings of the original tests and provided new study results that confirmed the environmental safety of these compounds. Following years of development, quantitative assessment of larval sea lamprey populations and their habitat has progressed to the point where streams can be selected for treatment to optimize control for the resources available (Johnson 1987, Christie *et al.* 2003, Hansen *et al.* 2003, Slade *et al.* 2003)

2. Require statistically sound designs and intensive monitoring schemes for pilot experiments involving alternative treatment techniques

Carefully designed experiments have yielded the most accurate information about the effects of alternative control methods. The implementation of sterile-male release followed an explicit experimental design that addressed a hierarchical series of hypotheses and culminated in implementation as a control technique on the St. Marys River (Bergstedt *et al.* 2003a, Schleen *et al.* 2003, Twohey *et al.* 2003a). This experimental design, however, was instituted only after the lake-wide release of sterile males in Lake Superior had failed to provide conclusions about effects on the sea lamprey life cycle

(Heinrich *et al*. 2003, Twohey *et al.* 2003a). The effects of sterile-male release and all alternative control measures that reduce recruitment are difficult to measure without many years of pre- and post-control observations because of the large variation in year-class strength observed in larval populations (Adams *et al*. 2003, Jones *et al*. 2003). An effective experimental design to improve the effectiveness of barriers and fish passage devices remains a critical need. Significant strides, however, have been made in the monitoring and evaluation of the environmental effects of barriers (see Dodd *et al.* 2003, Hayes *et al*. 2003, Lavis *et al*. 2003a). Emerging control methods based on the use of sea lamprey pheromones are currently at the stage where field studies are required (Twohey *et al*. 2003b).

3. Develop an intensive study of streams colonized by lampreys following pollution abatement

Models based on larval habitat quality, the expanded distribution of sea lampreys, and new streams requiring lampricide treatment support the hypothesis generated during SLIS I that improvements in stream water quality have increased sea lamprey production (Ferrari *et al.* 1995, Larsen *et al*. 2003, Sullivan *et al*. 2003). Nevertheless, changes in pollution status were not found to be a dominant factor in an evaluation of changes in sea lamprey production from the St. Marys River (Young *et al.* 1996). The development of quantitative representative sampling of larval sea lamprey populations (Slade *et al*. 2003) will allow evaluation of rivers with expanded productive habitat. The inventory of streams that are routinely assessed includes all streams with the potential to produce sea lampreys. Removal of dams to improve the ecological integrity of rivers has become an increasingly important priority of resource and environmental agencies throughout the basin (Lavis *et al*. 2003a). Today, these dam removals pose greater potential to increase the amount of nursery habitat available to sea lampreys than further pollution abatement.

4. Invest in a search for "natural" lamprey controls

The most promising new control methods are those involving the use of pheromones to affect migration and spawning behavior of sea lampreys and, thereby, increase capture efficiency and reduce spawning success (Li *et al*. 2003, Sorensen and Vrieze 2003). The mechanisms underlying dispersal and the reasons why some streams are colonized and others are not remain relatively unknown. Along with these methods of suppressing reproduction in sea lampreys, advances in the understanding of the biology of metamorphosis may offer the potential to affect this important step in the life cycle (Docker *et al.* 2003, Youson 2003). A global search for a natural parasite or specific disease organism for sea lampreys has been unsuccessful to date (*Bill Swink, USGS-BRD, personal communication*). Better understanding of the risks of natural controls during the past two decades has increased concern with this approach. The importation of sea lampreys from the Atlantic coast for use in sterile-male release in the Great Lakes was not begun, because of concerns about the risk of introducing non-specific diseases or new genetic strains (Twohey *et al*. 2003a).

5. Conduct large-scale experiments on the effects of reduced lamprey control and overfishing

The value of large-scale experiments to validate management actions in the aquatic world is well documented (Walters *et al.* 1980a, Hilborn and Walters 1992). Large-scale experiments have not been purposely undertaken in the Great Lakes. Nevertheless, the dramatic increase in sea lampreys in northern Lake Huron during the 1980s presented the magnitude of contrast envisioned by the SLIS I authors (Walters *et al.* 1980b). Quantitative assessment suggested that sea lampreys were limiting lake trout rehabilitation in Lake Huron and an evaluation of control options indicated that increased control was possible and that it would be cost-effective (Lupi *et al.* 2003, Schleen *et al*. 2003). Consequently, an extensive control program was undertaken on the St. Marys River, including both enhanced alternative methods and application of lampricides (Fodale *et al*. 2003a). This program was designed to provide maximum benefits and did not include a full experimental design, because of the perceived risks in such an approach to the valuable resources of Lake Huron. Nevertheless, an extensive assessment program was implemented; one that provided power sufficient to evaluate the predicted effects of this effort (Adams *et al*. 2003).

The investment in research and quantitative assessment of fish and sea lamprey populations continue to improve the understanding of the critical role of sea lamprey suppression as a component of ecosystem management in the Great Lakes and Lake Champlain. Scientific understanding since SLIS I has clearly indicated that both overfishing and sea lamprey predation were critical sources of mortality limiting rehabilitation of cold water fish communities (Hansen 1999, Bence *et al.* 2003, Larsen *et al.* 2003, Lavis *et al.* 2003b, Marsden *et al.* 2003, Morse *et al.* 2003, and Sullivan *et al.* 2003). To this end, the combination of effective sea lamprey control, significant lake-wide reductions in lake trout harvest, and lake trout stocking led to the rehabilitation of lake trout populations in Lake Superior (Heinrich *et al.* 2003).

6. Review and revise salmonid stocking programs

While not a focus of this symposium, the critical review of salmonid stocking with respect to prey abundance and trophic dynamics has dominated fishery management activities during the last decade and is covered elsewhere (Jones *et al.* 1993, Brown *et al.* 1999, O'Gorman and Stewart 1999).

7. Restrict exploitation rates on lake trout

Similarly, this topic is not explicitly examined in these proceedings, but the management of exploitation has been a critical element of all Great Lakes fisheries management plans developed since 1980 and is extensively examined elsewhere (Busiahn 1990, DesJardine *et al.* 1995, Eshenroder *et al.* 1995, Hansen 1996, Ebener 1998, Stewart *et al.* 1999).

8. Develop an overall fishing policy for species impacted by lamprey predation

Commercial fisheries in Lakes Superior, Michigan, and Huron are being managed by setting total allowable catch quotas that explicitly account for sea lamprey induced mortality (Sitar *et al.* 1999, Heinrich *et al.* 2003, Lavis *et al.* 2003b, Morse *et al.* 2003). The models for these estimates of sea lamprey damage originated during SLIS I (Pycha 1980) and continued through to the present (Bence *et al.* 2003). Sea lamprey predation and management targets have been incorporated into fish community objectives and lake trout management plans for all of the Great Lakes (Busiahn 1990, DesJardine *et al.* 1995, Eshenroder *et al.* 1995, Hansen 1996, Ebener 1998, Stewart *et al.* 1999).

9. Develop a rehabilitation program for native forage species

This concept and the debate about stocking and management of exotic prey species has dominated Great Lakes fishery management during the previous two decades (Eshenroder and Burnham-Curtis 1999) and is not a topic of SLIS II.

While progress on these key recommendations has been substantial, the "glaring gaps" identified by Walters *et al.* (1980b) remain as critical questions considered during SLIS II:

1. Regulation of sea lamprey numbers

Quantitative assessments of sea lamprey populations advanced to allow us a better understanding of the critical factors determining sea lamprey abundance. Methods have been developed to estimate larval sea lamprey abundance (Christie *et al.* 2003, Hansen *et al.* 2003, Mullett and Bergstedt 2003, Slade *et al.* 2003, and Steeves *et al.* 2003). Estimates of juveniles and adult sea lampreys in the lakes and in their spawning rivers have been completed (Bergstedt *et al.* 2003b, Mullet *et al.* 2003, Young *et al.* 2003). Together, these measures have yielded insight into the role of density-independent effects on year-class size in streams and into the large annual variation in recruitment of sea lampreys (Haeseker *et al.* 2003, Jones *et al.* 2003). These new estimates, however, have generated new questions and inconsistencies. Authors throughout this volume identify questions about sea lamprey abundance that if answered more accurately could improve control.

2. Importance of alternative sources of sea lamprey, other than the streams identified for control efforts

Assessments of larval sea lamprey populations are focused on streams identified for control (Slade *et al.* 2003). The techniques have been extended to look for the presence of larval sea lampreys in streams not regularly treated and in areas of nursery habitat in the lakes. New stream populations are regularly discovered, but these populations are small and are not thought to contribute significantly to adult populations (Heinrich *et al.* 2003, Larsen *et al.* 2003, Lavis *et al.* 2003b, Morse *et al.* 2003, Sullivan *et al.* 2003). Lentic populations have been estimated to be relatively large in areas of Lake Superior, but the contribution of these populations to the lake population remains unknown (Fodale *et al.* 2003b, Heinrich *et al.* 2003). There are discrepancies between the abundance of larvae estimated to be residual to stream treatments and the estimates of spawning-phase and juvenile sea lampreys in the lakes (Christie *et al.* 2003). The evidence provided in the symposium does not rule out the potential for alternate sources to exist and to be significant.

3. Parasitic feeding behavior and impacts on prey

The same improvements in assessment to estimate the abundance of the various life stages of sea lampreys coupled with improved understanding of the population dynamics of lake trout and other prey, reveal the need to acquire a better understanding of the damage caused by sea lampreys (Bence *et al.* 2003). There have been significant improvements in the models of feeding behavior and growth of sea lampreys (Cochran *et al.* 2003, Madenjian *et al.* 2003). Further, the understanding of wounding statistics and survival rates has been expanded through field work, modeling, and laboratory studies (Ebener *et al.* 2003, Rutter *and Bence* 2003, Swink 2003). Even with these advances, there remain significant questions to be addressed to better define the damage caused by sea lampreys in all of the lakes (Bence *et al.* 2003, Stewart *et al.* 2003).

INTEGRATED MANAGEMENT OF SEA LAMPREY—APPLICATION OF INTEGRATED PEST MANAGEMENT

Arguably the most important recommendation from SLIS I came from Sawyer (1980), who introduced the concept and advocated that the commission adopt an Integrated Pest Management (IPM) approach to sea lamprey management. The concept provided the framework that the commission adopted in its policy of Integrated Management of Sea Lamprey (IMSL) (Davis *et al.* 1982). Many of the papers in this volume (SLIS II) reflect the effects of the strategic transformation of the sea lamprey management program to IMSL. During the 1960s and 1970s, IPM emerged out of the integration between chemical and biological control in agriculture and provided an ecosystem approach to pest control. In its IMSL policy, the commission adopted three critical concepts of IPM, that were introduced by Sawyer (1980):

- deliver control that provides the optimum benefits to the fish community;
- use alternative control methods; and
- improve quantitative understanding and systems approaches.

The first IPM concept adopted in the commission's IMSL policy was that sea lampreys should be suppressed to levels where the benefits of the next control action are commensurate with its cost. Determining suppression targets in this way meant that the ecological, economic, and social benefits would be optimized in relation to all costs of control actions (Sawyer 1980). Thus, a primary objective of IMSL was to determine the tolerable level of sea lampreys and the optimal level of control. This target level of pest abundance is called the economic injury level (EIL) and is defined as the point at which the marginal costs of the next control action exceeds the value of the benefits of that action (Sawyer 1980, Koonce *et al.* 1993). The commission defined the benefits of sea lamprey control in terms of support for the fish community objectives that have been agreed to by all of the jurisdictions under *A Joint Strategic Plan for Management of Great Lakes Fisheries* (GLFC 1998). Defining the benefits of sea lamprey control was the responsibility of the fishery management agencies, while estimating the costs of sea lamprey control was the responsibility of the commission. The lake technical committees were the key forums for the development of the science required to support fishery management decisions.

The IMSL approach of defining a tolerable suppression target was quite different than the original objective of eradication, as defined in the commission's mandate. Conceptually, eradication offers large benefits, because control would no longer be required. While eradication has been achieved with remarkable success in a few instances (Smith and Swink 2003), in most pest control programs, the costs of eradication are much greater than its benefits. In the case of sea lampreys in the Great Lakes, eradication does not appear possible at any cost with the current control techniques (Christie *et al.* 2003). Lampricide treatments have been effective in reducing sea lamprey populations, but their effects showed a pattern of diminishing returns as the abundance of larvae was reduced. As with many pest control programs, it was very difficult to move away from the lure of eradication, especially given the dramatic success of the initial chemical control efforts.

The second IPM concept was the need to expand the use of alternatives to chemical methods of control. The application of a broad array of methods has been demonstrated to reduce the economic and environmental costs of pest control in agriculture (Smith and Swink 2003). A variety of control methods, affecting a pest at different stages in its life cycle, has the potential to provide more effective suppression in the long term (Sawyer 1980). Although successful in reducing sea lamprey populations, repeated stream treatments are needed to maintain this suppression, because the large reproductive potential of sea lampreys and density-dependent survival allow those larvae that survive, or that are recruited after treatments, to flourish. Integration of alternatives and enhancements to stream treatment techniques are key to increasing suppression. Examples of the integration of methods to reduce the economic and environmental cost of sea lamprey control include:

- The construction of barriers to block upstream migration of spawning sea lampreys. Barriers have been shown to be more cost-effective than lampricide treatments in some cases (Lavis *et al.* 2003a). Constructing barriers, where feasible and where the environmental effects of blocking fish passage can be mitigated, should improve the overall effectiveness and cost-effectiveness of control (Hayes *et al.* 2003, McLaughlin *et al*. 2003);
- The use of bayluscide as an economic synergist with TFM to improve lampricide cost-effectiveness. Bayluscide has been used in combination with TFM to reduce the cost of stream treatments and to reduce the mortality of select non-target organisms (Bills *et al.* 2003, and Brege *et al.* 2003); and
- The development of sterile-male release and enhanced trapping programs to reduce sea lamprey reproduction in the St. Marys River. The strategy for control that the commission adopted for the St. Marys River depended on both the initial use of the bottom-release granular bayluscide to directly reduce the larval populations and the ongoing use of sterile-male release and trapping to reduce recruitment to the larval population (Schleen *et al*. 2003). This integrated program was selected over other options, because it maximized the benefits and minimized the cost of control efforts.

The third IPM concept adopted in the commission's IMSL policy was the use of quantitative information and systems approaches to evaluate control tactics. Quantitative measures were needed to understand the response of sea lamprey populations to control. Following SLIS I, the techniques for collecting sea lampreys and estimating their abundance were improved. Early efforts were summarized during the Workshop to Evaluate Sea Lamprey Populations (Johnson 1987). The most significant advances, however, were made during the late 1980s and early 1990s when consistent, statistically based sampling protocols were developed. These protocols were adopted during the mid-1990s and population estimates were incorporated into the process of selecting streams for treatment (Slade *et al.* 2003). These assessments yielded databases that allowed direct comparisons of sea lamprey populations among streams across the Great Lakes. Consistent criteria for selection of streams for treatments with lampricides were then developed and applied (Christie *et al.* 2003). This rationalization of selection of streams for treatment has provided the commission with a foundation on which to quantitatively evaluate the effect and effectiveness of all control actions. Further, the improved quantitative measures provided the basis for explicit measures of variance or uncertainty. The design of the assessment program has been evaluated to improve precision and accuracy (Hansen *et al.* 2003).

Sea lamprey control involves reducing sea lamprey populations to improve the survival of fish populations that are being subjected to fishery management efforts, including stocking or exploitation control. Systems approaches are necessary to organize the understanding of population dynamics of the sea lamprey, the fishes they feed on, and the control program (Fig. 1). Building on the work of Walters *et al.* (1980b) and the approach of Adaptive Environmental Assessment and Monitoring (Holling 1978), the commission convened a series of modeling workshops to evaluate critical hypotheses about control actions and the population dynamics of sea lampreys and their prey (Koonce *et al.* 1982, Spangler and Jacobson 1985). The models emerging from these workshops became the basis of generalized decision support tools developed to evaluate the long-term patterns of sea lamprey production and the impacts on fish populations (Koonce and Locci-Hernandez 1989, Greig and Meisner 1991). The evolution of these strategic models to tactical models for evaluation of the effects of control actions on sea lamprey populations are documented in contributions to this volume (Christie *et al.* 2003*,* Schleen *et al*. 2003, Slade *et al*. 2003).

Applying the long-term simulation models, Koonce *et al*. (1993) estimated economic injury levels for sea lampreys in Lake Ontario. They applied the analytical approach prescribed by Sawyer (1980) to link the response of sea lampreys to control and the benefits to lake trout populations. Their results suggested that increases in control would be economically viable. Larsen *et al.* (2003) re-estimated the economic-injury-level targets for Lake Ontario applying the original model with a

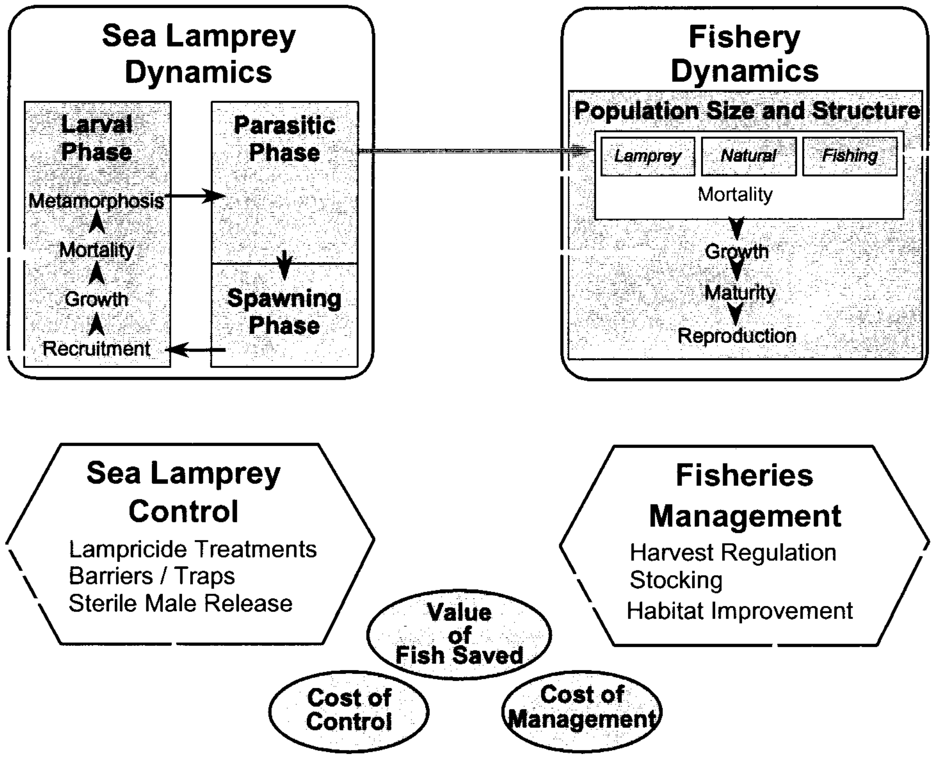

FIG. 1. Schematic of the components of sea lamprey and fish population dynamics and the effects of management options. Management of both sea lampreys and fish can be evaluated on the same cost-benefit scales. Tactical and strategic decisions about sea lamprey management involve trade-offs among options to minimize costs of control and to maximize the value of fish saved.

more extensive sea lamprey habitat inventory and came to similar conclusions.

The estimation of damage caused by sea lampreys and the value of fish lost are critical to establishing EIL targets (Koonce *et al.* 1993). These parameters have eluded consistent definition across the lakes and are the focus of studies in this volume (Bence *et al.* 2003, Bergstedt *et al.* 2003c, Lupi *et al.* 2003, Rutter and Bence 2003, Schleen *et al.* 2003, Stewart *et al.* 2003). Consistent estimations of these parameters are significant impediments to the full application of the theory of integrated pest management to setting targets for sea lamprey control (Stewart *et al.* 2003). Explicit estimations of the several components that comprise an estimate of value are possible. The development of the recreational fishery and the value of changes resulting from the St. Marys control strategy illustrate the cost effectiveness of the control program (Lupi *et al.* 2003). But, expanding this analysis to more jurisdictions, or to other sectors (commercial fisheries and non-market values), are large and difficult tasks. Estimates of damage caused by sea lampreys are varied among the lakes and among analytical methods (Bence *et al.* 2003, Rutter and Bence 2003). The commission has proceeded with the allocation of stream treatment efforts on the basis of an assumption of equality of the damage caused by a sea lamprey and the value of preventing that damage among all the lakes (Christie *et al.* 2003).

Management and science have been well connected and have improved the sea lamprey control program, with science informing management and the results of management suggesting new questions for scientific study. The development and use of systems tools have guided the evolution of quantitative assessments and analyses that direct decisions on sea lamprey control today. Many of the investigations published in this volume reflect this connection and their results will support development of new models. Explicit incorporation of uncertainty into these models is now possible based on the growing database of quantitative assessment results. Nevertheless, just as identified in SLIS I, ultimately experimental management may be necessary to fully evaluate the effect of management actions.

The Great Lakes Fishery Commission formalized its concepts for Integrated Management of Sea Lamprey in its Strategic Vision for the Decade of the 1990s (GLFC 1992). While the IMSL concept had been adopted as a principle during 1982 (Davis *et al.* 1982), it was not until this strategic vision statement was developed that a consensus on the program's direction was reached:

> *The Commission will provide an integrated sea lamprey management program that supports the Fish Community Objectives for each of the Great Lakes and that is ecologically and economically sound and socially acceptable (GLFC 1992, GLFC 2001).*

The vision explicitly connected the commission's sea lamprey control efforts to fishery management under the Joint Strategic Plan. The vision also explicitly recognized the trade-offs that needed to be considered in defining the future of sea lamprey management in the Great Lakes. The commission reiterated this same statement of its vision of integrated management in its updated strategic vision for the first decade of the new millennium (GLFC 2001).

The commission established a set of milestones against which to measure progress toward its strategic vision. The recommendations and questions that emerged from SLIS I were reflected in these milestones. The milestones include: development and application of explicit targets based on the economic injury concept; increased application of alternative techniques and reduced reliance on chemical lampricides; and emphasis on quantitative assessment information about control actions. Progress toward these milestones is presented in the papers that make up this volume.

The success of the Sea Lamprey International Symposium II is a reflection of the collective commitment to the use of sound science in decision-making and to the continuation of effective sea lamprey control in the Great Lakes—arguably the most successful program of control of an invasive aquatic species in the world.

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