

Ecosystem Health of Large Lakes: Identifying Utility and Metrics

A Proposal for a New Theme Area for the Fishery Research Program
Of the Great Lakes Fishery Commission

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Executive Summary

The GLFC in its Vision Statement embraces the concept of “Healthy Great Lakes Ecosystems” and more generally ecosystem health as goals for the commission and its partners. However, current milestones are qualitative and not necessarily indicative of ecosystem health. A theme area is proposed to determine if the health concept can be usefully and objectively applied to ecosystem management for great lakes and, if so, to identify useful metrics that can be used to guide management action and to evaluate progress. A series of questions concerning the theoretical and applied utility of the Ecosystem Health concept will be addressed in a series of four workshops bringing together scientists from around the world who are actively engaged in ecosystem analysis and management on great lakes and coastal seas. A Post Doctoral Fellowship in Great Lakes Ecosystem Health is established to facilitate the process and to assist participating scientists in synthesizing results and conclusions from the workshops. Outputs will be multi-authored review papers, based on the workshops, to be published annually over four years in *Reviews in Fish Biology and Fisheries*. The theme will be completed in time to inform and guide the next decadal revision of the GLFC vision statement in regard to healthy great lake ecosystems.

Introduction.

The strategic vision of the GLFC embraces the ecosystem concept as underpinning its approach to management and research. The concept recognizes the complexity of the issues confronting the fisheries and the extensive linkages and interactions with other phenomena that can affect the structure and productivity of the Great Lakes fisheries. The ecosystem concept is the basis for three vision statements meant to guide activities of the commission in the first decade of the current millennium. These statements address: 1) *healthy* great lakes ecosystems, 2) integrated management of sea lamprey and 3) institutional/stakeholder partnerships; and the commission’s vision establishes milestones for all three statements. However, in contrast, to the milestones for sea lamprey management that are quantitatively expressed and specify activities and geographic areas for attention or the milestones for partnerships that also call for a number of specific activities and timelines, the milestones for healthy ecosystems are broad and open ended. It may be inherently easier to specify actions or activities when only one species, e.g. sea lamprey, is targeted or when only human agencies and actions need to be mobilized and coordinated. In contrast, ecosystems inherently consist of multiple species, interconnections and processes so that expressing desirable outcomes may be the best we can do. But, accepting this limitation begs the question about how do we determine if an ecosystem is healthy or not; and, if it is not, how can the GLFC foster action to improve its health. If ecosystem health is going to continue to be a concept that guides the commission, it may be necessary to limit or at least define the commission’s use of the term in order to operationalize the concept through the setting of more quantitative milestones for fisheries and ecosystem management. One of the current milestones for the vision statement on healthy ecosystems identified the need to establish an international forum for exchanging information on issues affecting the health of large

lakes. Here we propose a task to examine the utility of the health concept to the management of the fisheries of large lakes and in particular to examine the applicability of the concept across a spectrum of systems that are considered to be under a range of environmental stress. The objective of the task will be to determine if there are symptoms or limits for ecosystem properties or rates that are indicative of unhealthy systems. If so, then can robust metrics be developed and used to assess the state of health of ecosystems as well as to guide corrective actions that would reduce the risk of deteriorating ecosystem health or to assess the efficacy of restorative actions?

Background

Ecosystem health. The application of the concept of health began to be formalized in its application to ecosystems and their management in the late 1980's (Rapport 1989) although its origins as a metaphor can be traced to even earlier times (Callicott et al. 1999). By the early 1990's, it was gaining widespread acceptance by management agencies such as the USEPA (and eventually the GLFC) although at that time there was also increasingly heated debate (Costanza et al. 1992) about its applicability to ecosystems. Callicott et al (1999) have most recently reviewed the concept and conclude that as a normative concept it is undoubtedly a useful metaphor for communicating environmental issues to the public, but they also conclude that it also has merit in the phenomenological sense in that scientists should be able to agree on a set of properties and rates for ecosystems that are acceptable or healthy relative to the services and benefits that we wish to enjoy from ecosystems. The analogy of ecosystem health with human health is nearly unavoidable (especially as applied by humans who are often preoccupied with their own individual health), yet the concept is certainly not a homology, e.g. ecosystems cannot die of ill health because they lack a central coordinating and controlling unit. Although constituent parts of an ecosystem can be lost due to changes in the boundary conditions for the species or ecosystem or through introduction of exotic species or pathogens into the system, e.g. chestnut blight, dreissenid mussels, etc., the ecosystem rather will transform into an alternative state or maintain its present state through a species substitution that maintains a critical function. Ecosystems do not die (as Lake Erie proved!), they transform. What can be lost as a result of transformations are historical behaviour, properties and species, but this begs the question of whether the transformed ecosystem is less healthy than prior to transformation..

Callicott (1995) considers ecosystems to be nested sets of hierarchical, linked *processes* and functions with differing temporal scales that can overlap spatially but need not have congruent spatial boundaries. All ecosystems are open systems that have conceptual boundaries through which mass and energy enter and exit. In lakes, these boundaries are effectively the air-water interface, the sediment-water interface and slope-velocity transitions at inflows and the lake's outlet. Within those physical boundaries, exists a diversity of biogeochemical reactions that process energy and mass crossing the boundaries. Many of these reactions/processes are linked and form feedback loops, including for example biological life cycles, that confer self-regulation (homeostasis) and a certain degree of stability and predictability on the species and process rates within "Healthy" ecosystems. These feedback processes limit variability in constituent

processes and species abundances within “historical” or normal range that allows the system to be sustainable over time.

Ecosystem health for Callicott is not necessarily dependent on persistence of individual species or even maintaining biodiversity, nor does it require maintenance of some reference “natural” condition that underlies the concept of “ecological integrity”. Communities can have species changes while maintaining essential process rates although changes in constituent species may accompany or cause “unhealthy” changes in rates. It is the change in process rate (and especially loss of homeostasis) and not the change in species that may signify a loss of health. Many of these ecosystem processes provide economic or aesthetic services that people value; therefore, our assessment of ecosystem health will be influenced by the debilitation of those valued services (Cairns and Pratt 1995). So our own species-specific view of the health of an ecosystem will be biased by our dependence on those services. Attempts to evaluate these services in monetary terms (Costanza et al. 1997) remind us of our dependence on ecosystems although placing these services into the economic domain at any instant in time raises concern about the value system applied and the sustainability of those services at current rates of utilization (e.g. what is a service worth when it is no longer available and what would it cost to restore it).

The health metaphor has been applied to other complex systems, e.g. the economic system. Turnover in the constituent mix of goods and services is expected in economic systems; and, although certain industries or sectors are said to be ailing or failing, the assessment of economic health is based on a broader set of indicators that economic managers use to determine if the system is healthy or corrective action is necessary. In economic systems, growth in outputs is usually considered a fundamental indication of positive health of an economy. The traditional analysis of economic health and success has recently been challenged by Jacobs (2000) who suggests that economists must take a more ecological approach to their analysis in recognition that economies are imbedded in ecosystems and those ecosystems provide services that may not be accounted for explicitly in the marketplace and consequently are not assigned monetary value. Ecologists would certainly reject the concept that overall growth of system outputs is necessarily indicative of health in ecosystems (except perhaps in early successional stages after disturbance), and they would prefer managing for balance of inputs and outputs over timeframes suitable for sustaining the longest lived organisms in the systems which in turn implies a balance among the network of processes and internal cycles (including life cycles) linking inputs and outputs. While rejecting the economic criteria of health that economists would apply to their system, is it possible for ecologists to define a set of metrics for ecosystem health or for sickness using ecological criteria?

Attempts have been made and might be broadly classified into: 1) theoretical approaches that draw on information theory and complex modeling (Ulanowicz 1992), 2) bioassessments including paleoecological assessment based on deviations in community composition and associated mass and energy fluxes from historic (or acceptable if historically unknown) conditions (Schindler 1995) or 3) real time monitoring of a broad array of properties and fluxes made possible through new, emerging technologies (Williams 1995) to establish “normal” system behaviour and identify abnormal deviations. The latter is perhaps closest in approach to modern medical practice although that does not mean it is most appropriate for ecosystems. The medical approach places

its emphasis on the patient and only secondarily considers illness as an expression of the patient's environment. These approaches are not necessarily in conflict, and may only indicate the newness of the ecosystem health concept and our ability to objectify and measure it. But all three approaches emphasize the need for measuring a substantial number of inputs and outputs as well as examining and understanding the interconnectedness of system components, particularly the food web in the case of fisheries. Given the complexity and volume of information required by these approaches, the choice of metrics becomes very critical to the utility of the concept because we cannot hope to measure everything all the time! Ecosystem analysis attempts to avoid the taxonomic complexity/diversity of systems by focusing on the flow of energy and materials through functional processors (groups of organisms). In simple systems a functional group may be represented by a single species; but such simple systems will be prone to energetic bottlenecks (Sherwood et al. 2002) and more prone to destabilizing oscillations than species-rich food webs characterized by numerous weak interactions (McCann et al. 1998).

Fisheries and ecosystem health. The vision statement of the GLFC embraces the health concept, and the related milestones are meant to foster and/or restore health to all the Great Lakes. The vision statement emphasizes healthy ecosystems with sustainable benefits (services) to society and self-regulating and naturally reproducing fish communities. The milestones call for: 1) the conservation of native biodiversity, 2) prevention of invasion of exotic fishes, 3) increase of natural recruitment for salmonids, 4) improved habitat and 5) new information on the lakes' sensitivities and risks to ecosystem health. The milestones and the vision statement itself recognize that currently the lakes, with the possible exception of Lake Superior, are judged to be in a condition of impaired health. The basis for this judgment is largely because current "desirable" fish populations and communities are not self-sustaining nor self-regulating. Active and costly sea lamprey control is necessary to allow large predatory species to flourish, and recruitment in salmonids is supplemented by stocking programs. There is also recognition in the milestones that there has been loss of critical habitats from the historic (natural) condition, but these losses and even trends are poorly known so their effect on the health of the ecosystem would have to be evaluated from other metrics. Callicott et al. (1999) might criticize the milestones as 1), 2) and 3) as being conservation and species oriented rather than addressing ecosystem health because of the focus on native species and the reference to "natural" conditions for habitat. The ecosystem health concept does allow for substitution or change in species assemblages and for deviation from natural conditions so invading species or loss of habitat or species *per se* do not necessarily indicate a loss of health. Only if these invaders or species losses affect internal cycles (e.g. Hecky et al. 2004), reduce or eliminate beneficial services, or effect lowered efficiency of trophic transfers might they have impact on the health of the ecosystem. Milestone 4) clearly suggests that there is good and bad "habitat" but offers no guidance for assessing habitat or tracking its improvement or degradation. The relation of habitat to health is intuitively clear but we currently have not agreed metrics built on that relationship. Only milestone 5) is clearly related to ecosystem health, but this milestone is more of a call for help than a call for action.

Fisheries are important outputs from the Great Lakes ecosystems. They are also the product of complex energetic interactions linking radiant energy from the sun and

nutrient inputs to those desired outputs. Although ecosystem health does not necessarily recognize the value of individual species, the loss of a functional group of species might cascade up or down through the ecosystem and effect the aggregate energy and material flows through the ecosystems. In the pelagic system of the Great Lakes today as well as historically, salmonids have provided a primary energy output for human use as well as regulating, as top predator, the abundances of forage fishes that gather and transfer energy to them and controlling the population of potential competitors and exotic invaders through their numerical dominance/cultivation effects (Walters and Kitchell 2001). Loss of this control function theoretically can cause a cascade of effects down through the food web as the forage fishes and their prey and potential competitors adapt to the elimination of mortality from juvenile and adult salmonids. Similarly, a change in boundary conditions at the bottom of the food web such as historic eutrophication of the lower lakes (and other great lakes of the world) will cause an upward cascade of effects as the energy pathways change and excess fixed energy can cause habitat degradation by deoxygenation and debilitation of consumers by toxic algae favored under conditions of excess nutrient availability.

The SOLEC (State of the Lake Ecosystem Conferences) indicators, which now number over 100, are meant to provide guidance about the health of the Great Lakes and are somewhat related to the approach proposed here are related somewhat, but the differences are important. SOLEC is a reporting mechanism to assess how remediation programs are doing in meeting the overall goal of the Great Lakes Water Quality Agreement, which is based on the idea of ecosystem INTEGRITY. The indicators to a large extent are species specific and even lake specific, and they primarily measure deviation from historical conditions. Inasmuch as a complete state of integrity is an impossible goal for four of the Great Lakes because of the large number of invasives as well as extinction of some species and habitats (Callicott et al. 1999), SOLEC policy documents focus instead on ecosystem HEALTH, without any attempt to bridge between these two divergent ideas. More important here, however, the SOLEC indicators are not intellectually tied to a holistic evaluation of ecosystem HEALTH: they emerged essentially ad hoc from committee meetings, which accounts for why there are so many of them. Although SOLEC indicators may have utility within individual lakes and individual portions of the lakes, they do not provide a basis for evaluating health of “any” other great lake ecosystem e.g. Great Slave Lake or Lake Victoria.

The link between healthy fisheries and healthy ecosystems may be transparently obvious which makes health an effective metaphor for public communication and discourse. But, what are the ecosystem conditions required to insure delivery of ecosystem services desired by society? **The answer to this question becomes relevant to ecosystem management and the GLFC through two related questions. First, can fisheries be managed and exploited to maintain or restore health in ecosystems? Secondly, what are the allowable changes/limits in ecosystem health that will still sustain healthy fisheries?** This Fishery Research Program (FRP) theme area would attempt to provide answers to these questions through cross-ecosystem comparisons in well-studied large lakes and fisheries of the world that are experiencing a broad range of ecosystem stresses. This comparative multi-lake approach is critical because the concept of ecosystem health is not species-dependent. Systems with very different species composition and even species diversity may maintain similar balance between inputs and

outputs. A cross-cultural comparison of large lake ecosystems may also reveal that different societies have different standards of ecosystem health and acceptable deviations in ecosystems just as they do in cross-cultural assessment of human health (Jamieson 1995). Such a comparison may identify cultural biases in our assessment of health as opposed to objective measures. If so, the GLFC vision statement should recognize this bias and limit its use of the ecosystem health concept or replace the generic term with more specific metrics.

The recently completed FRP theme on “Fitness of fish communities in large lakes” and the 2004 GLFC sponsored symposium on “Great Lake Canaries; The Shallow Great Lakes” have identified a common global suite of ecosystem stressors affecting large lake (and semi-isolated coastal marine e.g. Baltic and Black Seas) fisheries but with different intensities in different ecosystems. The annual sessions sponsored by GLFC have also identified an international network of fisheries and ecosystem scientists who could be drawn upon to evaluate the utility of ecosystem health for fisheries management. Ongoing and completed studies of ecosystems provide a wealth of comparable data, e.g. fisheries catch data, hydroacoustic assessments of fish stocks, measurement of critical process rates such as primary productivity and sedimentation rates, and documentation of food web structures using common metrics, e.g. stable isotope analysis of trophic webs, that would enable a cross-ecosystem comparison. This is especially true for the African Great Lakes, which have important and intensely exploited fishes, where the World Bank, Global Environmental Facility, and other donors have financed major studies of the lake ecosystems and their fisheries in order to improve their management for sustainable use. These global studies now invite global analysis of the data sets with knowledgeable collaborators to determine if valid and rigorous metrics for ecosystem health can be identified and ecosystem health objectives established for management.

A list of well-studied ecosystems that could provide input and benefit from meetings focussed on fisheries and ecosystem health are given in Table 2 along with possible collaborators. It is also serendipitous that these systems are on different trajectories in regards to some stresses (e.g. eutrophying Lake Victoria and Lake Winnipeg and oligotrophying Lake Erie and Lake Tanganyika) and are at different levels of stress intensity (low in Baikal and Superior; high in Victoria and Erie). The GLFC through its FRP has stimulated the development and application of trophic dynamic models suitable for modeling energy and material processing especially by food webs, and these models could be the basis for comparison across systems, as well as the generic ECOPATH and ECOSIM models which have already been applied to some of the African systems (Walters et al. 1997), to search for critical metrics indicative of healthy systems. However, these models have limitations in incorporating in a dynamic manner the changes in primary production and algal community structure that can alter trophic efficiencies linking primary production to fish production. Increasingly sophisticated water quality models that are driven by 3D hydrodynamic models and dynamic loading inputs are also available and being applied across this broad spectrum of large lakes, e.g. ELCOM and CAEDYM developed by the Center for Water Research in Australia is being applied to Lake Erie and Lake Victoria. One outcome of an international approach to these issues should be the development of more realistic ecosystem models that more directly link nutrient and energy flow to community dynamics, diversity and stability (McCann 2000). Using a global lake database will enable validation and assessment of

model performance outside the ecosystem of calibration. Successful validation across a range of ecosystems and stresses will provide improved confidence in these models when applied to the Great Lakes.

Relevance to SCOL 1 and 2. The native fish communities of the Laurentian Great Lakes were considered to be adapted to oligotrophic lakes and dominated by salmonids, in particular Lake Trout, which historically has been the sentinel species for the lakes. There were exceptions to this generality e.g. the western basin of Lake Erie and other large shallow embayments, such as Saginaw Bay, which offered warmer, mesotrophic conditions favoring dominance of other species. Concern about the apprehended loss of those oligotrophic conditions together with the impact of the introduced sea lamprey led to an extensive review of the Laurentian Great Lake fisheries up to 1970, Salmonid Communities of Oligotrophic Lakes. More recently this historical analysis was updated through the end of the twentieth century. SCOL 2 recognizes some favourable changes, especially in fisheries management, reduction in eutrophication and sea lamprey control, which have been achieved in the latter part of the 20th century. However, it also offers an expanded list of concerns. In particular, concerns about non-native species have expanded into a recognition of the multitude of effects that species introductions can have (top-down, bottom up, food web disruptions etc) and the realization that anticipated climate change will continue to aggravate these problems through range expansions and contractions of species within North America while the trans-oceanic deluge of species is likely to continue. Climate change itself may also directly affect the primary productivity of the lakes, but even directions (oligo- or eutrophication) are uncertain because interactions are complex. Concern over eutrophication has subsided at the whole lake scale (SCOL 2) although coastal eutrophication and especially nuisance algae such as *Cladophora* and *Microcystis* may be returning due to the activities of dreissenids. The bottom up effects of the redirection of energy and nutrient flows by dreissenids (Hecky et al 2004) together with concerns about food web disruptions by dreissenids and other invaders (Shuter and Mason 2001 White Paper on GLFC website) have put the future of Great Lake fish communities into *terra incognita* where the past is no longer an acceptable guide to future management. The continued perilous state of “sentinel” Lake Trout populations outside of Lake Superior may indicate that although progress has been made on several fronts the ecosystems themselves remain far from their historic natural state and that the natural state may be unattainable. The larger questions of whether the lake ecosystems are unhealthy perhaps should not be tied to a single species or historic time frame but should be investigated at an ecosystem scale and across ecosystems.

The implications of broad scale changes (beyond the direct control of fisheries managers) in ecosystem fluxes are potentially substantial and could threaten ecosystem health and valued fisheries. If significant, they would likely require adjustments in management regimes to accomplish fish community objectives; and, in the worse case, they could require adjustment in the objectives. In particular there is concern even today that nutrient control and the subsequent “oligotrophication” of the lower lakes may have undesirable effects on production of salmonids and valued prey species. The fact that the salmonid communities must share the lakes’ energy flows with a continually widening range of species aggravates this concern. Adequate supply of nutritious prey for salmonids and algal rations (for prey populations) are the basis of healthy ecosystems (and healthy immune systems) just as they are the basis of healthy human populations.

Consequently concerns about the possible consequences of phosphorus reduction and its possible effects on primary productivity and food quality for consumer species are already emerging. How much reduction in the quality and quantity in primary production can the Great Lakes endure before fish communities (perhaps maintained at artificially high levels) become nutritionally stressed. Have we already reached a crisis condition for some species as declining lake wide primary productivity (especially in the lower lakes) and redirection of energy and nutrient flows is shared by an increasing number of species. Or, is increasing diversity of consumers leading to increased efficiency of energy and nutrient utilization because new species replace less efficient species or utilize formerly untapped food resources. The paradox of the insertion of benthic grazing dreissenids into the Lake Erie ecosystem where it now accounts for 90% of benthic production (apparently all additive to pre-dreissenid benthic production) without affecting relationships between zooplankton and phytoplankton production (Johansson et al. 2000) suggests that there is scope for increased secondary production in the lakes even at current (and below historic maxima) levels of primary production. These data in Lake Erie suggest *increasing efficiency* of secondary production in a lake that some have characterized as “inefficient” in its use of nutrient loading. Such a paradox on arguably the world’s best-studied great lake begs explanation and highlights the limitation of our current understanding of ecosystem function.

SCOL 2 emphasizes the increasing complexity of issues facing fishery managers and the mix of signals they are receiving. For example on the positive side, lake-wide eutrophication is apparently receding and “traditional” contaminant levels are generally falling from historic maxima while lamprey abundance is being controlled. However, energy and nutrient pathways may be shifting (Hecky et al 2004) to the advantage of littoral fish communities and perhaps at the expense of pelagic fisheries. The thiamine stress on reproductive lake trout is also an example of a nutritional stress potentially linked to diets, food web pathways, and altered microbial populations. Also despite continuing to meet pelagic water quality objectives meant to reduce excess algal growth, blooms of nuisance algae such as *Cladophora* and toxic *Microcystis* are resurgent in coastal shores and embayments while the increasing frequency of beach closings due to *E. coli* and the spread of botulism Type E (and related die offs of fish and piscivorous birds) have been linked to these changes in coastal environmental conditions. Increasing concern about coastal conditions in the lower Laurentian Great Lakes and ecosystem health may lead to a call for even more stringent nutrient control to maintain shoreline uses and economic values at a time that elements of the fishing community are expressing concern about excessive oligotrophication. Oligotrophication is also a concern in the deep tropical lakes Tanganyika and Malawi where it has been suggested that global warming is leading to reduced primary production and perhaps reduced fisheries production (Verburg et al. 2003; O’Reilly et al 2003; Vollmer et al. 2005). If oligotrophication is reducing fish populations, at what level of primary production will population dominance be lost for different fish species, when will cultivation effects be lost and fishery communities and production becomes destabilized by bottom up effects. In exploited fisheries, losses in dominance and cultivation effects would likely be accelerated by continued fishing unless effort is reduced in recognition of reduced stocks. In many large lakes of the world and coastal seas, eutrophication is still the greater concern at the moment and massive restoration efforts are underway (Baltic Sea) or being

developed (Lake Victoria), but these efforts must also address the issue of interdependence of fish production among fisheries exploitation, primary production, algal community composition and ecological efficiencies of food webs prior to setting targets for nutrient reductions and control.

Key Research Questions

It is proposed that the GLFC through the FRP address these various challenges identified above all of which relate to general state of ecosystem health in diverse large lakes and seas ecosystems by establishing an international forum on the interactions of trophic states, processes and fisheries. The theme will have particular focus on: 1) how do trophic state (eutrophic to oligotrophic), food web structures, and fisheries management interact to stabilize or destabilize fish yields, 2) how do nutrient loading, food web species composition (exotic or native species) and fishing activities affect ecological efficiency of nutrient and energy transfer to target fish species, 3) how do ecosystem nutrient balances and food web structures affect nutritional status and reproductive potential of fisheries, and 4) how successfully are current “ecosystem” models addressing these issues. The major objective will be to determine if there are simple metrics of ecosystem and fish community properties that can be taken as indicators of healthy ecosystems and be adopted as fish community objectives for the Laurentian Great Lakes and other large water bodies of the world. Relevant workshops and prioritized questions to be addressed are in Table 3.

Research Approach

Project activities and timeline: A series of sequential activities focused on workshops to be held at annual meetings of International Association of Great Lakes (or a suitable alternative if appropriate) will be held over four years. Under this time line, the results of the task will be available by 2010 in time to inform and guide the decadal revision of the GLFC vision statement, especially its statement and milestones on Healthy Great Lakes Ecosystems. The project task leaders will also take advantage of relevant international meetings and conferences to amplify and disseminate the results of current research in large lakes and coastal systems around the world and to invite participants to the GLFC funded workshops. Topics and associated questions for the four annual special sessions at IAGLR and the associated workshops will be:

1) *Biodiversity, Food Web Structures and Ecosystem Health:* Do large lakes and enclosed coastal waters provide evidence for metrics of ecosystem health that can be related to fish community changes (especially species loss, gain or replacement; Table 1) and exploitation stresses experienced by the lakes? Are both species gains as well as losses equally detrimental? Is the “natural” state the only desirable goal for ecosystem managers or are healthy alternative states also possible and desirable? What are the quantitative indicators of an “unhealthy” ecosystem, and how can ecosystem health be assessed by knowledgeable practitioners?

2) *Fisheries Management and Ecosystem Health*: Is there evidence that fisheries management regimes and practices applied along trophic gradients can contribute to a debilitation or restoration of ecosystem health? Has “fishing down the food web”, altering fish community structure and yields, occurred in lake fisheries to the detriment of ecosystem function and provision of ecosystem services as has been suggested for many marine systems? Can overfishing lead to depensation as well as compensation in fisheries recruitment and lead to suppression/loss of desirable predatory fish species with related consequences for ecosystem characteristics?

3) *Nutrient management and Ecosystem Health*: Does ecosystem trophic state affect fish health and consequently the health of ecosystems? Can deficiencies in micronutrients, e.g. thiamine, arise because of ecosystem alteration or interaction with contaminants? Can toxic algae originate from altered/anthropogenic trophic states with consequences for ecosystem function and services? Are there optimum nutrient ratios, as well as concentrations, for balanced growth that favour ecosystem efficiencies for fish production?

4) *Managing for Ecosystem Health*: Are there relatively simple and robust metrics and models that fisheries managers can use to determine the risk of degradation of ecosystem health or assess ecosystem reorganization to alternative structural states? Are there successful examples of managing for ecosystem health? Are there alternative ecosystem states and especially fish community structures that can be considered “healthy”? What is the public perception of “healthy” ecosystems and are current policies and administrative structures appropriate for achieving healthy systems?

Implementation and Outputs

The products of the workshops will be multi-authored integrated annual summary review papers (one per year) on the topic of the annual special session and workshop at IAGLR. The review will be published in *Reviews in Fish Biology and Fisheries* (Kluwer). GLFC will provide travel funds to international scientists based on their willingness to co-author the review and provide relevant data. Funded participants must present at the IAGLR special session and also provide a five page summary position paper (with supporting data) for discussion at the workshop. The workshop will be held the Friday following the IAGLR session. Funded scientists will be encouraged to prolong their stay to interact with regional scientists and to enhance their contribution to the summary review paper.

The GLFC project will also provide funds for a post-doctoral fellow to support organization of the annual special session and to assist in the collation and summation of data for the annual review based on workshop contributions and discussions. The post-doctoral fellow should have familiarity with ecosystem modeling and the capacity to interact with invited scientists to bring contributed data into a modeling environment in order to stimulate workshop discussion. These post-doctoral appointments will be GLFC post-doctoral Fellowships for Healthy Great Lakes Ecosystems. This commitment by GLFC will provide the forum for intercontinental information exchange on issues affecting large lakes identified under its Vision Statement on Healthy Ecosystems and

advance its objective to rehabilitate and conserve “healthy aquatic ecosystems”. Other international organizations, e.g. International Joint Commission, International Development Research Centre (Ottawa) and Global Environmental Facility (Washington), have been approached and have indicated interest in the theme and a willingness to collaborate and contribute to the funding to insure maximum international participation.

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Table 1. Fish Species Richness in the World's Great Lakes

Lake	Native	Endemic	Introduced	Current
Malawi	845	805	0	845
Victoria	545	502	4	300(?)
Tanganyika	325	289	0	325
Edward	81	56	0?	81
Albert	48	6	0?	48
Turkana	44	10	0?	44
Kivu	23	15	1	24
Baikal	52	31	6	58
Laurentian	158	5	23	172

Table 2. Candidate ecosystems and possible collaborators.

Superior	Hrabik, Kelly, Johnson, Kitchell
Michigan	Brandt, Eshenroder, Jansen, Klump, Lehman, Dobson
Erie	Johnson, Koonce, MacIsaac, Charlton
Ontario	Minns, Brandt, Mills, Johansson, Casselman, Taylor
Huron	Mohr, Howell, Smith
Winnipeg	Lysack, Salki, Franzin, Abrahams
Victoria	Ogutu-Ohwayo, Seehausen, Cowx, Kitchell, Mugidde
Tanganyika	Sarvala, Molsa, Jarvinen, Cohen
Malawi	Pitcher, Bootsma, Ribbink. Banda, Reinthal, Carleton, Dobson
Baikal	Melnik, Sideleva, Smith
Black Sea	Aksnes, Fiksen
Baltic Sea	Jarvi, Axenrot, Jonsson
Coastal NW Pacific	Healey, Pauly, Watson and others

Table 3. Key topics and questions to be addressed in Workshops.

Workshop I. Biodiversity, Food Web Structures and Ecosystem Health

Primary Question: Do large lakes and enclosed coastal seas provide evidence for metrics of ecosystem health that can be related to fish community changes (especially species loss (extinctions or extirpations), gains (exotics/invasives) or replacement (natural succession)?

Secondary Questions:

- 1) Are both species gains as well as losses equally detrimental?
- 2) Is the “natural” state the only desirable goal for ecosystem managers or are healthy alternative states also possible and desirable?
- 3) What are the quantitative indicators of an “unhealthy” ecosystem, and how can ecosystem health be assessed by knowledgeable practitioners?

Workshop II. Fisheries Management and Ecosystem Health:

Primary Question: Is there evidence that fisheries management regimes and practices when applied along trophic gradients can contribute to a debilitation or restoration of ecosystem health?

Secondary Questions:

- 1) Has “fishing down the food web”, altering fish community structure and yields, occurred in lake fisheries to the detriment of ecosystem function and provision of ecosystem services as has been suggested for many marine systems?
- 2) Can overfishing lead to depensation as well as compensation in fisheries recruitment and lead to suppression/loss of desirable predatory fish species with related consequences for ecosystem characteristics?
- 3) Are there examples of fishery management regimes specifically targeted to restore ecosystem functions or health?

Table 3 (continued).

Workshop III. *Nutrient management and Ecosystem Health*

Primary question: Does ecosystem trophic status affect fish health and consequently the health of ecosystems?

Secondary questions:

- 1) Can deficiencies in essential micronutrients, e.g. thiamine, arise because of ecosystem alteration or interaction with contaminants?
- 2) Can toxic algae originate from altered/anthropogenic trophic states with consequences for ecosystem function and services?
- 3) Are there optimum nutrient ratios, as well as concentrations, for balanced growth that favour ecosystem efficiencies for fish production?

Workshop IV. *Managing for Ecosystem Health*

Primary question: Are there relatively simple and robust metrics and models that fisheries managers can use to determine the risk of degradation of ecosystem health or assess ecosystem reorganization to alternative structural states?

Secondary questions:

- 1) Are there successful examples of managing for ecosystem health?
- 2) Are there alternative ecosystem states and especially fish community structures, relative to the natural state, that can be considered “healthy”?
- 3) Is the public perception of “healthy” ecosystems the same in different cultures or does managers necessarily manage for different states of health?
- 4) Are current policies and administrative structures be applied to large lakes and seas appropriate for achieving healthy systems?