GREAT LAKES FISHERY COMMISSION

Project Completion Report [1]

Formulating a vision for fish health research in the Great Lakes

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June 2002

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FORMULATING A VISION FOR FISH HEALTH RESEARCH IN THE GREAT LAKES

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Prepared for the Great Lakes Fishery Commission
June 2002

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executive summary

The objective of this report was to identify a future approach to fish health research that will help to link the objectives of the Joint Strategic Plan for Great Lake Fisheries with the activities of the Fish Health Committee. Our goals were to discover the underlying intellectual and scientific obstacles to implementing a coherent approach to fish health research in the Great Lakes and to recommend potentially fruitful lines of inquiry.

The report is divided into three main sections. Section 1 is a review of fish health literature in combination with a consideration of relevant aspects of population health, epidemiology and ecology. Section 2 summarizes the workshop held to explore key fish health issues specific to the Great Lakes. Section 3 presents a framework for future fish health research in the Great Lakes.

The goal of section 1 was to uncover the academic direction for future fish health research based on current understanding, intellectual gaps and management needs. This section explores three main questions. First, are we capable of accurately characterizing the health and disease status of Great Lake fishes? Second, is there evidence that disease has sufficient impact on fish communities to make it a management priority? Third, can fisheries and lake management affect the distribution and abundance of disease in wild and feral fish stocks?

Section 1 not only highlights that disease can be an important and under appreciated population regulating factor, but also that ecological, and especially anthropogenic environmental changes, can have profound impacts on fish health and disease. Reference to basic principles of disease ecology and epidemiology lead to the conclusion that one cannot study the causes and impacts of disease in wild fishes without examining them within a social, ecological and population context, just as one cannot address fisheries management problems through a single-species approach. Section 1 also revealed how there is a significant deficit in the understanding of how fish health, fish management and environmental changes interact. Management decisions are, therefore, not being made on informed predictions regarding the epidemiological consequences of specific decisions.

Section 1 concluded that the first step in the evolution of a new framework for fish health research is to emphasize health rather than disease as the primary focus of research and management. To be health-oriented, we need to spend some time understanding what health is. This paper highlighted how fish health research has primarily focussed on identifying pathophysiological and etiological processes that affect the manifestation of disease in individual fish, rather than a more comprehensive understanding of the processes that affect the health of wild fish populations. A population approach to fish health was defined in this report as research and actions that considers the biotic and abiotic factors that influence the capacity of different populations to meet social and ecological expectations as well as those that affect the distribution and abundance of disease in fish. Shifting fish health research from disease pathogenesis in individual fish to an ecosystem model before understanding health at a population level is both premature and unlikely to form a working bridge between the current approach and the goals of ecosystem management.

In section 2, which summarizes the workshop on fish health issues specific to the Great Lakes, participants concurred that there are significant methodological obstacles to studying fish health and disease under natural conditions. Problems in measuring health and sampling populations were key impediments to research. It was acknowledged that disease concerns have and will continue to be central health issues for fish culturists and fisheries managers due to recent events in the Great Lakes. There was, however, general agreement that fish health cannot be defined as a state characterized solely by the absence of disease. Instead, health was seen as a positive notion that was represented by measures such as efficient energy transfer, sustainability, reproduction, survival and commercial/recreational use. It was acknowledged that health was a normative concept, and in the absence of defined thresholds or measurements of normality, establishing whether or not a fish population is healthy is problematic and subjective. The idea of a suite of indicators that best reflect health was advocated rather than a search for a single measure. There was also agreement that appropriate measures of health would differ at different levels of biological organization (individual, population, community).

The major health problems identified at the workshop varied from species to species but there were consistent themes. Exotic invaders, unstable ecosystems (particularly food-web disruption), fish introductions and fish community interactions underlined many of their concerns. Participants agreed that the major problem for endemic species (reproductive failure) was different from that of introduced species (disease). An overall question that arose during the discussion was “how could we move from a reactive to a preventive model of fish health?” To date, research and actions have been directed towards “hot topics” which have manifested in a large scale or dramatic fashion, rather than on evidence of impacts on fish health and ecology. Workshop participants saw three main foci for future research: methods and measures of health, disease ecology, and determinants of fish health. They noted an urgent need to fill gaps in expertise required to tackle some of the issues that arose in the workshop

Section 3 presents a framework for future fish health research in the Great Lakes including the advocacy of a population-health approach as well as specific research themes and constraints. Four main research themes were identified. The first was concerned with the need to develop reliable and predictive indicators of fish health. The second dealt with the critical need to develop methods and measures of fish health. The third theme revolved around research intended to identify ecological and management determinants of health. The fourth involved research support that would build expertise and the necessary partnerships to respond to the recommended research themes.

While it was tempting to summarize the results of this project by listing a series of specific research questions such as, “does stocking non-native fish infected with *Renibacterium* increase the risk for BKD in indigenous fish populations,” such an approach would be unlikely to serve as a sound foundation for an ecological approach to fish health. Too often, such an approach, whether in fisheries or other sectors, provides only brief encouragement of new approaches to old problems, but fails to build new ways of thinking or long-term capacity. Therefore, we strongly advocate that the Great Lakes Fishery Commission seize this opportunity to lay the foundation for a population-based approach to fish health that will serve as a transition and link between the current system of fish disease management and the desired comprehensive and ecological approach to fisheries management.

section 1 – literature review

✍ background

One of the primary responsibilities of the Great Lakes Fishery Commission (GLFC) is to "develop coordinated programs of research on the Great Lakes, and, on the basis of the findings, to recommend measures which will permit the maximum sustained productivity of stocks of fish of common concern." [1] The Joint Strategic Plan for Great Lakes Fisheries serves as a guide for the activities of the GFLC (Great Lakes Fishery Commission, 1997). The plan advocates coordinated interjurisdictional fisheries management based on an ecosystem approach. The 1997 revisions to the plan sought to integrate fisheries and environmental ecosystem management initiatives. A common objective of fisheries agencies involved in the plan is "*to secure fish communities, based on foundations of stable self-sustaining stocks, supplemented by judicious plantings of hatchery-reared fish, and provide from these communities an optimum contribution of fish, fishing opportunities and associated benefits to meet needs identified by society for: wholesome food, recreation, cultural heritage, employment and income, and a healthy aquatic ecosystem".* The Great Lakes Fish Health Committee of the GLFC coordinates efforts in the Great Lakes basin to prevent the introduction and dissemination of communicable fish diseases. One of their ways to achieve this goal is to recommend and foster research related to fish health and disease control.

The objective of this report is to identify a future approach to fish health research that will help to link the objectives of the Strategic Plan with the activities of the Fish Health Committee. The Fish Health Committee has a strong role to play in identifying and supporting the research needed to meets its management objectives. This project, therefore, will serve as a framework from which researchers in government and academia can build an ecological approach to fish health management in the Great Lakes.

Three main hierarchically arranged questions guided the formulation of this report. First, are we capable of accurately characterizing the health and disease status of Great Lake fish in a manner that allows us to detect impacts and changes in response to management actions? Second, is there evidence that disease has sufficient impact on fish communities to make it a management priority? Third, can fisheries and lake management methods affect the distribution and abundance of disease in wild and feral fish stocks? The answers to these three questions serve to establish the significance of fish health as a research and management priority as well as to help identify key areas for future investigation. We undertook a review of the peer-reviewed and grey literature as well as consultation with experts via direct contact and a workshop to answer these questions. ***Our goal was to identify the underlying intellectual and scientific obstacles to implementing a coherent approach to fish health research in the Great Lakes and to recommend potentially fruitful lines of inquiry.***

[1] http://www.glfc.org

✍ key questions

Question 1: Are we capable of accurately characterizing the health and disease status of Great Lake fish in a manner that allows us to detect impacts and changes in response to management actions?

There are four requirements that must be fulfilled in order to characterize the health of a population and relate changes in health status to specific management or environmental events. First, we need to know what it is we are measuring, that is, we need to identify measurable parameters that identify the optimal healthy state and deviations from that state. Second, we must be capable of accurately classifying the health status of individuals and populations through careful clinical observation, reliable tests and precise counts of cases and non-cases. Third, we need to be able to sub-divide and enumerate the population into those that are healthy, those that are not and those that are at risk. Finally, we must be able to characterize the populations and environments where cases and non-cases occur.

What is Health?
Mitchell (2001) suggested that learning about the health of fish is paramount to understanding and protecting the finfish resource; but what is fish health? The fish health literature is roughly divided into three “camps”. First, there are publications concerned with the effects of disease on the survival, growth and carcass quality/safety of cultured fishes. Second, there are publications interested in documenting the pathological and community structure response of fish to anthropogenic pollutants. In these cases, the aim is not necessarily to examine fish health *per se*, but instead to use fish health as an indicator of effects on ecosystems. Finally, there is a small body of literature examining the effects of microorganisms on ecologically important functions in wild populations. Typically, these publications attempt to examine isolated effects of specific parasites or other biological agents on ecological outcomes such as fecundity or growth. As each of these “camps” have different objectives, it is not surprising that health is defined differently from situation to situation.

An operational definition of health is essential before we can determine how fish health research can inform environmental management decisions that ensure the sustainability and safety of Great Lakes fisheries. Having a clear definition of the preferred state of an environmental target (in this case, fish health) is essential if one is to identify when harm occurs (Calow and Forbes, 1997). Many will agree that there is a range of elements that determine the health of individuals, populations and communities, but they would most likely hold different views as to the elements that contribute the most to overall health, the parts that are most important to examine and the features that can most reliably measure health status. The lack of a shared definition of fish health has made it difficult for managers, veterinarians, ecologists, biologists and policy-makers to integrate a concept of health into overall management of wild fish stocks. The lack of a shared definition, therefore, serves as a significant obstacle to developing a coherent plan for fish health research that addresses the objectives of the GLFC.

There are three general ways in which health problems can be studied: in the laboratory, in the one-to-one diagnostic setting and in the population (White, 1997). Until very recently, fish health research has focused almost exclusively on the first two settings particularly as they relate to parasitology and microbiology. Early fish health researchers were more interested in parasite taxonomy than pathology. It was not until the 1950s that fish disease research shifted away from its preoccupation with identification and characterization of parasites and began to examine the role of other pathogens and toxins in fish disease (Mitchell, 2001). The desire to use fish as bioindicators of pollution and the growth of commercial and public fish culture served as driving forces for an intensification of fish disease research (Mollers and Anders, 1986). Indeed, much of what we know about fish health is derived from studies in cultured species, especially salmonids, carp and catfish. By the 1960s the role of environmental stressors in fish disease became an important subject of investigation and a key consideration for diagnosticians. Fish health researchers and investigators began to consider the "classical triad of disease"; the interaction of host, agent and environment necessary to bring about disease. However, an examination of today's literature will reveal that the vast majority of fish health research is still primarily focused on the pathophysiological or microbiological features of isolated disease-causing agents on individual fish. Table 1 is the summary of a cursory examination of the titles of articles published in ten recent issues of Diseases of Aquatic Animals and the Journal of Aquatic Animal Health. It reveals the primary focus of current fish health research on levels of organization of the individual or lower and the emphasis on pathological effects and infectious agents. The emphasis on infectious agents and disease has lead to a dependence on relatively simple, laboratory-based criteria for establishing causal relationships, such as Koch's postulates, rather than more sophisticated models for causation that have been developed and applied in human and veterinary medicine to describe the role of environmental, social and ecological factors in the genesis of naturally occurring disease. Most reports of the ecological implications of fish health are not found in fish health publications, but instead are found in publications concerned with ecology, animal behaviour, zoology and fisheries sciences.

Table 1. Broad categories of subject matter found by an examination of titles in the 10 most recent issues of Diseases of Aquatic Organism and the Journal of Aquatic Animal Health as of July 2001

Describe pathology or host response to exposure to an infectious/parasitic agent (42 articles)	Isolation or detection of a pathogen/parasite (32 articles)
Taxonomy, structure (24 articles)	Therapeutics (22 articles)
Aspects of basic microbiology (15 articles)	Fate of a pathogen in a host (including infection trials) (13 articles)
Environmental/nutritional effects (10 articles)	Transmission, dissemination and lifecycle of infectious or parasitic agent (9 articles)
Description of epidemiology/fate in ecosystems (7 articles)	Surveys of pathogen/parasite (6 articles)
Response to toxins (5 articles)	Descriptions of neoplasia (5 articles)
Stress physiology (4 articles)	Vaccines (4 articles)
Effects of management on disease (2 articles)	Fate of pathogen/parasite in the environment (2 articles)
Other (6 articles)	

An emphasis on the pathological effects of infectious and parasitic disease agents can also be found in virtually all policies and regulations affecting the management of fish health and fish translocations (Stephen and Iwama, 1997). Fish health policy typically focuses on the exclusion of infectious and parasitic agents from commercially important species through a system of testing and quarantine. This approach is reflected in the working objective of the Great Lakes Fish Health Committee (*to prevent the introduction and dissemination of communicable fish diseases*). The preoccupation with infection and disease in both research and regulation leads one to conclude that the prevailing working definition of fish health is the absence of disease, especially infectious or parasitic disease.

The prevention and loss of fish due to disease is a constant activity for fish enhancement operations (Meyer *et al*, 1983). Disease is a major management consideration that has "plagued the life of the hatcheryman through the years" (Wood, 1979). Fish health research has evolved from a subset of natural history to an essential element of fish culture. Indeed it was recognized by the US Fish Commission as early as 1898 that fish disease control was a priority for successful fish culture (Mitchell, 2001). Significant advances have been made in recent years on the causes and management of disease. The lack of clinical illness may serve as a reasonable measure of health in culture situations when disease is a pervasive and significant factor, but it may not be a reasonable measure in fish communities where factors other than disease are the predominant determinants of sustainability and productivity. While it may be possible to relate the effects of a single factor to the well-being of a single fish, it is another matter to interpret the response of multi-species fish communities to a suite of stressors, of which disease is only one component (Kelso *et al*, 1996).

With the advent of improved clinical practices, better environmental quality and improved preventive programs, disease have become less of a factor for many human and animal populations. The absence of disease, therefore, is no longer a sufficient criterion to differentiate healthy from unhealthy. The concept of health has evolved to a state of equilibrium between an organism and its environment that is compatible with full functional activity of that organism (Last, 1983). It is also defined as a state characterized by anatomical integrity, ability to perform expected individual, population and community roles; ability to deal with physical, biological and social stresses, and freedom from risk of disease and untimely death (Last, 1983). These definitions see health as the sum of attributes necessary for survival as well as for meeting expectations. The population health approach views health as a capacity rather than a state. An ecological model of health presents health as a product of the interdependence between individuals and various components of an ecosystem (Green *et al*, 1996).

A key element of the above definitions of health is the concept of measurable expectations and roles. In some cases, such as food animal medicine, identifying and measuring expectations is relatively simple. The principle objective of population health in food-producing animals is to maintain a level of animal welfare and productivity that is considered economically optimum (Radostits *et al*, 1994). Veterinarians and farmers can assess an individual's or group's health by seeing how well it meets economic targets of productivity such as milk production or feed conversion. It becomes more difficult to define expectations for wild species not only because of a lack of information on the nature of specific ecological functions but also because of conflicts between ecological, economic and social values that are applied to wild species. Historically, the guiding expectation of fisheries management has been to sustain harvestable populations of fish that are commercially or recreationally important (Miller, 1996). Indeed, the GLFC objectives include maximizing sustained productivity of stocks of fish of common concern. Healthy fish populations are, therefore, those that are able to withstand changes in the Great Lakes ecosystem in a manner that allows for a functional fish community that produces a sustainable yield of safe fish for consumption or recreational use. Fish disease management has served to address this expectation largely by reducing losses of hatchery-reared stocks that are to be released as part of stock enhancement programs. An important expectation of disease management programs is to maximize the survival of cultured fish by decreasing microbial and parasitic biodiversity within hatchery populations. Programs are designed to prevent the entry, and to reduce or eradicate infectious and parasitic disease-causing agents or to manage host-parasite relations in a manner that has the least negative impact on overall fish population health.

Any new direction for fish health will require the current model for defining health to be expanded beyond the absence of disease. The new definition will establish the boundaries within which fish health research and management will be conducted. Developing this definition is an essential part of developing an ecological approach to fish health. It will, however, be essential to avoid philosophical traps, such as those encountered in attempts to define ecosystem health. Health definitions for population management should be problem-based and suited to addressing management needs.

Classifying health or disease status

The most definitive indicator of health is its complete absence – death (Last, 1998). Once we depart from this indicator, measurements become increasingly elusive. Any attempt to identify the fate of a fish, associate its health with a specific risk factor or select a specific intervention to manage its health requires that we consistently label and classify a fish's health status (modified from Sackett *et al*, 1991). Because health and disease are biological continuums rather than absolute extreme states, we need to set consistent and biologically meaningful boundaries that decrease the likelihood of misclassifying healthy and unhealthy fish. The ability to identify and account for investigative biases that result from misclassifications is essential for any population or ecological-based system for health research.

Diagnostic tests

The correct classification of the true health status of a fish population must be the cornerstone of research efforts intended to identify the impacts of management and ecological change on fish health. It is also essential for evidence-based risk assessment regarding the movement of fish (including plans for enhanced stock releases) and trade in fish products. Diagnostic consistency can be compromised by many factors including the failure to apply standard case definitions, the use of imprecise or inaccurate tests, reliance on subjective or overlapping diagnostic criteria, unequal diagnostic experience or poor quality diagnostic material (Stephen *et al*, 1995). Increasing attention is being focussed on the assumptions underlying the interpretation of standard tests used to diagnose fish diseases because of the importance of their results to fish management and trade (Bruneau *et al*, 1999). Two main issues affect the interpretation of a test (Martin *et al*, 1987). First, is the frequency of false positive and false negative results. Second, is the prevalence of disease in the tested population. A review of diagnostic records for Ontario salmonid populations found that objective measurements of the frequency of false-positive and false-negative results for tests used at federal and provincial laboratories were not available (Bruneau *et al*, 1999). Due to the virtual absence of systematic and representative surveys and ongoing surveillance of fish diseases, we also lack reliable information on the prevalence of key fish diseases. Therefore, the foundations upon which diagnostic tests can be reliably interpreted are alarmingly inadequate for fish disease.

A diagnostic test cannot be applied in a vacuum of information on the population from which the tested fish originated. Most tests used to assist in the diagnosis of fish diseases were developed and evaluated in laboratories. Fish were typically exposed to uniform yet abnormal doses of the same strain of a single pathogen through unusual routes. The fish were housed artificially with little exposure to other elements that could affect the accuracy of the test system such as co-infection with different pathogens. Unfortunately, this resulted in a setting significantly different than that in which a diagnostic test would be used later. The performance of a test will vary along the spectrum of disease from infection, through preclinical and clinical stages (Martin *et al*, 1987). Host tissue type, strain, differences in the challenge with cross-reacting pathogens, stage of infection, and management conditions can each affect the frequency of false test results (Greiner and Gardner, 2000). In addition, the likelihood of false positive and false negative test results changes as the prevalence of the disease in the population changes, so much so that the international animal health agencies recommend that tests should be re-validated after substantial changes occur in target populations (OIE, 1996). The effects of host variation on the interpretation of tests was re-enforced by Thorburn (1996) who found the current homogenous approach used in Canadian fish diagnostic laboratories to screening fish for disease is unlikely to achieve the same results for all species and all pathogens.

It is not uncommon for the apparent reliability of a diagnostic test to differ when applied under field conditions than when first tested in the laboratory. Saksida *et al* (1999), for example, examined the performance of an immunofluorescent antibody (IFA) test to diagnose plasmacytoid leukemia in farmed Chinook salmon. Previous studies suggested that this test was more reliable than histopathology for diagnosis, the latter being the basis for diagnosing the disease prior to the new test. However, when the test was applied to fish that naturally developed the disease rather than on laboratory models, the IFA test was found to be unreliable and in fact, agreed with histopathological diagnoses no better than random chance. Other studies on the diagnosis of this disease found that histopathology itself was an unreliable method for consistent diagnosis due to the high level of intra and inter-observer variability (Stephen *et al*, 1995). Another example involves a field evaluation of an indirect fluorescent antibody-based broodstock test used to screen for bacterial kidney disease. The test was found to be unsuitable for screening populations under field conditions due to the high level of inter-laboratory variability (Armstrong *et al*, 1989).

We lack a critical assessment of the tools needed to classify the health and disease status of fish and fish populations. This largely reflects a lack of effort dedicated to aspects of clinical epidemiology such as the field evaluation of diagnostic test performance and sampling methodology. The slow spread of epidemiological concepts to the study of aquatic disease (Bakke and Harris, 1998; Thorburn, 1999) coupled with the focus on a laboratory based model of diagnosis has left clinical epidemiological studies of the validity and precision of diagnostic tests used in regular diagnostic settings as a low priority for many regulatory and funding agencies. However, the increasing reliance on test results to determine the disease status of commercial facilities and trading zones has focused attention onto the importance of knowing the predictive values of specific tests under specific circumstances. It can, therefore, be anticipated that clinical epidemiological studies will become a greater priority in the future.

In fisheries management, the unit of concern is typically the population. Many disease management decisions are based on the classification of the disease status of populations. Therefore, diagnostic test performance must be evaluated at both an individual and a group level. The following variables all affect the ability of a test, applied to a sample from a larger group, to correctly classify the infection status of the source group: individual-animal level false-positive and false-negative rate, within-group prevalence, sample size, size of the group, and the cut-off number of test positive animals used to classify a group as positive (Audige and Beckett, 1999). Consideration of this list illustrates that the ability to interpret the results of a diagnostic test conducted on a population sub-sample requires knowledge of the epidemiology of the disease (distribution, prevalence and sampling methods) as well as the clinical performance of the test. In addition, it reveals that, with the knowledge that no test is perfect, the decision to make the finding of one positive animal adequate to classify the entire group as positive may be misleading. Very little work has been done in this area in fish health. Bruneau *et al* (2001) demonstrated that substantial uncertainty exists regarding the ability to interpret the test-positive status of Ontario hatcheries for infectious pancreatic necrosis and *Aeromonas salmonicida*. Much of this uncertainty was affected by the sample sizes used and the cut-points selected to classify a hatchery as positive.

Addressing this deficit will require us to study disease along its full spectrum in individuals and in populations. This information is needed not only to make better prognoses, but also to provide the necessary context to construct sampling strategies and interpret the predictive value of tests used under field rather than laboratory conditions. In addition, it will be important to link observations of fish disease with observations of fish health in order to be able to understand the impacts of disease on important population health parameters such as fecundity and survival.

Sampling and Surveillance

Testing protocols used in existing policies or practices typically require one to extrapolate the disease status of a sample of individuals culled from a group to the remaining members of that group. How the group was sampled will be one of the most important considerations when trying to decide the validity of extrapolation. For example, most disease surveys in Atlantic salmon has been done on the more accessible, but demographically less important adult returning fish, rather than on early life stages or marine survival (Bakke and Harris, 1998). Imposing the results of surveys of returning adults to younger stock at sea is inadvisable unless one can demonstrate that the ecology of these two age-stages is sufficiently similar as to homogenize their exposure risks and susceptibility to disease. Similarly, much of what has been derived on the epidemiology of bacterial kidney disease in the Great Lakes has been based on weir surveys rather than systematic samples across age classes and habitats. The health status of fish may, in themselves, affect our ability to sample a population in a representative sample. Evidence from wild species and cultured fishes demonstrate that fish will differentially distribute themselves with respect to their healthy cohort, which, in turn, affects their probability of being included in a sample. Pathogens may cluster in different sub-groups within populations and communities due to differed histories of exposure and susceptibility. Specific pathogens in Ontario hatcheries have been more commonly detected in certain species and age classes, indicating clustering within a location (Good *et al*, 2001). In such a setting, investigators may be better to conduct purposive sampling targeting higher risk groups than to conduct random sampling to detect disease. Social status can also affect disease status, therefore, disease prevalence can differ within population sub-groups due to differing ecological interactions. Diagnostic samples based on social or age sub-groups, therefore, are unlikely to present a true picture of population health status (Stephen and Ribble, 1995). Samples that rely on the sub-population of ill fish risks over-estimating the prevalence and impact of disease, while samples focusing on the healthy cohort, risk underestimating disease effects. Such problems have been encountered in netpen salmon farming (Stephen and Ribble, 1995). Underestimation is a particular concern when sample methods require the fish to actively interact with the capture methods (e.g. hook and line) while methods that require fish to evade capture (dipnets) may over-represent less fit fish. Finally, the capture method itself may affect what one can observe. For example, methods used by Bristow and Berland (1991) to survey wild salmon in Norway were not suitable for detecting external parasites simply because the capture methods and post-capture handling tended to cause ectoparasites to be dislodged from the fish. While there has been some work conducted on the effects of specific sample methods in cultured fish (e.g. Thorburn, 1992) very little is known about how different field sampling methods affect our ability to extrapolate the results of health assessments on sampled fish to their source population.

The prevailing reliance on periodic field surveys alone as a method for describing population health can be misleading as it fails to account for other population and environmental factors that may be changing the number of cases of disease detected. Periodic fish disease surveys must be distinguished from surveillance. Surveillance is the systematic and regular collection of information using methods that are practical, uniform, reliable and timely. Its purpose is to detect trends in time to initiate a response, whether that is investigation or control. Often, fish disease surveys are not actually looking for disease. Instead they focus on identifying the prevalence of specific etiological agents or are part of efforts to document biological effects of pollutants. These surveys can provide “snapshots” of the types of etiologic agents in a population, but they are inadequate for generating the data needed to establish cause-effect relations or to establish population impacts. For example, surveys for the presence of antibodies to *Renibacterium salmoninarum* tell us something about a fish’s historic exposure to the organism, but not their current state of infection. Surveys that detect *R.salmoninarum* tell us about the current infection state of the fish, but not about its state of health or dysfunction. Surveys for pathological lesions of bacterial kidney disease tell us something about the prevalence of disease, but not about the impact on the population. Periodic surveys are faced with the further challenge of separating true non-random patterns from spurious patterns that are only a reflection of the sampling methods and the characteristics of the population of concern. Take, for example, marine anemia of farmed chinook salmon. This disease was initially described as a spreading epidemic that was moving from farm-to-farm causing catastrophic losses. This impression was based on samples of slow-swimming fish; a sample that later was shown to be biased towards chronically ill fish (Stephen and Ribble, 1995). Furthermore, this impression was based on an assessment of cases being submitted to a reference laboratory. When the disease was examined by looking at farmed fish populations, it was shown that the disease was not moving from farm-to-farm, but that it simply followed the pattern of spread of fish farms (Stephen and Ribble, 1995b). Once a farm arrived in a region, so too did the disease. Furthermore, when the entire population was examined, rather than just surface moribund fish, the disease was shown to be endemic and contributing significantly less to overall mortality rates than first thought. By looking at how the population changed and searching for the disease by sampling a more representative part of the population, an entirely different impression of this disease emerged. This case provides an important cautionary tale for situations such as the Great Lakes where the knowledge of the recruitment, movements and distribution of fish is limited.

Because the distribution and abundance of disease is variable and under the influence of a wide variety of factors, a single, large-scale census tends not to be as effective as a sampling scheme that has a random component and samples only a portion of the population at frequent intervals (Farver *et al*, 1985). Take, for example, the findings of viral hemorrhagic septicemia virus (VHSV) in returning salmon in Washington State (Amos *et al*, 1998). The initial finding was interpreted as evidence of the occurrence of an exotic disease in the State. However, subsequent surveys of wild marine fish found it not to be new, but instead to be a previously unrecognized, endemic infection. Establishing sample size, timing and location requires some understanding of the epidemiology of diseases. Given the dearth of understanding of the epidemiology of most wild fish diseases, investigators are often limited in their ability to make evidence-based sampling schemes; instead they have to rely on analogy, best guesses and budgetary limitations. Unless investigators understand the capacity of their sampling method and the nature of the sampled population, it is not possible to confidently extrapolate the results of a survey to the general population.

Population health measures

Fish play a major role in structuring aquatic ecosystems (Steele, 1985). Therefore, diseases that affect the restoration or sustainability of fish communities have the potential to impact ecosystem structure and function. While it may be relatively easy to describe impairments in individual fish health through observations of pathological changes such as tumours or infectious disease, it is another thing to link them to specific population or ecosystem-level effects. Assessing the health of populations or communities is complicated by five factors (Koonce, 1995). First, different causal factors may result in similar population outcomes. For example, hepatic megalocytosis can result in chinook salmon due to exposure to anthropogenic toxins or naturally occurring algal toxins (Stephen et al, 1993). Second, populations and communities have a greater capacity for adaptation than do individuals. Many healthy states may be equivalent, allowing for a variety of “preferred states.” Third, it is difficult to identify the optimal state of health for populations that have been modified over years due to the wide variety of insults that operate in the Great Lakes. Fourth, the concept of health is value-laden, making definitive endpoints hard to identify. Finally, as most of our traditional measures of health have been taken at the individual level, it is unclear how many sick individuals can be in a healthy population. Measures of health at the population, community and ecosystem level are imbedded in a hierarchical set of interactions. Ideally, measures of population and community health should follow ecosystem objectives. Unfortunately, ecosystem objectives are often not specific enough to generate measurable endpoints or identify relevant measures of health (Koonce, 1995). This results in value judgements rather than objective measurements being the basis for assessing health.

Measurements of population health reflect our ecological and socio-economic expectations. It is important that the assessment endpoints for population health reflect the stated expectations for that population and that measurement endpoints serve as reliable indicators of how well we are meeting our expectations. For domestic species, the goal is to produce agricultural products in an economic and humane fashion. Therefore, physiological indices of health are often derived from production outcomes for individual animals such as milk yield, weaning weight and feed conversion rates. Such measurements are the foundation of herd health programs. With people, population health measures may include indices such as income, level of education and quality of life measures. For fish populations, the goal of the GLFC of having *"secure fish communities, based on foundations of stable self-sustaining stocks",* serves as a foundation for identifying fish health assessment endpoints. Measurement endpoints can include age and size structure, recruitment, escapement, catch statistics, reproduction, dispersal, and distribution. Ecologists have long used the kinds and relative abundances of species as indicators of the condition of populations and communities. Traditional fish health programs, with their focus on disease diagnostics, rarely generate or incorporate such health data into their management plans. Fisheries management agencies, which do generate such measures, do not explicitly view them as health indices and thus have had little formal interaction with fish disease programs. In order to make the leap from pathogen surveys to fish community health management, the interrelationships of disease measures and health outcomes must be addressed in a more explicit fashion.

Shuter (1990) proposed a suite of population-level indicators of stress in fish. Based on Selye's general adaptive syndrome, Shuter proposed that a relatively small series of state and process variables could be used to monitor three critical population properties; habitat occupation, well-being of the average population member, and the balance between birth and death rates. Measurable parameters such as age distribution, individual growth rate, body condition, size distribution, spatial distribution, and catch per unit effort could be combined to identify populations under stress. He noted that indicator selection would benefit from new measurement tools (telemetry, acoustic sampling, genetic methods) as well as improved sampling design. His discussion raised the issue of the need to determine what is "normal" (expected) before launching an environmental monitoring program. Most importantly, Shuter concluded that a monitoring program would be more effective if one avoids an "all-purpose" design in which a single suite of variables is measured in all settings, but instead tailors indicators to the issues and populations of concern.

Adams (1998) proposed that lipid storage and dynamics within an organism are important attributes of fish health and population success, as they effect not only survival and fitness of individuals but also the success of future reproduction and recruitment. Overwinter starvation and depletion of lipid levels can result in increased mortality as well as increased susceptibility to environmental stressors including contaminants, parasites and pathogens. These effects can be manifested through energy depletion, impaired osmoregulation and altered immune functions. For example, there is a strong correlation between total body lipid and the number of *Uvulifer* cysts found on wild bluegills (Esch, 1994). Adams discussed the value in monitoring lipids and fatty acid composition of major prey species as a means to predict impeding impacts on fish at higher levels in food webs. Timing of breeding, hatching success and larval survival are all influenced by lipid storage and allocation. Energy allocation patterns can be species-specific and changes that compromise fish populations may lag behind significant environmental changes. Lipid levels in Lake Michigan chinook have fluctuated over the past two decades, with the past 10 years being characterized by decreased lipid levels. Some have concluded that declining lipid levels predicted later declines in sport fishing Chinook catches (Wright, 2001). These and other observations have prompted some to nominate lipid analysis as an important indicator of population health.

Question 1 Conclusions

Are we capable of accurately characterizing the health and disease status of Great Lake fish in a manner that allows us to detect impacts and changes in response to management actions?

There are significant obstacles to accurately characterizing the health and disease status of Great Lakes fishes. A fundamental difficulty lies in problems we have in defining what we want to measure. The traditional view of health as the absence of disease will not be compatible with desires to manage fish health within an ecosystem framework. Alternatively, a move to a definition that does not acknowledge the ongoing concerns about disease is likely to be viewed as inadequate in the short term. It will be essential to build a bridge between current disease concerns and desires to manage at an ecosystem level by expanding and applying a broader concept of health. While the task of developing a socially and ecologically relevant definition that is operational may seem daunting, we should be encouraged by progress in the fields of population health in agricultural and medicine.

A related problem is deciding how we can best measure what we want to measure. Improper classification of the health status of individuals and groups of fish will prevent accurate characterization of health risks. Major research obstacles include the lack of data on the predictive value of standard diagnostic tests and lack of evidence-based methods to detect and track disease. Moreover, we lack validated indices of health for Great Lakes fishes.

We can conclude that, in the absence of a more comprehensive definition of health and the development of appropriate tools to measure differences in health status, our capacity to detect impacts and changes in response to management actions is very limited.

Question 2: Is there evidence that disease has sufficient impact on fish communities to make it a management priority?

Four basic biological processes affect the numbers of individuals in a population: birth, death, immigration and emigration (Scott and Smith, 1994). One would find little argument that disease can affect the rate of death and some agreement that it can affect the birth rate in wild populations. By definition, a parasite is an organism that reduces the fecundity or increases the mortality of its host. A variety of studies have revealed the importance of disease as a mortality factor in wild mammals, birds, insects, and, to a lesser degree, fish. The ability of a bacteria or virus to regulate a host population is dependent on its pathogenicity exceeding the host population growth rate (Anderson and May, 1979b). Pathogens and parasites can amplify the effects of other regulating factors. For example, they can intensify the effects of low levels of nutrition, thus making an important contribution to density-dependent population regulating effects (Anderson and May, 1979a). Despite a strong theoretical underpinning, there are very few field-based studies that conclusively evaluate the role of disease in fish populations. Difficulties in collecting many of the key variables needed to understand disease-induced population regulation in wild populations makes conclusions regarding the role of disease in the Great Lakes hypothetical rather than a measured parameter. Therefore, we are resigned to making a reasoned argument rather than presenting a measured outcome to answer the question of whether or not disease has sufficient impact to make it a fisheries management priority.

There is a large and growing body of literature on the importance of infectious and parasitic diseases on the population dynamics, population genetics and evolutionary biology of humans (Dobson and Grenfell, 1995). Theoretical, experimental and observational studies have begun to demonstrate the important population regulating roles of infectious diseases in a variety of species and settings (Anderson, 1991). Information is expanding for domestic species in terms of the impacts of disease on animal productivity and population dynamics. Agricultural examples, such as trichostrongylid parasites of ruminants, clearly demonstrate how parasite infestation can have sub-lethal, yet physiologically important negative effects on their hosts (Coyne and Smith, 1994). There is growing interest in the role of disease in wild animals, primarily for two reasons (Schubert *et al*, 1998). First, disease may be an important factor in the decline of endangered species. For example, canine distemper has lead to the near extinction of black-footed ferrets, rabies has been implicated in the decline of African wild dogs and a variety of parasites have significantly impacted Hawaiian avifauna (Schubert *et al*, 1998). Based upon their review of existing literature, NASCO (1993) concluded that damage to wild stocks arising from the introduction of exotic diseases could be so severe as to render certain wild salmon stocks extinct. Secondly, there is growing concern that environmental or animal management practices may influence disease and population dynamics of wild species, leading to unanticipated effects. In addition to these reasons, there is an increased awareness of the role of disease and parasites as population density and non-density dependent regulating factors in wild species. Long-term population studies of red grouse in Scotland, for example, have revealed that the host-parasite interaction is the primary cause of long-term cycles in grouse population size through their effect on grouse fecundity (Dobson and Hudson, 1994). Just as parasites exploit animal behaviours such as breeding, foraging and social aggregation, animals modify their behaviours based on their infestation status (Apanius and Schad, 1994). Some animals select forages apparently based on the relative risk of exposure to certain parasites or adopt other behaviours such as migration pathways and group dynamics to avoids exposure. A variety of animals appear to choose mates based on secondary clues that indicate their parasite load. The latter has been documented for stickleback and the ectoparasite *Ichthyophthirius multifiliis* (Apanius and Scah, 1994). Changes in host population dynamics can affect the rate of transmission of microbes, thus affecting evolutionary pressures exerted on the microbes and the hosts (Anderson and May, 1979b).

Literature on the population effects of disease in fish is sparse. Two types of impacts due to diseases predominate the literature; mortality and loss of markets; the latter arising from mortality or trade restrictions being imposed because of disease (Rohovec *et al*, 1986). These impacts have been reported in hatchery or farmed fish in most cases. However, there are some reports of impacts in wild stocks. Whirling disease, for example, is thought to be the primary cause of dramatic decreases in the size of wild trout populations in some American states (Walker and Foster, 1998). The cost of whirling disease in California and Michigan due to direct control efforts and impacts on fisheries has been estimated at several million dollars per state (Hedrick, 1996). To rid their rivers of an apparently introduced parasite (*Gyrodactylus* sp.), the Norwegian government poisoned all fish in many rivers in an attempt to eliminate suitable parasite hosts (Johnsen and Jensen, 1991). This dramatic action has resulted in both drastic economic and ecological costs. No examples were found in the literature that followed a fish population after the occurrence of a new disease to assess medium to long-term impacts. There were also no reports found that evaluated impacts of fish pathogens or parasites from an ecological integrity viewpoint.

Conflicting evidence from laboratory and field based studies has created two schools of thought regarding infectious and parasitic disease effects in fish and wildlife. Studies associating the presence of disease agents with pathology have lead some to speculate on the existence of demographically important effects while the lack of evidence of ecologically significant disease-related mortality in natural populations has caused others to minimize the importance of disease in wild species. Fox rabies, as an example of the former perspective, regulates hosts and severely depresses density in a predictable 4-year cycle with only a relatively small proportion (5%) of the population infected (Anderson, 1991). Infections with *Kudoa paniformis* in Pacific hake have been associated with dose-related depressions in female fecundity (Alderstein and Dorn, 1998). Outbreaks of *Ichthyophonus hoferi* in North Sea herring were estimated to have significant effects on stock size (Patterson, 1996). Holmes (1982) is representative of the latter viewpoint, concluding that among vertebrates, mortality from infectious disease was mostly compensatory and thus, non-regulating. Many ecologists find it difficult to accept that disease plays a predominant role in affecting the long-term stability of naturally occurring fish populations (Bakke and Harris, 1998). Some authors have suggested that epidemics of disease tend not to play an important ecological role in wild fish populations below a certain optimum density, but may limit excessive population growth by acting as a density dependent factor regulating the number and type of organisms that can thrive in a given environment (Croze, 1981; Moller and Anders, 1986; Smith and Scott, 1994). The potential importance of disease as a population-regulating factor was emphasized by Levy and Wood (1992) who felt that the cyclic abundance of sockeye salmon could be best explained by a pathogen. Although some authors have concluded that disease is a significant force structuring fish communities

(Li *et al*, 1987 in Mesa *et al*, 1998), the lack of ecological and epidemiological data has limited our understanding of the mechanisms and magnitude of disease effects.

The causes and impacts of disease in wild populations are complex. Investigators of one of the earliest reported large scale kills of alewives in Lake Ontario in 1892 recognized this by suggesting that the die-off resulted not from a single factor but from the interplay of lack of food, storms, fungal infections and temperature changes (Mitchell, 2001). Dramatic die-offs of wild fish have most often been associated with abrupt environmental changes, although outbreaks of infectious diseases have also been reported (Sindermann, 1963; Moller and Anders, 1986; Kent and Fournie, 1993). Historically, only a small number of diseases, such as furunculosis, *Gyrodactylus*, ulcerative dermal necrosis, *Ichthyophonus* and a few other bacterial pathogens, have been associated with widespread, conspicuous epidemics in wild fish (Patterson, 1996; Bakke and Harris, 1998). This most likely reflects the fact that significant disease problems in wild stocks go unnoticed or unrecorded (Traxler, 1986; Moller and Anders, 1986) rather than reflecting an absence of disease in wild settings. This is particularly true for chronic parasitic infections that do not result in mass mortalities (Kent and Fournie, 1993). While significant initial proportional mortality rates due to novel infectious diseases in local populations have been described, no examples were found that followed a wild fish population after the occurrence of a new disease to assess medium to long-term impacts.

Models of the dynamics of exploited fish populations tend to assume that “natural” mortality is constant and time-invariant. This simplification ignores the effects of unusual events, such as when outbreaks of disease occur over a short period of time (Patterson, 1996). Very few attempts have been made to evaluate the role that disease plays in so-called “natural mortality” of fish. The ecological literature has tended to view infectious disease in terms of suddenly occurring epidemics that sweep through a population and then disappear. This has given rise to the view that infectious and parasitic diseases are unpredictable population regulating factors (Anderson, 1991). The lack of predictability may reflect problems in our ability to detect changes in, or understand the complexity of ecological relations affecting the occurrence of disease, rather than being a reflection of the ecological importance of disease. To date, it has rarely been possible to directly measure the effects of disease on natural fish populations (Moller and Anders, 1986). Increasing evidence suggests that pathogens and parasites affect basic ecological parameters such as immune function, genetic diversity, behaviour, predation, mate selection, reproductive success, community structure, species diversity and demography (Spalding and Forrester 1993; Dobson and Hudson, 1986; Thrusfield, 1986;). For example, parasitism was judged to be one of the main causes of death in fish in a Manitoba lake but the effects were not through direct mortality (Szalai and Dick, 1991). In this case, fish that were infected with the parasites were smaller than non-infected fish; smaller fish in this system were more susceptible to predation. A similar relationship was noted in the Netherlands where cormorants caught a disproportionately higher number of fish infected with a tapeworm (*Lingula intestinalis*) than non-infected fish (van Dobben, 1952). Mesa *et al* (1998) demonstrated that Chinook salmon challenged with *Renibacterium salmoninarum (*the etiologic agent of bacterial kidney disease) were more susceptible to predation by northern squawfish and smallmouth bass under experimental conditions. Despite these examples, little is known about the ecological aspects of fish disease. Instead, most attention has been placed on mortality and economic effects. Examining disease from a bioenergetic and ecological perspective may better help to elucidate the role of disease in fish populations than the historic methods of looking for clinically sick or dead fish.

The prevention of deaths due to disease is a constant activity for fish culturists and has been the most important factor limiting the success of fish farms. A 1992 salmon farming industry report, for example, identified disease as a critical factor limiting the growth and development of the industry (Stephen and Iwama, 1997). It has been estimated that fish disease increases the cost of fish production in the Great Lakes by 20-30% (Hnath, 1993). Kent and Fournie (1993) identified several reasons for the increasing prominence of disease in fish culture in recent years including; (1) the cultivation of larger numbers and new species, (2) the development of new methods for fish rearing, (3) the use of new geographic regions for fish farming and (4) the involvement of more researchers in the field. The primary focus of research to date on disease of cultured fish has dealt with lethal diseases, as large-scale mortality rates are still commonplace in aquaculture. However, there are economic effects of disease that extend beyond the costs associated with death. Disease can have direct biological effects on other parameters, such as growth rates and feed conversion, by impacting on physiological processes. It can also have indirect economic effects that arise from the costs of disease treatment, impacts on management activities and resource allocation, genetic losses, loss of markets, pubic health risks and reduced opportunity to use animals for certain production purposes (Radostitis *et al*, 1994). There has been little attention placed on quantifying total economic costs of disease in aquaculture and, thus, no basis on which to conduct cost-benefit analyses of health promotion programs.

One can challenge the proposition that the presence of disease invariably results in undesired population effects. Yasutake *et al* (1986) detected six different parasite species in Columbia River coho, but did not find any relationship between parasite burden and survival. A wide number of parasites, bacteria and some viruses were detected in wild fish in northern BC, but only *Ceratomyxa shasta* was associated with disease (Anon., 1984). Similarly, there are jurisdictions that have *Myxobolus cerebralis* present without apparent effects on wild stocks (Modin, 1998). The results of a project that tried to plant infectious pancreatic necrosis virus (IPNV) infected fish into Rocky Mountain lakes showed how difficult it is to transfer the infection to resident fish, let alone to maintain the virus without ongoing introductions of new infected fish (Yamamoto and Kilistoff, 1979). This reflects the experience in European lake net pen culture of trout where investigators could find no evidence of transfer of IPNV from escaped, presumably infected trout to wild stocks (Stephen and Iwama, 1997). These experiences are similar to when trout with bacterial kidney disease and furunculosis were purposely introduced into wild conditions with minimal transfer of disease to wild trout (Krueger and May, 1991). In his review of diagnostic results and surveys of wild fish in Great Britain, Bucke (1993) found only three events since the turn of the century where diseases possibly impacted wild fish, despite a long history of opportunities for disease interactions between wild and cultured stocks. All of these cases must be interpreted cautiously as the level of population surveillance was unspecified in these reports and the conditions present in the reported cases may not mirror those in the Great Lakes basin. The numerous insults to the surrounding land and water compromise the environmental quality of the Great Lakes and, therefore, can increase the risk of disease. There is a growing body of data that indicates that compromised environmental conditions are required for some diseases, such as *M. cerebralis* infections, to result in negative population impacts (Stephen, 1999).

Most investigation and modelling of disease have dealt with single diseases in relatively homogeneous populations. Reality is far more complex due to the interactions arising from multiple populations in the presence of interacting etiologic agents in a varying environment. In a lake, there are many different fish populations that interact to varying degrees. One group of fish can be virtually separate from other members of a lake community because of its habitat requirements and behaviours. Variables such as age, spawning behaviour, feeding patterns and life-history can greatly affect chances for parasites and pathogens to be transmitted and maintained within sub-groups of the same species. For example, Bailey and Margolis (1987) showed that, within the same lake, there could be ecologically isolated groups of juvenile sockeye salmon that use different parts of their environment and thus have different parasites. The nature of fish community interactions is unlikely to be the same within and between lakes. Variations in water and habitat quality will undoubtedly affect the number and types of fish at particular locations within the lakes. Altered habitats affect biological community compositions and therefore alter species interactions and opportunities for transfer of pathogens and parasites. Scott and Hall (1997) found that undisturbed streams in Maryland were characterized by a diverse array of fishes that utilized a variety of habitats whereas disturbed streams were characterized by a lower relative abundance and by a relative increase in the proportion of fish that were habitat or trophic specialists. New competitive interactions may result in patchy distributions rather than a homogenous mix of resident and introduced fishes. Competition can magnify differences in habitat and food selection, resulting in segregation rather than co-mingling (Burgner, 1991). Even in the absence of intense competition, fish in the same habitat may partition resources so as to reduce interaction with other fish (McMicheal and Pearsons, 1998). The food web plays an important role in determining which agents an animal will be exposed to (Thrusfield, 1986). Ecological changes leading to changes in prey selection or availability could result in new exposures to disease-causing agents (Solomon and Scott, 1994). These changes in habitat choice, rate of growth and predator-prey interactions can affect vulnerability to disease and exposure to disease agents.

When populations mix we have to be concerned with interacting strains of the same pathogen or multiple pathogens circulating within and between populations at the same time. The wide variety of immune responses and population responses that occur in the face of one disease make it very unlikely that coexisting diseases will act independently (Adler and Brunet, 1991). For example, the virus responsible for erythrocytic inclusion body syndrome is thought to increase the susceptibility or effects of other disease agents in salmonids (Rodger *et al*, 1991; Leek, 1987). In theory, if one disease decreases a fish's ability to fight infection, it will be more susceptible to a second disease, making it easier for the second disease to become established in the population. On the other hand, if a disease kills a fish quickly, it will reduce the number of fish left in the population that can be infected by another disease, making it less likely for the second disease to become established in the population. Virtually no work on fish diseases exist that explore disease interactions under natural conditions or even under culture conditions. However, given the diversity of species and diseases that exist in the Great Lakes, it is reasonable to conclude that models that describe disease impacts by looking at single populations and single diseases are unlikely to predict what will occur in response to management changes and that precisely predicting the exact nature of disease impacts will be next to impossible given our current understanding.

Regardless of ones perspective on fish health (reductionist versus ecological), or on ones assessment of the role pathogens and parasites play as regulating factors, infectious disease theory shows that we cannot uncouple population ecology and infectious disease research. Epidemic theory tells us that five variables determine whether or not an infectious or parasitic agent will persist in a population: the density of the hosts, the probability of transmission per contact between susceptible and infectious hosts, the disease-induced mortality rate; the per capita death rate of uninfected hosts and the rate of recovery from infections (Anderson, 1991). The design of effective disease control programs cannot consider only one of these factors in isolation, but instead needs to consider both pathogen and host dynamics. The same can be said for non-infectious diseases. For example, Johnson *et al* (1998) concluded that a significant impediment to understanding the population level impacts of sediment contaminants on English sole was not a lack of information on toxicology, but on the complexity of the animal's life cycle and population structure. Moreover, the need to understand and study disease from a population perspective is essential to properly classify health status. This, in turn, is essential to allow one to associate disease with a specific factor.

Our understanding of how population and environmental factors affect fish diseases is limited because of incomplete descriptions of the number and nature of diseases affecting fish and a lack of studies of the population impacts of disease in wild species. It has been estimated that less than 2% of fish diseases are known and our understanding of the known diseases is incomplete (Stewart, 1991). The main reason for the uncertainty regarding the role of disease in wild fish is that the outcome of interactions between a fish and disease causing organisms is under the influence of a large variety of ecological and environmental factors. This variability leads to often unpredictable outcomes. The environment in which fish live harbours a wide variety of microorganisms capable of causing disease in wild and farmed fish (Hastein and Lindstad, 1991). The mere presence of these organisms does not necessarily mean that disease will arise nor that, if disease occurs, that significant population impacts will arise. Under one set of conditions, a microorganism may be harmless to a group of fish, whereas in other situations, it may bring about mass mortality. The detection of an agent theoretically capable of causing disease or the detection of a particular symptom in some fish rarely provides the basis from which to reliably predict the nature of population effects that will occur. This is especially true for new or previously unrecognized pathogens. Despite problems in associating specific pathogens or parasites with significant effects in wild fish, many regulations strive to prevent the entry or movement of infectious organisms.

Disease is a major limiting factor in fish culture, thus making it a management priority. There is strong theoretical support that it plays an important role in wild populations. Given the vulnerability of Great Lake fish due to multiple insults, disease has the opportunity to "be the final straw." But, we lack empirical data to support this claim. Moreover, we are limited in our understanding of the primary determinants of the abundance and distribution of disease under culture conditions. It has often been assumed that treating and preventing disease is the right thing to do. However, there may be unanticipated population and community level impacts of treating illness in individuals. For example, mass vaccination of young animals increases the average age of infection (Anderson, 1991). Treatment for *Aeromonas salmonicida* is often effective at stopping disease-related losses, but may leave a high percentage of asymptomatic carriers in the population. There is limited literature on the impacts of fish health management decisions. Where they do occur, the reports tend to focus largely on whether or not a disease outbreak occurred subsequent to decisions (Bartley and Subasinghe, 1996). The population, community and ecosystem-level implications of current disease management strategies have yet to be explored.

Question 2 Conclusions

Is there evidence that disease has sufficient impact on fish communities to make it a management priority?

While the absence of disease does not equal health, infection and disease can be important determinants of health. Studies in a variety of species have shown how disease and infection status can influence fundamental ecological parameters such as growth, reproduction, migration and survival. However, there has been little work done on the impacts of disease in fish population and community ecology. There is a growing concern that environmental and management changes may lead to unanticipated disease impacts on populations and that these effects may be particularly important for threatened or vulnerable species. The lack of work on disease ecology, particularly studies that look at disease interactions, makes predictions of the effects of environmental change and changes in disease status on fish health difficult. Given the diversity of species, disease and other insults in the Great Lakes, it is reasonable to conclude that the historic approach of examining single health risks on single species is unlikely to predict what will occur in response to management changes. However, we can also conclude that disease is already a management priority. Millions of dollars are spend annually on disease management in cultured fishes and disease concerns affect other management plans, such as those involving translocations. A more accurate accounting of the effects of disease on fish health is required for an evidence-based cost: benefit analysis of current disease management strategies for the Great Lakes.

Question 3: Can hatchery, fishery and lake management strategies affect the distribution and abundance of disease in wild and feral fish stocks?

Despite the varied etiologies, pathogenesis and epidemiology of recently emerged diseases, they all shared strikingly similar underlying factors driving their emergence. Daszak *et al* (2001) reviewed a variety of wildlife diseases and concluded that the two key drivers of emergence were (1) spill-over of pathogens from domestic stock to wildlife and (2) anthropogenic movement of pathogens into new geographic locations. Environmental change, both natural and anthropogenic, that have lead to habitat alterations, environmental stressors and new species interactions have also been associated with emerging diseases in people and animals (Stephen and Ribble, 2001). Ecosystem instabilities brought about through management decisions and land/water use decisions can give rise to new interactions between hosts, vectors and disease agents (Anon, 2001). Interactions between different stocks can further affect wild fish health by altering infectious disease population dynamics as well as resulting in genetic effects on stocks that affect their susceptibility to disease (Windsor and Hutchinson, 1994). The significant movement of people, products and biota throughout the Great Lakes coupled with the ongoing introduction of cultured stocks and habitat alterations presents the plausible hypothesis that lake management actions could lead to the emergence, re-emergence or amplification of disease problems in wild and feral fishes in the Great Lakes. Indeed, environmental stressors have been suggested to be the primary determinants of the chinook salmon die-offs that occurred in Lake Michigan in the late 1980s (Holey *et al.*, 1998).

Ecology and epidemiology, like all branches of science, strive to make predictions about the future behaviour of a system, based on past and present observations and analysis. An early warning or predictive system requires not only a certain level of confidence in our capacity to identify relevant indicators and their thresholds for action, but also the capacity to identify groups or habitats that are vulnerable, an understanding of how disease observed in individual fish relates to potential population impacts, and knowledge of how different variables affect the outcomes of interest. Prediction usually requires some sort of model that allows us to anticipate how new information will affect what we anticipate will happen in a given system. Models that survive over time tend to be those that are predictive of an outcome of concern (Kimmins, 1997). However, uncertainty plagues attempts to predict health risks and can arise from several sources including, lack of understanding of the system of concern, failure to capture salient risk factors in the predictive model, imprecise estimates of model parameters from a limited or variable data, inability to make reasonable estimates of model parameters in the absence of data, omission of important processes or features in the model, and stochastic variability in measured parameters (Anon, 1997). Fundamentally, all prediction about the behaviour of natural systems is dependent on the quality and quantity of data available on the variability in the system of concern.

In systems, it is possible for phenomenon to emerge at the population level that cannot be observed by just recording individual level events[2]. The behaviour of a system depends upon the pattern of connection among individuals. For infectious diseases, individuals are connected into a transmission system. There often are differences in the

[2] Koopman JS. Transmission System Analysis. http://www.sph.umich.edu/~jkoopman/Web606/TSA/TSA.htm

way populations cluster and the extent of contact between clusters that can make big differences in the transmission of disease agents and thus, the manifestation of a disease in a population. Replicating variability in transmission systems is rarely possible in laboratory settings or via theoretical modelling. Observational studies remain a very important method for uncovering relationships affecting disease dynamics and health under natural conditions. Moreover, observational studies serve as an important tool to evaluate the generalizability of laboratory and theoretical results before they are applied in a management setting. Observational studies feature prominently in Kelsey *et al*'s (1986) conceptualization of the sequence of the discovery of a causal association (Table 2)

Table 2. Sequence of events in the discovery of a cause-effect relationship (adapted from Kelsey *et al*, 1986).

1.	Observations of a health problem lead to the first clues of a causal association
2.	Descriptive epidemiological studies describe associations between agents and outcomes on a population level
3.	Analytical observational studies, like case-control and cohort studies, establish associations at an individual level
4.	Experimental reproduction of the disease reveals pathological mechanisms
5.	Intervention studies examine the effects of removal of the causal factors on the incidence of disease

Observational studies that exploit natural experiments are often very revealing. A system using this research approach must be opportunist and able to respond quickly to naturally occurring events such as disease outbreaks. Investigations of unexpected or unusual events will often be the initiator of the sequence to discovering a causal relationship. Table 2 also emphasizes the role of an adaptive management approach as a means to complete the final step in the casual sequence. Observational studies, though essential for establishing cause-effect relationships, will be limited until issues of measurement of health outcomes can be addressed.

There is an accumulating body of evidence that suggests that pathogens and parasites in natural communities play a part that is analogous or complementary to predator-prey interactions or resource limitations in constraining the growth of populations (Anderson and May, 1979a). Much of this evidence has been derived from dynamic mathematical models. Such models not only have provided important insight into the evolutionary and ecological aspects of disease, but also have helped guide large-scale public health disease control campaigns such as malaria control and vaccination programs (Anderson, 1991). It can be anticipated that reliable models would help managers predict and avoid disease impacts on fish populations. Reliable models are important aids to decision-making and can help shape our thoughts and understanding of ecological processes. New technologies, such as geographic information systems (GIS) and expanding computer computational power have generated rapid advances in infectious disease modelling (Anon, 2001). However, there is an almost complete absence of fish disease models that fisheries managers can use for Great Lakes fish disease issues.

A basic rule of modelling is " we model what we can count" (Scott and Smith, 1994). An important first step in developing any model is to identify and quantify the various components and their inter-relationships. The theoretical approach is entirely dependent upon an understanding of the dynamics of the host population and the dynamics of the etiologic agent along with the relationships between these two elements. Mistakes in describing or enumerating these factors can lead to erroneous model outcomes. An equally, if not more, important step is determining what questions you want the model to help answer. This requires knowledge of the problems facing the populations of concern. Two of the most critical steps in model building are, therefore, dependent upon the capacity to observe, count and consider populations in their natural setting.

The utility of quantitative models is limited by the variables that can be included in the model. The fisheries and ecological literature are replete with methods to enumerate populations. The fish disease literature is full of methods for detecting pathological or contaminant agents in fish. There has, however, been little attention paid to merging these two sets of methods in a manner that helps to accurately characterize fish disease dynamics. There are significant gaps in our understanding of the transmission and natural history of the vast majority of diseases that affect fish outside of a culture situation. Experience with human diseases has shown that ecological models fail to provide practical disease management outputs in cases where they have been developed in the absence of epidemiological data (Bradley, 1982). There are very few instances where there are enough data to support even simple models of field-, rather than laboratory-based, host-parasite dynamics (Scott and Smith, 1984). Attempts to create dynamic models of fish diseases run the risk of generating spuriously elegant yet incomplete and potentially misleading representations of reality. To date, we have relied largely on qualitative or intuitive approaches to extrapolate what we know of fish pathophysiology, microbiology, parasitology and toxicology from the individual to population level. An important question to consider is whether a quantitative modeling approach would be more informative or predictive. Although advocates of the modelling approach hail this as a method to integrate a variety of variables and thus, examine complex dynamic situations, even the most complex model is a simplification of reality and, thus, a form of reductionism. No model, therefore, can ever be completely correct for a biological system. Whether or not a model is judged as good depends on whether it provides a representation of reality that allows for decisions that do more good than harm.

In the absence of predictive models, we are resigned to take a "weight-of-evidence" approach to examine questions of whether or not anthropogenic factors can influence fish health

Stocking programs

Salmonid fisheries in the Great Lakes, apart from Lake Superior, are dependent on artificial propagation and restocking to sustain current populations (Koonce, 1995). Tsukamoto (in Fushimi, 2001) felt that there are three factors affecting the effectiveness of stocking programs: quality of the fish, environmental conditions and releasing technique. Tsukamoto defined fish quality, also called ecological robustness, as the ability of a fish to adapt to natural conditions at release sites. Quality was seen to be affected by behaviour, morphology and physiological attributes. Improvements in the form, function and ability of fish pre-release was deemed to be an essential goal of fish enhancement so that fewer fish need to be released, thus decreasing risks through competition, genetic deterioration and the spread of pathogens. Bakke and Harris (1998) went even further, concluding that the success of efforts to manage, conserve and reintroduce wild Atlantic salmon is ultimately dependent on our success in understanding the role of disease processes in salmon ecology.

Perhaps the most tangible management actions that could influence the health of Great Lakes fishes are fish culture activities. Fish culture has occurred in the Great Lakes for well over 100 years.[3] Billions of fish have been released to support existing fisheries or create new ones. Many of these fish have been introduced from regions outside of the Great Lakes or have been moved extensively within and between the lakes. The ecological interactions that arise from the presence of exotic invaders such as sea lamprey and rainbow smelt, and stocked exotic species, primarily Pacific salmon play an important role in defining the constraints and opportunities for ecosystem management (Kitchell *et al*, 2000). Concerns have been raised that intensive culture of hatchery-reared fish poses a threat to native fishes by artificially increasing the disease and parasite ‘reservoir' that native fishes are exposed to in the wild (Crawford, 2001). The concern about disease impacts of fish culture on wild fish has been a major thrust of criticisms against public and private fish culture (Noakes *et al*, 2000).

The movement of fish associated with stocking and conservation programs has, in the opinion of Klontz (1988), been the main method for moving fish pathogens and parasites throughout North America. Many diseases, particularly those involving intermediate hosts, have strict geographic boundaries (Blackmore and Hathaway, 1980). In the case of fish, the distribution of various agents and diseases often correlates with watersheds. Animals that can physically contact each other or share similar food and water are more likely to share the same diseases than are fish from different bodies of water. Moving fish outside of their normal geographic distribution can bypass natural barriers and, therefore, change the distribution of disease agents, the abundance of susceptible hosts or other factors that predispose a population to disease.

It is widely held that pathogens move from wild to cultured fish (Kent and Fournie, 1993). Unfortunately, most of the information regarding the transmission of infectious and parasitic agents from cultured to wild fish is circumstantial in nature and often equivocal (Iwama, 1991). Pathogenic bacteria and parasites such as *Aeromonas salmonicida, Myxobolus cerebralis*, *Philonema oncorhynchi, Ergasilus nerkae* may have been introduced to the Great Lakes along with the introduced fish, thus creating new opportunities for exposure of naïve native fishes to significant disease-causing organisms (Crawford, 2001). There are publications that implicate cultured fish as the origin of disease causing agents in wild stocks. Johnsen and Jensen (1994), describe the spread of furunculosis in Norwegian rivers after *Aeromonas salmonicida* was introduced with the international movement of fish for culture purposes. The increase in sea-lice in wild salmonids in Europe has been attributed to increased environmental levels of this parasite due to fish farming (Wootten *et al*, 1992). The introduction and dispersal of the parasite *Gyrodactylus salaris* in Norway has been associated with stocking practices that used fish from infected hatcheries (Johnsen and Jensen, 1994).

[3] http://texas-sea-grant.tamu.edu/wpaquaculture.html

Despite these examples, irrefutable evidence that fish introductions are a significant mechanism for introducing pathogens or parasites to wild stocks is lacking (Stewart, 1991). There are cases where there have been no know changes in the pattern of disease agents or evidence of effects in wild stocks after fish have been introduced into an area. For example, of the 48 transplanted parasites identified by Hoffman (1970), only one was found to affect wild fish, the rest had impacts on hatcheries and fish farms only. The types of evidence used to link fish movement with changes in disease patterns has largely been the concurrent findings of new diseases after fish have been introduced, apparent patterns of spread of some fish diseases, and similar examples from other species. The environmental juxtaposition of fish populations is not enough to ensure that disease agents will be transmitted or that diseases will occur. Yamamoto and Kilistoff (1979) were unable to detect transmission or population impacts on wild stocks after fish of the same species infected with IPNV were introduced into Rocky Mountain lakes. For both ceratomyxosis and whirling disease, there is evidence to show that the presence of the parasites is insufficient to result in disease (Hoffmaster *et al*, 1988,Modin, 1998). Environmental stressors are likely to play an important role in the manifestations of these diseases.

There are many reasons why it is difficult to demonstrate the movement of pathogens from cultured to wild stocks (Windsor and Hutchinson, 1994). Reasons include the lack of ongoing surveillance of diseases in wild fishes; inadequate understanding of the mechanisms and dynamics of disease transmission under natural conditions, problems in detecting and tracking pathogens in aquatic environments, and problems in monitoring the interactions of wild and cultured stocks (Stephen and Iwama, 1997). Methods used to capture fish can generate biased estimates of the rate and distribution of disease in a population. In part, this is due to the fact that a fish's ability to evade capture, to respond to lures and interactions with its cohorts are all affected by the behavioural and physiological limitations that accompany disease. For example, both sick Chinook salmon in net pens and parasitized wild menhaden do not stay in the same school as their healthy cohort (Guthrie and Kroger, 1974; Stephen and Ribble, 1994). It is assumed that sick wild fish are captured by predators at a rate higher than healthy fish often before man has a chance to capture them (Kent and Fournie, 1993). The example given above where infested fish in a Manitoba lake were more susceptible to predation (Szalai and Dick, 1991) substantiates this assumption. Linking diseases occurring in wild and cultured or feral fish is also influenced by our assumptions regarding the genesis of similar pathological lesions under different circumstances. As mentioned before, plasmacytoid leukemia of farmed Chinook salmon is inconsistently diagnosed using the standard histopathological definitions, making it possible that fish with the same disease are classified differently (Stephen *et al*, 1995) Alternatively, there are diseases with the exact histopathological and gross pathological lesions that are induced by different etiological agents as previously described for hepatic megalocytosis seen in wild and farmed salmonids (Stephen *et al*, 1993). Given that different fish species react differently to pathological insults, estimating the rate of exchange and impacts of pathogens shared between wild and cultured fishes becomes problematic.

In some cases, a parasite may infect more than one host while others may be relatively host specific. A tapeworm of sockeye salmon (*Eubothrium salvelini*), for example, has 15 known fish hosts, which contrasts with another sockeye parasite (*Philonema oncorhynchi*) which has only five known fish hosts, four of which are Pacific salmon (McDonald and Margolis, 1995). The same can be said for viruses, bacteria and other pathogens. Increasingly we are finding fish pathogens that affect a wide array of hosts with different effects (Kent *et al*, 1998; Amos, 1998). Some organisms are more likely to establish themselves in a new environment than others. The presence of a direct lifecycle, suitable hosts in the new environment and relatively little host specificity are characteristics of agents more likely to become established while a lack of suitable hosts, an indirect lifecycle and strict host specificity tend to be characteristics of agents unlikely to establish themselves (Arai and Mudry 1983).

Stocking programs could affect the pattern of disease in the Great Lakes without introducing foreign pathogens or parasites. Often, fish without a history of exposure to an agent are more susceptible to that agent. Buchanan *et al*, (1983) showed how strains of steelhead from areas without *Ceratomyxa shasta* were highly susceptible to this parasite. As a general rule, a disease is better able to spread in populations that are entirely susceptible than in populations with some degree of immunity, as immune individuals act to break the cycle of transmission (Scott and Smith, 1994). For populations without previous exposure to a pathogen, the majority of the population may be susceptible, making it more likely that an epidemic would occur. This assumes that behavioural mechanisms or innate immune responses would be inadequate for resident fish to fight off infection of introduced pathogens or parasites. In a large isolated population, it is not uncommon for a major outbreak to occur after introduction of a new pathogen or parasite (Smith and Scott, 1994). However, unless there is a concurrent input of susceptible fish, the disease will fade out (Yorke *et al*, 1979). In order to maintain an introduced pathogen, there must be an ongoing recruitment of susceptible fish. For this to occur, resident fish must not be able to mount long-lasting immune responses, new susceptible fish are born into the population regularly, or there must be an ongoing immigration of susceptible fish.

Usually, important changes in disease patterns are associated with changes in the demographics of a population or environmental changes (e.g. degraded habitat, new trophic relationships, reduced environmental quality) rather than changes in microbiology (Tuljapurkar and John, 1991; Spalding and Forrester, 1993). Most fish disease literature has failed to consider disease risks associated with demographic changes. Changes in age distribution, species composition and abundance, population densities and other demographic variables can result in changing patterns of disease in populations without the introduction of a new disease agent (Tuljapurkar and John, 1991). For example, the low parasite species richness in lake trout is believed to be due to their large size at stocking and to the loss of historical host-parasite relationships that followed the absence of this fish species in Lake Huron for 26 years (Muzzall and Bowen, 2000). McCarty and Miller (1998) determined that the probability that a susceptible animal will become infected is affected by; (1) total size of the population, (2) the number of hosts in the total population that are infectious and (3) the number of contacts an infectious host has with a susceptible host. The size and “make-up” of a fish population is affected mainly by four processes; birth, death, immigration and emigration. These parameters, in turn, affect the ability of a disease to spread (Smith and Scott, 1994). Reducing the overall death rate of a population or increasing the size of the susceptible population both make it more likely for an introduced disease to grow to epidemic proportions, all other factors being equal. Diseases, even those caused by particularly virulent agents, can be maintained if there is a rapid and regular replenishment of susceptible individuals (Yorke *et al*, 1979). By mixing a group of susceptible fish with a more resistant group, the threshold number of susceptible fish may be reached, making a disease outbreak likely (Smith and Scott, 1994). Several studies have shown that different species and strains of fish have different susceptibilities to infection and disease so it can be anticipated that stocking programs could affect the level of susceptibility in fish in the Great Lakes. However, it is not know if this will increase or decrease the susceptibility; either is possible. Each disease has its own critical threshold of infectious and susceptible individuals beyond which the rate of disease will increase, but ultimately, it is the number and proportion of susceptible fish in the population that will determine what will happen when a disease is introduced (Smith and Scott, 1994). Unfortunately, there are no valid estimates of critical thresholds for fish diseases of concern to the Great Lakes. Therefore, we are left to speculate as to whether or not stocking programs allow for the ongoing recruitment of susceptible or infectious fish to a degree that basic disease dynamics are notably affected.

The rapid turnover of individuals that can be seen in fish populations allows pathogens to move back and forth between pockets of susceptible fish within a larger body of water, such as a lake. If the disease agent can be perpetuated within an individual fish, it may persist and cycle between overlapping generations of susceptible individuals, especially in relatively isolated populations (Yorke *et al*, 1979). For pathogens or parasites of fish which reproduce annually, the disease agent must be able to survive in the environment, overwinter in alternative or intermediate hosts (as is the case with whirling disease), or must not exhaust the pool of susceptible fish over the course of a year if it is to survive between the annual influx of newly hatched susceptible fish. Newly hatched fish and fry can be more susceptible to certain diseases. Fish are not born with the same ability to fight off infections as their parents. While parent fish can pass some specific protection to their offspring through the yolk, this is typically not long lasting. Moreover, because of different life histories, juveniles and adults can have different exposures to disease-causing agents in natural environments. Disease control efforts need to consider the multi-generational dynamics of diseases in fish communities.

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One could conclude that rare or endangered species are somewhat protected from virulent pathogens as their population sizes may be too small to reach threshold values needed to support an ongoing epidemic (Lyles and Dobson, 1993). Historically, disease has only been linked to extinction or near extinction when the resident population was severely compromised or an exotic pathogen was introduced (Spadling and Forrester, 1993). However, if a pathogen is introduced into these smaller populations, it could be transmitted between rare hosts if their distributions overlap, allowing for contact between infected individuals or contaminated environments. Furthermore, if there is an ongoing introduction of disease agents with re-introduced fish, an epidemic could be artificially maintained even in a rare population.

Genetic aspects of pathogens and parasites affect their host-specificity and how they interact with fish. Although we have a poor understanding of the specificity of fish pathogens (Chevassus and Dorson 1990), there are examples of how the susceptibility of salmon varies with the strain of pathogen, such as for IHNV (Traxler *et al*, 1993). We have a better understanding of the genetic basis of fish's response to the pathogens (Fjalestad *et al*, 1991;Schrek, 1981). Genetic-based variation in critical host responses to infections will result in substantial variations in the susceptibility of individuals within the same group (Wakelin, 1994). Different disease resistance patterns are seen in different Pacific salmon stocks (Winter *et al*, 1980). For example, Beacham and Evelyn (1992) showed how different strains of chinook and pink salmon had different resistance to common salmon diseases including vibriosis, bacterial kidney disease and furunculosis. Concerns have been raised that interbreeding between wild, feral and cultured stocks may influence the genetic basis of fish susceptibility (Stephen and Iwama, 1997). Theoretical and empirical studies have revealed that host genetic factors affecting innate susceptibility or immunological response play a large role in parasite distribution in natural host-parasite relationships and that parasite distribution (aggregation) is a determinant of whether or not the parasite has a host regulating role (Anderson, 1991). The interplay of ecological and genetic factors is a ripe area for research.

Our inability to accurately predict the impacts of changing distributions of disease-causing agents coupled with case histories of severe negative effects of disease in aquaculture or enhancement situations have lead regulators to err on the side of caution and manage fish resources to avoid changes in disease status whenever possible. This has resulted in management strategies that revolve around preventing the introduction or extension of the distribution of disease-causing agents. There are a number of provincial, national and international regulations and codes of practice designed to prevent the movement of diseases with fish movement. Unfortunately, diseases do exist in fish populations, thus control and treatment is an important aspect of fish disease management not covered by regulation.

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Anthropogenic Stressors

Fisheries managers have historically considered fisheries exploitation as the major anthropogenic impact on fish populations. In recent years, other factors such as habitat destruction and pollution have been identified as important contributors to the decline in fish stocks (Johnson *et al*, 1998). There is now a small, but growing literature that examines the impacts of infectious disease on populations. However, there has been little research directed towards examining how habitat and fisheries management decisions affect fish disease status. Little of the range of many fish stocks in the Great Lakes remains uninfluenced by anthropogenic factors. Biological, chemical and physical stressors are pervasive in this lake system including; over-exploitation, introduction of exotic species, persistent toxic chemicals and the loss and degradation of habitat. Factors such as these can act as stressors that directly and indirectly affect the ability of fish to remain in optimal health. Chronic exposure to stressors can have impacts both on individuals and populations. Depending on their duration and intensity, chronic stress can result in decreases in growth, disease resistance, reproductive success, smolting, swimming performance, recruitment and productivity (Stephen and Iwama, 1997).

Environmental stressors, including culture conditions, water quality and pollutants affect fish at all life stages. A fish's susceptibility is affected by a variety of environmental and internal factors, and can be overwhelmed (Pickford *et al*, 1971; Ellsaesser and Clem, 1986; Schrek *et al*, 1993; Schrek, 1996). It has been suggested that certain fish pathogens require some form of environmental or social stress to turn an infection into a disease. For whirling disease, it has been suggested that environmental quality is an important determinant of whether or not a population manifests negative affects (Modin, 1998). If a fish is unable to adapt to new stresses its health is compromised through reduced growth, increased disease susceptibility, reduced swimming performance and other physiological effects. These responses can, in turn, decrease the recruitment and productivity of the community (Stephen and Iwama 1997).

Fish disease is more common in polluted waters (Moller, 1985). The GLFC has recognized the need to determine the effects of toxic substances and disease on fish populations as a milestone in their plan for a healthy ecosystem approach to lake management (GLFC, 2001). There is a growing body of data to indicate that pollutants can compromise a fish's immune function; making it more susceptible to disease (Sanders *et al*, 1998; Casillas *et al*, 1993). Industrial, domestic and agricultural activities can add a variety of contaminants to the environment that can affect fish at all life stages. Pollutants can have direct effects on fish disease through the induction of various neoplasms or indirect effects via pollution-induced immunosuppression (Bakke and Harris, 1998; Johnson *et al*, 1998). Although, interactions between parasites, pathogens, and pollutants or other environmental stressors have been insufficiently examined, existing results suggest the potential for synergist interactions. For example, Arkoosh *et al (*1998) concluded that contaminant-associated immunosupression in juvenile salmon increased their susceptibility to *Vibrio anguillarum*. Other data, such as those examining the effects of chronic gas saturation on the effects of experimental exposure of rainbow trout to *Myxobolus cerebralis*, do not show synergistic effects (Schisler et al, 1999). Physical conditions such as crowding, heat stress, and exertion can also affect fish's ability to withstand the effects of disease agents and other stressors (Johannson and Bergstrom, 1977; Pickering, 1987). Such stressors are most likely more immediate and significant factors in culture settings than under wild conditions. Fish population density can affect the intensity of competition between fish (McMichael and Pearsons, 1998), which in turn can affect stress and susceptibility. Host nutritional status plays a very important role in parasite-host dynamics as infection aggravates nutritional deficiencies and nutritional deficiencies aggravate infections (Solomons and Scott, 1994). Extremes in water quality parameters (such as dissolved oxygen, pH, gas content) and pollutants can unduly stress fish and lead to disease (Meyers et al, 1983; Wood, 1979). The most well studied effect of water diversions that result in gas supersaturation is acute mortality (gas bubble trauma). However, sublethal supersaturation can result in a variety of effects including reduced growth, increased susceptibility to predation, impacts on swimming performance, effects on blood chemistry and thermal tolerance and impaired lateral line function (Mesa and Warren, 1997). All of these effects can be modulated by other factors including exposure time, water depth, temperature and fish size.

In other cases, anthropogenic effects affect the likelihood that wild fishes are exposed to pathogens and parasites. For example, water management strategies that result in the slowing of water flow or the development of shallow water habitats can support larger and more varied invertebrate populations that, in turn, can provide more vectors or intermediate hosts for pathogens (Bakke and Harris, 1998). Eutrophication can alter the balance of invertebrates, favouring some such as the oligocaete *Tubifex tubifex* that is an important intermediate host of *Myxobolus cerebralis*. Habitat modification and the introduction of exotic species influence population interactions. The colonization of the Great Lakes with Rainbow smelt, for example, was associated with significant disease effects (Hall and Mills, 2000). Table 3 lists examples in which the investigators have linked the movement or introduction of disease causing agents with the movement of fish.

It becomes difficult to quantify the contribution of specific stressors when a suite of stressors affects a population. Johnson and Landahl (1994) for example, felt the effects of differential fishing pressures confounded their estimates of contaminant-induced mortality rates in English sole. This becomes even more complicated when one considers that decisions affecting population management must not only consider biological evidence, but also social values and resources available to implement decisions. Decisions that rely largely on values and resources can be called opinion-based decisions (Gray, 2001). It could be argued that, due to the historical approach to fish health, which has focused on the examination of isolated components of the fish health system, we lack the type of data needed to move us from opinion-based to evidence-based management of fish health.

Table 3. Examples found in the scientific literature of the movement of disease agents associated with fish transfers or translocations.

Disease Agent (Disease)	Condition of transfer	Reference
Aeromonas salmonicida (Furunculosis)	Movement of trout between Europe and North America for stocking and farming purposes	Stewart 1991
Freshwater parasites	Movement of 48 different parasite species linked to movement of fish	Hoffman, 1970
Aeromonas salmonicida (Furunculosis)	Rainbow trout moved from Denmark to Norway	Heggberget *et al*, 1993
Aeromonas salmonicida (Furunculosis)	Movement of salmon smolts from Scotland to fish farms in Norway	Heggberget *et al*, 1993
Yersinia ruckerii (Enteric Redmouth)	Movement of salmon from Finland to Norway	Munro 1988
Angillicola craccus (Eel parasite)	Eels introduced from New Zealand or Asia into Europe.	Stewart, 1991
Ichthyophthirius multifiliis (Ich)	Multispecies disease outbreak linked to the introduction of the parasite via introduced exotic fish known to be carriers	Wurtsbaugh and Tapia, 1988
Infectious Pancreatic Necrosis Virus (IPN)	Pacific coho introduced to the Great Lakes	Dumont *et al*, 1998
Infectious Hematopoietic Necrosis Virus (IHN)	Movement of infected sockeye eggs from Alaska to Japan	Krueger and May, 1991
Gyrodactylus (external parasite)	Moved from Sweden to Norway with fish for enhancement purposes	Johnsen and Jensen, 1991
Renibacterium salmoninarum (BKD)	Introduced to South America when Pacific salmon were transported there for aquaculture	Rohoved *et al*, 1986
Renibacterium salmoninarum (BKD)	Stocked hatchery trout transmit the infection to wild trout in Wyoming	Mitchum *et al*, 1979
Digenean parasite	Translocation of a species of whitefish in Finland resulted in the re-introduction of this parasite	Gibson and Tellervo Valtenen, 1988

A large and growing theoretical framework coupled with increasing experience in terrestrial wildlife and fish convince us that environmental and fisheries management can affect the health of fish in the Great Lakes. The capacity for a disease to become established in a population and the magnitude of the impacts of that disease is a result of interactions between host population dynamics, agent dynamics and environmental factors. Factors modifying these dynamic relationships will affect the distribution and abundance of disease in Great Lakes fishes. Unfortunately, we lack sufficient knowledge of how these variables interact to predict how specific management actions will affect fish disease.

Question 3 Conclusions

Can hatchery, fishery and lake management strategies affect the distribution and abundance of disease in wild and feral fish stocks?

Any factor that influences the level of susceptibility or nature of exposure of a population to disease causing agents will influence the population's disease status. Fundamental changes in population dynamics can be as influential on health and disease as can the introduction of infectious or toxic agents. Management strategies can affect these parameters, but lack of research results prevents us from quantifying their impacts on fish disease dynamics. Our ability to quantify the effects of management on fish health will be limited until we can develop reliable tools to measure health in free ranging and cultured fishes. A challenge to future research will be to isolate the effects of particular determinants of health for fish that reside in an environment influenced by a great diversity of stressors. However, the same can be said for any population. Researchers are encouraged to look to successful examples for other species where investigators have been able to "dissect" out the contribution of specific health determinants using observational and epidemiological methods.

section 2 -summary of the workshop on fish health

Great Lakes Fishery Commission
Ann Arbor, Michigan
March 4-5, 2002

Participants

Marg Dochoda -- Great Lakes Fishery Commission
Randy Eschenroder -- Great Lakes Fishery Commission
John Hnath --Michigan State Department of Natural Resources
Mike Jones --Michigan State University
Chuck Kreuger --Great Lakes Fishery Commission
Sue Marcquenski --Wisconsin Department of Natural Resources
Craig Stephen --Centre for Coastal Health
Roz Stevenson --University of Guelph
Meg Thorburn --Ontario Veterinary College
Gary Whelan -- Michigan State Department of Natural Resources
Randy White --Purdue University
Greg Wright --Chippewa Ottawa Resource Authority

Each participant of this workshop was provided with an abridged version of a draft paper examining research needs and opportunities for wild fish health. Participants were asked to consider six questions prior to attending the meeting that would be used to “inspire” discussions during the two-day workshop. These questions were:

1. What is your definition of a healthy fish population and what are the best parameters to measure health?
2. What, in your opinion, are the most important health problems confronting wild stocks in the Great Lakes (justify your priorities)?
3. What are the most significant fundamental scientific unknowns that serve as obstacles to a complete understanding of the nature and role of disease in wild fishes?
4. What are the principle methodological obstacles to dealing with these priorities and unknowns?
5. What would be the primary obstacles to integrating population, community and ecosystem concepts into ongoing fish health research and management?
6. Do you feel that there is a need for a new approach to fish health research? If so, is the ecological approach the way to go?

An overarching conclusion of the two days of discussion was that these questions could not be answered based on evidence, but instead answers would be opinion-based. The group frequently encountered significant unknowns when trying to discuss the assigned questions. The primary obstacles to answering the questions were:

1. Lack of data on which to base selection of the best indicators of fish health,

2. Lack of methods capable of measuring health indicators across all relevant populations and,
3. Lack of a good monitoring system, relegating us to seeing mainly catastrophic events and thus, having a misleading view of fish health.

✍ what are healthy fish?

It was acknowledged that disease concerns have and will continue to be central health issues for fish culturists and fisheries managers due to recent events in the Great Lakes. There was, however, general agreement that fish health cannot be defined as a state characterized solely by the absence of disease. Instead, health was seen as a positive notion that was represented by measures such as efficient energy transfer, sustainability, reproduction, survival and commercial/recreational use. There was also agreement that appropriate measures of health would differ at different levels of biological organization (individual, population, community).

It was acknowledged that health was a normative concept, and in the absence of defined thresholds or measurements of normality, establishing whether or not a fish population is healthy is problematic and subjective. We explored the applicability of a modification of the concept of population health used in human and veterinary medicine as," the capacity of fish to respond to changing environmental conditions in a manner that allows them to access the resources for daily living and meet expectations." Expectations included ecological (survival long enough to allow for the successful reproduction of at least one generation of progeny) and socio-economic factors (ability to provide sustainable fisheries and meet cultural needs).

Factors affecting capacity to access resources included:

- ✍ Physical ability (anatomical integrity, ability to capture and defend resources)
- ✍ Physiological ability (disease, toxins, nutrition including food web dynamics)
- ✍ Ecological interactions (growth, survival, reproduction, competition from exotics)
- ✍ Environmental limits (habitat quality and availability, restrictions on movement)

Factors affecting expectations included:

- ✍ Survival (> 1 generation, premature death)
- ✍ Altered ecological relationships (exotic species, habitat alterations, climate change)
- ✍ Socio-economics (fisheries management and stock enhancement strategies, growth)

Many of the expectations for Great Lakes fish stocks have been outlined in the Joint Strategic plan and include stable self-sustaining stocks, an optimum contribution of fish and fishing opportunities, wholesome food, recreation, cultural heritage, employment and income, and a healthy aquatic ecosystem.

It was not possible to derive a single measure of health given the preceding discussion. Therefore, the idea of a suite of indicators that best reflect health was advocated rather than a search for a single measure.

✍ what are the most important health problems confronting wild stocks in the Great Lakes?

The major problems varied from species to species but there were consistent themes. Exotic invaders, unstable ecosystems (particularly food-web disruption), fish introductions and fish community interactions underlined many of the concerns. There was a divide identified in which the major problem for endemic species was reproductive failure and for introduced species, it was disease. Early Mortality Syndrome was discussed for two reasons. First, it was an immediate concern with respect to impacts on reproduction. Secondly, it was linked to the issue of exotic species (macro and microorganisms) and their effects on disease ecology and food-web dynamics. Contaminants, while acknowledged as a major health determinant, were not discussed in much detail as participants felt there were funds and efforts already directed towards this issue. However, it was acknowledged that better links between people working on infectious and non-infectious determinants of health were required.

The dependence on the hatchery system was nominated as an important determinant of disease status of Great Lakes fishes. The reliance on artificial propagation of top non-native predators not only was seen to likely affect the disease status of fish, but also to affect – primarily via competition - other key measures of health in a variety of aquatic species. Discussion centred on how the introduction, distribution and abundance of important pathogens may influence wild fish disease, and on how demographic changes in fish populations might affect infectious disease dynamics. The discussion was tempered by the acknowledgement that there is little known on the demographic impacts of disease in fish populations. The population dynamics of infectious and parasitic disease was, therefore, identified as a major health issue.

An overall theme that arose during the discussion of question 2 was how we could move from a reactive to a preventive model of fish health. To date, research and actions have been directed towards “hot topics” which have manifested in a large scale or dramatic fashion, rather than on evidence of impacts on fish health and ecology. It was agreed that understanding how factors such as exotic species and climate change interact or predicting the next hot topic will require a more thorough knowledge of disease ecology. Specifically, people were interested in how fisheries and lake management could create ecological conditions to impact fish health or select for certain diseases. From this perspective, disease was seen not as an outcome, but as a health indicator. This view is consistent with a population health approach applied to other species.

✍ what are the most significant fundamental scientific unknowns and what are the principle methodological obstacles?

Three main unknowns were common to all responses:

1. Our understanding of population interactions is insufficient to prevent health effects or to predict their occurrence.
    a. Key populations were native fish, stocked fish, introduced aquatic organisms, pathogens and parasites

2. Lack of field methods for tracking populations and correctly classifying their health, disease and infection status seriously impedes research of disease in wild stocks and hampers efforts in cultured stocks.
3. Lack of knowledge of what are appropriate predictive indicators of fish health at individual, population and community levels.

A lack of systematic and ongoing surveillance has created significant uncertainty about the infection status of fish populations, the association of biotic and abiotic variance with changes in fish health and disease, and thresholds of stressors that result in adverse impacts. However, without validated sampling and measurement methods, surveillance will be limited (but not without value).

Discussions of the first three questions lead us to identify the concept of the determinants of fish health as an overarching theme for future research. The broad concepts of the determinants of health have changed over time and differ with species. However, in large, the fish health community has focused its efforts to date largely on the role of pathogens and parasites in determining disease and not on the impacts of other ecological phenomena on determining fish health. The workshops participants strongly voiced the opinion that this focus needs to change.

The following research themes emerged on day 2 of the workshop.

1. Methods and measures
    a. Identifying and validating predictive indicators of health
    b. Improved methods for sampling/counting fish and pathogens
    c. Validated methods for classifying health and exposure of individual fish and populations
    d. Integrated health information management and health policy research and development

2. Population Ecology of Disease
    a. What are the population regulating effects of disease?
    b. Transmission dynamics
        i. Aspects of the agents (ex. microbial ecology)
        ii. Aspects of host interactions
        iii. Descriptive ecology (what is there and where is it?)
3. Ecological determinants of health
    a. How do management decisions affect the manifestation of fish health and disease?
        i. Exotics, stocking practices, toxins
    b. How do non-anthropogenic variables affect the same?
        i. Climate, nutrition, genetics etc
    c. Can management effectively respond to major ecosystem disruptions?

4. Research Development and Support
    a. Training of highly qualified individuals
    b. Pre-planning workshops
    c. Outbreak/response capacity (need to see the events and investigate)
    d. Need to think about how to move forward in a multi-risk, multi-disciplinary fashion

It was seen that the transition to a broader concept of health would have to progress through the following steps:

Step 1: Thinking
- ✍ Increased interdisciplinary discussions that would facilitate new ways of thinking about how health and management are related as well as to "borrow and adapt" methods from different disciplines to solve some of the identified problems

Step 2: Capacity Building
- ✍ There is currently a tremendous deficit in people trained to examine fish health at a population, community or ecosystem level. Increased ability to train highly qualified individuals and to forge interdisciplinary working groups was seen to be a priority to facilitate transition to a new concept of fish health. In addition, fish disease data are poorly linked with each other or with other potential fish health data. It was emphasized that we need to facilitate inter-institutional cooperation.
- ✍ Non-research field personnel need to be encouraged and provided a system to record unusual observations and to preserve unusual samples.

Step 3: Methods and Measures
- ✍ Significant efforts need to be directed towards improving the tools needed to classify and track the health of fish populations. This includes clinical epidemiology (diagnostic and other tests), population sampling (counts of live, dead and moribund fish at all life-stages, size-structure, etc.) and health informatics.

Step 4: Descriptions
- ✍ A fish health status report will be a priority to allow us to develop evidence-based priorities for research and management of health issues affecting fish. Basic descriptions of the health of stocks and the status of risk factors threatening health will be an essential foundation for effective research and management.

Step5: Hypotheses
- ✍ Arising from sound surveillance and description based on validated measures will be prioritized and testable hypotheses.

While this list of steps is hierarchical, it was acknowledged that some of these steps could and should be concurrent. However, strong efforts should be directed towards the first four steps in the next five years, with a transition to increased focus on the final step after that.

At the end of the workshop, participants were asked to give the title of proposals they would like to see coming though for funding. This discussion was revealing for two reasons. First, it demonstrated that, even after two days of concluding that an ecological approach to health was needed, people still wanted answers about today's specific disease issues. Therefore, it could be proposed that research and management have two arms, one that develops intellectual tools, and the other that responds to problems. There is a long history of such an approach in veterinary colleges that have academic researchers housed together with individuals who respond to health needs and develop problem-based solutions on a best-evidence basis. Second, it emphasized how many of these questions could not be addressed until better field research methods were developed. The questions/issues identified are paraphrased below.

1. Nutritional determinants of health
    a. Role of lipids in determining and predicting health status
    b. Role of thiaminase producing organisms in Great Lakes ecosystems
    c. What changes in nutrient cycles have zebra mussels caused?
    d. Modeling the outcomes in shifts in nutrient stores due to invaders
    e. What is the relation of parental nutrition to reproductive success?
2. Disease ecology
    a. What is the nature and significance of differences in susceptibility to specific diseases between different fish species?
    b. What is the source of *Renibacterium* in the whitefish subfamily?
    c. How do fish stocked disease-free become infected with *Renibacterium*?
    d. What is the role of piscivorous fish in the transmission of fish diseases?
    e. What are the vectors and movements of Large Mouth Bass virus and heterosporidia?
    f. What are the interactions and dynamics of populations of *Aeromonas salmonicida* and fish populations?
    g. How are diseases transmitted within and between species?
    h. What affects the virulence of IPNV?
3. Surveillance and descriptive epidemiology
    a. What are the geographic ranges of important pathogens?
    b. Can we develop sentinel salmon broodstock as predictive indices of EMS?
    c. What is the species distribution of important pathogens and what do they do?
    d. What are the pathogens and parasites found in the Baltic-Caspian that can be moved in ballast water?
    e. What are the reservoirs of disease agents in lake ecology?
    f. What is the nature of gonad development of fish influenced by sewage outflow (estrogen mimics issue)?
4. Testing and Sampling
    a. EED diagnostic tool
    b. Can non-lethal methods for sampling for *Renibacterium* be developed?
    c. Development and application of sampling and testing wild fish (field methods).
    d. Statistical sampling approaches for wild fish pathogens.
    e. What is the fate of hatchery released fish post-stocking in the lakes?
5. Disease Control
    a. When should salmonids not be moved past barriers (from a disease perspective)?
    b. Do the supposed advantages of broodstock culling for *Renibacterium* outweigh possible genetic losses?
    c. Can immunostimulants be protective against BKD in hatcheries?
    d. Does vaccination in hatcheries increase pathogen virulence?
    e. Controlling parasites in the Great Lakes: Why isn't Whirling Disease a problem here?
6. Disease causation and impacts
    a. Cancers versus colds – How to differentiate diseases that are themselves a big concern versus those that simply reveal underlying stressors
    b. Stress mediated diseases
    c. What are the impacts of energy pathways on BKD transmission?

d. What are the nitrate levels in the Great Lakes and how do they influence fish health?
e. What are the causes of natural mortality and how do we accurately estimate the amount of mortality – natural and otherwise – in wild fish?

section 3 - recommendations

✍ developing a conceptual framework for an ecological approach to fish health

We are advocating that research has to move towards a health rather than disease model. Yet, we have spent the majority of this report talking about disease. Why? First, there has been little attention spent on thinking and writing about fish health as we have described it. Second, disease is an ongoing and pervasive concern of Great Lakes fish managers and cannot be ignored. But, perhaps most importantly, an examination of disease has allowed us to identify and explore the key issues that confront us when trying to move from the current approach to an ecological approach to fish health. Thinking about disease has served as a bridge.

One cannot study the causes and impacts of disease in wild fish without examining them within a social, ecological and population context, just like one cannot address fisheries management problems through a single-species approach (Jones and Taylor, 1999). A fundamental principle of epidemiology is that optimal animal production decisions are likely to be those based on an objective and holistic analysis that is embedded in a systems approach (Martin *et al*, 1987). Indeed, the Joint Strategic Plan for Great Lake Fisheries conflicts, on the surface, with the historical approach to fish disease that has tended to be unicausal rather than multicausal; the latter approach being one of the pillars of ecosystem sciences.

Increasingly, fish health researchers are developing ecological concepts of causation. For example, the GLFC concluded that a dramatic increase in Chinook mortality due to bacterial kidney disease should be “considered the result of an ecosystem imbalance rather than the ‘fault’ of any one pathogen” (Koonce, 1995). As in any other disease system, the laboratory and single-species/single-pathogen approach is good for identifying pathological and microbiological mechanisms of disease, but is less well suited to uncovering how various elements interact to affect the distribution of disease or its contribution to population health. Johnson *et al* (1998), for example, concluded that the direct effects of contaminants observed in the laboratory could be modulated in the natural environment by indirect effects on the community that interacts with the fish of interest. Similar to our conclusions, Bakke and Harris (1998) stated that it was “very clear that the study of disease in wild salmon populations is in its infancy” and that, while {biomedical} viewpoints are well represented in the literature, an ecological focus on salmonid diseases is almost entirely lacking.” Management decisions are, therefore, not being made on informed predictions regarding the epidemiological consequences of specific fish management decisions (Bakke and Harris, 1998).

Factors underlying the emergence of disease in human and animal populations are predominantly ecological, with many being derived from anthropogenic environmental changes (Daszak *et al*, 2001). This conclusion is not reflected in the historical approach to fish health. This paper has highlighted the imbalance that has occurred in previous fish health research, in that the principle focus has been on identifying pathophysiological and etiological processes that effect the manifestation of disease in individual fish, rather than a more comprehensive understanding of the social and ecological processes that affect the distribution and abundance of disease as well as influence the health of wild fish populations. Moving beyond the historical approach to fish health will require strong interactions and collaborations between different disciplines, crossing boundaries between reductionist sciences, an ecological perspective, and social and management needs.

An **ecological approach** to fish health can be defined as an *approach that considers the biotic and abiotic factors that influence the capacity of different populations to meet social and ecological expectations as well as those that affect the distribution and abundance of disease in fishes*. One of the reasons that an ecological approach has not emerged in great strength is because of the lack of the application of a health model in fish research. This has lead to a separation of disease specialists and population specialists. The need for an ecological approach perhaps derives from the inability of the historical approach to fish health to provide fisheries managers with the information needed to anticipate and/or manage disease outbreaks and threats to the safety of lake food products, or to understand how lake management actions impact the well-being of Great Lake stocks. This inability to predict is not unique to fish health, but is common across many health fields. Typically, we are restricted to reacting to new problems rather than predicting and preventing them (Eckardt, 1994). Application of epidemiological, social and ecological tools have increased our capacity to identify key determinants of health in human and animal populations and thus structure management plans that allow for a prevention rather than reaction model. Therefore, it can be anticipated that a similar approach would yield similar benefits for fish health.

The adoption of an ecological approach does not argue for the abandonment of the efforts dedicated to preventing, controlling and, as required, eradicating infectious diseases. As long as fish culture is part of the stock management program for the Great Lakes, it will be essential to continue to develop methods to detect and control infectious and parasitic diseases in culture facilities. Significant financial waste can occur when considerable portions of cultured stocks are lost due to disease. Moreover, it is a reasonable precautionary approach to assume that it is undesirable to introduce infectious or diseased fish as part of re-stocking programs even in the absence of information telling us that those diseases have a negative ecological impact. The adoption of an ecological approach also does not argue in favour of irreconcilable complexity. The relationships between health, disease, ecosystems and social system are infinitely complex. Concerns have been voiced that an ecosystem approach based on complexity and multiple causation can limit the capacity to react to threats to the Great Lakes as reliance on complexity prevents one from attributing specific cause-effect relationships to specific manageable variables (Gilbertson, 1996). In our opinion, any health program must be problem solving oriented. Understanding how changes in one component will affect the health and disease status of a particular group of fish will require an integrated approach to problem solving. While the concepts of multiple causation allow us to gain a better understanding of how social, ecological and management changes affect fish health, they should focus on finding key determinants; those factors that can be manipulated in order to ensure populations are meeting expectations and health goals (Martin *et al*, 1987). Adopting an ecological approach will not require the development of a new research paradigm or the creation of a new theoretical framework for research. However, a new conceptual framework will be required.

Six principles emerged from our efforts (Table 4). These principles reflect the desire and scientific justification for evolving the direction of fish health research and management from its current focus on disease eradication or control to one that seeks to promote healthy fish populations and sustainable fish ecosystems.

Table 4 – Guiding principles of fish health research development
1. Health is not characterized solely as a state of an individual living in the absence of disease
2. Fish health is reflected in the capacity of an individual fish, population and community to adapt to, respond to, and meet life's challenges as well as meet our social and ecological expectations.
3. Fish health is everyone's business and not relegated to a small sub-set of disciplines. Rather, it requires a multi-disciplinary and integrated approach.
4. Most indicators of fish health reflect population functions. Furthermore, population dynamics play a key role in affecting fish health and disease. Hence, a population approach to health is necessary.
5. Disease management will remain a priority activity for all situations where cultured fishes play an ecologically or economically significant role.
6. Managing health and disease in populations requires reliable indicators of health, knowledge of how the complex interactions of biotic, abiotic and social factors affect a fishes ability to survive, grow and reproduce, and the ability to determine which risks to health warrant intervention.

✍ a population health approach

A population health approach focuses on factors and conditions that influence the health of populations at all stages of an individual's life. It identifies systematic variations in their patterns of occurrence of deviations from health and the determinants thereof, and applies this knowledge to develop and implement policies and actions aimed at improving and maintaining healthy populations. It addresses the range of individual and collective factors that influence health. We can utilize developments made in other species to identify the key components of a population health program.

<u>key components of a population health program</u>

(adapted from Anon, 2001)

1. Focus on the health of populations
    a. This acknowledges that diseased individuals can be present in healthy populations and that sick populations may not be suffering from disease.

   b. It also shifts us towards measures of productivity and abundance, rather than infections and disease, as key indicators of health
2. Examine the determinants of disease and their interactions with each other, especially anthropogenic variables
   a. A determinant of health is any variable – a specific agent, a host factor, an environmental factor – that directly or indirectly alters the state of health. Identifying determinants is, therefore, dependent on your definition and measurements of health
3. Base decisions on a best-evidence approach
   a. This requires proper classification of the health, disease and risk status of populations of interest and importance as well as the capacity to integrate information from different disciplines.
4. Work collaboratively across disciplines and agencies
   a. This is essential if one is going to try to best characterize fish health as well as untangle multiple effects of the web of determinants present under natural settings. It requires recognition of the multi-factoral determinants of health.
5. Work “upstream”
   a. Efforts need to be directed towards finding causes for deviations from optimal health rather than reacting to dramatic events of disease.
6. Utilize measurable health outcomes to gauge success of research conclusions and management interventions
   a. An ongoing and systematic monitoring of fish health is required to detect changes and to identify successful strategies.

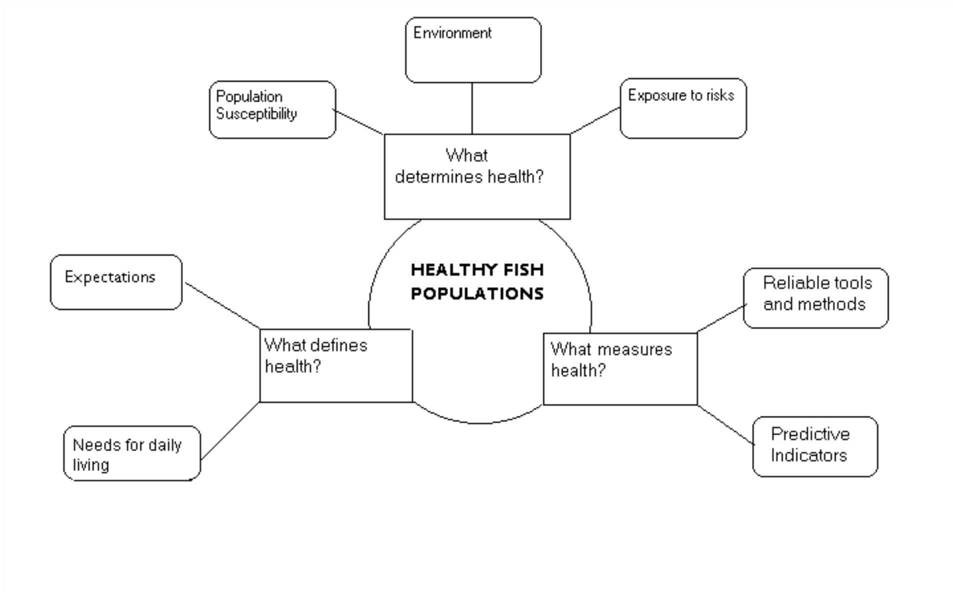
The first step in the evolution of a new framework is to emphasize health rather than disease as the primary focus of research and management. It is important to ensure that the shift to a health focus is not simply a new guise for the old disease focus. To be health-oriented, we need to spend some time understanding what health is. We are advocating an evolution towards a population health approach. Shifting fish disease to an ecosystem health model is both premature and unlikely to form a working bridge between the current individual disease model and the goals of ecosystem management.

Figure 1 establishes the fundamental principles and action points for a population approach to fish health. An important consideration is that none of these elements act in isolation. For example, measures of health status must be linked to measures of the determinants of health to see how they interact.

✍ recommended directions for fish health research in the Great Lakes

In the course of this project, we were made aware of many important questions about wild fish disease that require etiologic research. Critical management decisions are having to be made in the absence of adequate information. However, while it is tempting to summarize the results of this project by listing a series of specific research questions such as, “does stocking non-native fish infected with *Renibacterium* increase the risk for BKD in indigenous fish populations or what is the cause of whitefish die-offs in Lake Ontario” or “do thiaminase-producing bacteria contribute to early mortality syndrome” such an approach would be unlikely to serve as a sound foundation for an ecological approach to fish health. Too often, such an approach, whether in fisheries or other

Figure 1. Key Elements of a Population Health Approach to Fish Health



sectors, provides only brief encouragement of new approaches to old problems, but fails to build new ways of thinking or long-term capacity. Therefore, we strongly advocate that the GLFC seize this opportunity to lay the foundation for a population-based approach to fish health that will serve as a transition and link between the current system of fish disease management and the desired comprehensive and ecological approach to fisheries management.

Funding for future fish health research should be hierarchical in that it should move through a series of overlapping steps over a 10-15 year timeframe. The first phase of research funding should encourage the transition to a population approach to health. Preliminary efforts should encourage "thinking." The transition towards interdisciplinary methods demanded by an ecological approach will require educational support and discussions that would facilitate new ways of thinking about how health and management are related as well as how to "borrow and adapt" methods from different disciplines to solve some fish health problems. This phase includes capacity building. There is currently an important deficit of people trained to examine fish health at a population, community or ecosystem level. Increased ability to train highly qualified individuals and to forge interdisciplinary working groups should be seen as a priority and long-term investment in the transition to an ecological model of fish health. In addition, fish disease data are poorly linked with each other or with other potential fish health data. Significant efforts need to be directed towards improving the tools needed to classify and track the health of fish populations. This includes clinical epidemiology, population sampling and health informatics. Therefore, early efforts must focus on developing and evaluating population health methods. The second phase of research should be largely descriptive in nature. While it may seem self-evident that evidence-based priorities for research and management of health issues requires evidence, we have a very poor empirical understanding of the nature of health in Great Lakes fishes. Basic descriptions of the health of stocks and the status of risk factors threatening health will be an essential foundation for effective research and management. The third phase of the research plan, hypothesis driven population-health research, will naturally arise from the other phases. Sound surveillance and description based on validated measures will help to prioritize testable hypotheses. We have, therefore, chosen, to focus on issues that are critical to the first and second phases of research funding in the recommended research themes presented in the following section.

research themes

The six principles and six components of the population health approach outlined above form the foundation for identifying research themes.

theme 1: health status indicators

"An indicator is a sign or signal that relays a complex message, potentially from numerous sources, in a simplified and useful manner." [4] A health indicator is a measurement that, when compared to a desired level, provides information regarding a health outcome or important health determinant. A population health approach recognizes that any analysis of the health of the population must extend beyond an assessment of traditional health status indicators like death, disease and disability. However, the current state-of-the-art greatly limits our ability to measure even these variables in a wild setting and restricts some aspects of their measurement in cultured settings. There are other available parameters that have traditionally not been used for fish health assessments such as measures of growth, survival, and reproduction that must be considered as key components of health assessments if we are to move beyond a disease focussed, reactive model of fish health research. Health indices can also measure risks to health. Distribution and abundance of pathogens and parasites, contaminant levels, food chain alterations, water temperature, habitat loss and other such factors all impinge on fish health and should be incorporated into health indices. The challenge is to identify indicators that (1) represent the populations or communities of concern; (2) are measurable and reliable; (3) are timely and predictive and (4) are meaningful. Health indicators must allow for comparison across very different issues to help managers make rational choices about competing priorities for action and research.

One of the challenges of a population health approach is to move from a generic holistic definition of health to a definition that facilitates management decisions. Developing operational definitions of health is difficult for a variety of reasons. Fish populations exist within a macro environment that has many social and ecological dimensions that can influence health. Single endpoints are increasingly being seen as insufficient to describe population health impacts. For example, Hartwell *et al* (1992) noted that the risk from any single toxin would be the result of an amalgamation of stresses because: (1) many spatial scales of exposure are involved; (2) many different types of hazards can occur due to the exposure of a wide variety of organisms; and (3) there are many different modes of action of a toxin with an ecosystem. Assigning a single value to the "risk to the environment" therefore, does not give decision makers any information on the variety of

[4] (http://www.epa.gov/bioindicators/html/about.html).

responses and the relative priority of their effects. Our limited understanding of what makes and keeps populations healthy makes it difficult to identify and weigh appropriate measurements in order to collapse them into indices of fish health. We will be required to identify and use indicators of health and risk that are reliably predictive and timely enough to allow us to act in time to prevent degradation of fish health. Without being able to determine who/what is at risk, “acceptable” levels of risk or changes in performance cannot be decided and relevant measurement endpoints cannot be developed. An important part of population health is ongoing research to strengthen our understanding of what is required and desired of a population so as to identify achievable health targets that are sustainable. Baseline data collection, and target and threshold setting are important aspects of the population health approach. Without targets, expectations and policy direction can be vague. Without thresholds, actions cannot be evoked in a consistent and evidence-based fashion.

Research has shown that setting health targets can be difficult (Anon 2001b). The task of defining health goals cannot be uncoupled from efforts to determine what is reasonable to be expected given existing social and ecological constraints. Two key problems that will be encountered when moving from a disease to a health model is defining what is normal and finding ways to reconcile differing values, opportunities and constraints. Effective evaluation programs promote population health by helping to correct and adjust goals and targets, and by providing a rationale to adjust programs and policies. There will need to be surveillance, monitoring and research to determine if or how well a program or policy is meeting fish health goals as well as ongoing impact evaluation to measure immediate results of a program or policy. Researchers should be encouraged to develop methods for evaluation that consider social and ecological issues together, rather than separately examining different impacts on different aspects of health. Specific methods for health impact assessment can be adapted to Great Lakes fisheries management as a means to link health research and management to other aspects of fisheries and habitat management.

Three main research questions address this theme:

1. Can we develop a shared vision of health that will be acceptable to stakeholders and can be reported regularly, comprehensively and systematically?
2. Can we empirically derive a manageable number of measurable indicators, which are simple, yet adequately represent major categories of fish health determinants and measures?
3. Can this core set of indicators be used to detect or model the direct or indirect influences of determinant variables (especially management decisions) on fish population health outcomes?

Answering these questions will require that a series of constraints be removed.

Constraint #1 - Lack of a shared vision of fish health that crosses jurisdictions and disciplines yet is scientifically and socially defendable.

Enormous quantities of data are available and are becoming increasingly easy to access due to information technology. However, it is inadvisable to allow data accessibility to determine health indicators. Instead, it is advisable to first set objectives and priorities and then seek data to address those issues.

Question 1: Can shared goals and expectations for fish health be developed across agencies and across species?

- ✍ Project examples
    - o Application of participatory research methods to develop consensus on fish health goals, differentiating core indicators from recommended or optional indicators.
    - o Enhancing capacity, understanding and acceptance of a population health approach through basin wide extension and education.

Question 2: What data are available for use as indicators?

- ✍ Project examples
    - o Inventory of fish health data in the Great Lakes Basin with an emphasis on assessment of data quality, scale and availability over time and between jurisdictions.
    - o What data gaps prevent us from meeting the monitoring and assessment needs as required by shared fish health goals?
    - o Which species or locations have the features required for ongoing, systematic monitoring and for integrating various measures of health?
    - o Development of health informatics tools for ongoing acquisition and integration of multi-discipline and multi-agency fish health data

Question 3: How do we initially screen candidate indices for their usefulness?

- ✍ Project examples
    - o Retrospective analysis of Great Lakes fisheries data and fish disease data using methods such as path analysis or principle components analysis to identify key indicators that could contribute to population health profiles and in establishing criteria for indicator selection.
    - o Adapting existing criteria for indicator assessment for fish health by developing a set of evaluation criteria such as: is the indicator a reasonable measure, does the measure behave in an expected way, does the measure predict risks to or changes in health, and do selected measures collected in different ways lead to similar interpretations?

Constraint #2 – Lack of understanding of how the determinants of health operate in the Great Lakes

In human health, the leading indicators of health can be grouped into 4 main categories:

1. Fitness
2. Exposure to situations or substances that are known to result in disease
3. Environmental quality
4. Access to situations or substances that promote health and allow individuals to meet expectations

Extrapolation of these broad categories helps to categorize several measures that must be included in a fish health program such as:

1. Fitness (e.g. mortality rates, growth, fecundity, age-structure)
2. Exposure to hazardous substances/situations (e.g. toxic substance distribution, introductions of exotic pathogens and parasites).
3. Environmental quality (e.g. habitat quantity and quality, water quality; food quality and quantity)
4. Health promotion (e.g. fisheries pressures, size distribution, hatchery management)

While there may eventually be an extensive list of health determinants identified for Great Lake fishes, determinants of priority to stakeholders include (1) the effects of disease on mortality and recruitment; (2) the effects of exotic invaders on food web relationships and disease ecology; (3) the role of nutrient balance and availability of survival, growth and reproductive success and (4) stocking practices. Prior to generating hypothesis-based health determinants research, it will be important to first describe the basic ecology of important determinants.

Question 1: What is the descriptive ecology of significant pathogens and parasites of concern in Great Lakes fish populations?

- ✍ Project examples
    - o What is the spatial, temporal, species and age distribution of key pathogens such as *Renibacterium salmoninarum, Aeromonas salmonicida,* Y*ersinia ruckerii,* infectious pancreatic necrosis virus, large mouth bass virus and *Heterosporis* spp. in cultured and free-ranging fishes?
    - o What is the degree of “sharing “ of pathogen sub-populations between wild and enhanced fishes?

Question 2: What is the spatial and temporal variation in nutritional status of ecologically and/or economically important fish in the Great Lakes?

- ✍ Project examples
    - o What is the distribution of thiaminase producing bacteria in Great Lakes forage fish?
    - o How do energy stores in fish vary by species, life-stage, season and location?

Question 3: What aspects of the distribution and invasion ecology of exotic and introduced species present the largest health risks to Great Lake fish stocks?

- ✍ Project examples
    - o Health risk assessment of existing introduced species, with an emphasis on ranking species in terms of their capacity to impact key determinants of indigenous species health.

Question 4: Is there systematic variation in environmental quality and fish health on a macro and micro-scale?

- ✍ Project examples
    - o Modeling the relationship between shifts in nutrient stores and temporal variation in survival, disease outcomes and early larval death.

- o Correlation of contaminant loads and population manifestation of *Renibacterium salmoninarum* or other key pathogens in enhanced stocks.

Constraint #3 – Lack of validated measurement tools to derive data to be used in indicator development

See Theme 2 below

theme 2: methods and measurements

Arising from the first theme is the question; can we reliably and repeatedly measure the core variables that make up health indicators so we can confidently track the state of lake fish health? Population-health surveillance systems include information on health outcomes (e.g. fitness, fecundity, harvest sustainability); epidemiological data (e.g. death, disease, disability); risk data (e.g. distribution of pathogens and contaminants; habitat alteration; exotics introduction); socio-economic data (e.g. fisheries pressure; competing resource use; fish flesh contamination) and health management data (e.g. disease control outcomes). To select rational priorities and interventions and to assess the effects of your actions, it is necessary to have consistent and reliable tools and methods to measure population health variables over time and throughout all stages of lifecycles.

One model that can be used to predict the risk of a particular management action is historical consistency: what happened yesterday is likely to happen today given similar conditions. There is no ongoing, systematic, cross-species program dedicated to collecting, archiving, and synthesizing and interpreting information on Great Lakes fish health and disease, thus, we really don't empirically know what happened yesterday. Estimating the probabilities and outcomes of events that flow from the initiation of a management decision to their final outcomes can be undertaken to assess risks in the absence of historical data. In this case, probabilities and outcomes may be generated through analogy or prospective research. If there is still insufficient information, it seems reasonable to question our ability to assess the health risks of certain management options.

Health surveillance has evolved from counting the number of dead individuals to tracking the number of sick to identifying trends in factors that put population health at risk. Historically, measurement endpoints have been selected because of convenience rather than their usefulness. This is one reason disease, deformity and premature death have been standard surveillance measures. They are often obvious outcomes that have readily measurable features. However, these outcomes may not best reflect the impacts of disease causing agents as they underestimate the impacts of disease on individual and population performance and are "terminal" endpoints rather than measures of risk. An important impediment to understanding disease processes in fish populations is the lack of methods for following the progress of infection and disease within individual fish. Most diagnostic methods used in fish require one to euthanize the animal. This precludes the opportunity to follow the progress of a disease within an individual and limits our ability to recognize subclinical effects. The lack of non-lethal methodologies coupled with an absence of validated methods for tracking the dynamics of hosts and parasite populations greatly reduce our ability to generate sufficient data to make models that allow accurate prediction of cause-effect relations between management actions and fish health outcomes.

A radically holistic view of fish health could not exclude any variable from its measurement program due to the interconnectedness of fish health with all aspects of their environment. However, pragmatic matters preclude such an all-encompassing approach. Instead, surveillance of the ecological determinants of fish health must focus on activities, resources or features that are important to the local fish populations and that can be influenced by management. This may not be feasible yet for fish due to our limited understanding of the relationship between environmental alterations and health impacts Yet, this should not restrict us to surveillance only of changing patterns of disease? The selection of the appropriate surveillance measurements will be linked to the goals established for fish health. However, they will also be based on ongoing evaluation regarding their predictive value as well as on research intended to identify important determinants of health. These steps will help us to identify effective surveillance measurements (those that can predict adverse outcomes). Ongoing research and evaluation will be needed to determine not only which measures are reliable predictors of outcomes of interest, but also which ones generate the required information in a manner that allows for actions to prevent or mitigate observed anticipated effects.

Two elements affect the reliability of a health surveillance system: (1) the capacity to correctly identify the status of individuals and (2) the ability to collect a sample of the unit of concern in a manner that reflects the true distribution of characteristics in that unit. Substantial efforts are being or are planned on being directed towards surveillance of fish disease in Canada and the United States. However, there remain some very important methodological questions that must be addressed before the results of these efforts can be integrated into a program intended to link fish health and ecosystem management. These questions fall into two broad categories. First, are the sampling methods capable of describing the distribution and abundance of the health outcome of concern among relevant fish communities? Second, is the health outcome measured meaningful and useful?

The fundamental questions associated with this theme are:

1. How can we sample and examine wild and cultured populations in a way that provides a representative, reliable and informative picture of health?
2. How can we collect and integrate a variety of information that will allow us to establish what is considered normal or desirable, and thus, help set thresholds for management interventions?
3. How do we take issues of multiple causation into account when developing measurement tools?

Constraint #1 – Problems in following population health over time

Most sampling for fish health has been opportunistic. Few of the existing sampling methods or programs can examine the distribution of a disease through all life-stages or populations within a fish community let alone examine trends in health determinants. A convenience sample of fish taken at a given time and focusing only on commercially important species has been the backbone of many fish disease surveys. Moreover, many surveys have focused on seeking evidence of infection rather than documenting impacts on fish health. Such an approach is unlikely to fully paint the picture of the ecology of a disease. Fish-parasite relationships have been shown to be affected both by factors acting at small geographic areas (tens of kilometres) and time (weeks to months) as well as larger scale spatial and temporal features (Jones and Taggart, 1998). Limiting ourselves to a single host, spatial or temporal scales will not allow a full elucidation of the important determinants of health in fish populations, thus limiting our ability to uncover the relationship between ecosystem management and fish health. Unfortunately, we will always be limited as to the resources and opportunities we have to examine the infection, disease or health status of wild species. There is a great need for critical examination of the biases associated with specific capture methods as well as an evaluation of new or combinations of methods to ascertain health information from wild populations. This will be an important first step to evolve from opportunistic sampling to evidence-based sampling.

Question 1- Are population field sampling methods capable of describing the distribution and abundance of the health outcome of concern among relevant fish communities?

- Project examples
  - Statistical sampling approaches for wild fish pathogens.
  - Application of new telemetry and acoustic technology to follow the fate of hatchery released fish.
  - Is there systematic variation in the evaluation of population health with different sampling methods?

Question 2- How does the health status of a fish affect its probability of capture using current field sampling methods?

- Project examples
  - Comparison of individual and population health indices for species captured by different methods and in different niches.
  - Mesocosm experiments examining behavioural changes in fish based on health and disease status.

Question 3 – Which sampling methods can be used for early life stages?

- Project examples
  - Establishing diagnostic techniques for early lifestage mortality
  - Establishing the equivalent of body condition or comparable individual fitness score for larval fishes
  - Comparison of methods for capture and health evaluation of early life stages

Deleted: -

Question 4 – Are there methods capable of following single populations and individual fish over time to establish temporal aspects of cause-effect relationships

- Project examples
  - Application of physiological monitoring equipment to population sampling
  - Development of non-lethal disease tests to be used in mark-recapture projects.

Constraint #2 – Inability to consistently and confidently classify the health status of individuals and groups of fish.

There are two levels to consider when evaluating a measurement tool. The first is the capacity to truly classify the health status of an individual fish. The second is the capacity to correctly classify the status of a group of fish, based on a sample from the group. The latter is termed the “group-level” performance of a diagnostic test and is often the more relevant parameter when making fish health management decisions (Thorburn, 1999). Typically, fish health is managed at a facility, zone or population level. Greiner and Gardner (2000) showed that diagnostic test performance could vary among populations and sub-populations, depending on the distribution of influential covariates such as disease status of the population, age-structure, management history and sampling methods. It is unrealistic to expect that we will ever have precise measures of all tests in all settings; this is elusive in all forms of health research. Therefore, an additional focus of research should be on how to account for uncertainty in diagnostic tests. Smith and Slennin (2000) examined various methods for including uncertainty associated with diagnostic tests in decision analysis using pay-off tables and decision trees. They were able to show how analytical techniques can be used to account for diagnostic uncertainty at both population- and patient-oriented applications.

Question 1- What are the validity and reliability of standards tests used to diagnose fish infection or disease under field conditions?

- Project examples
  - Clinical epidemiology of techniques used to detect *Renibacterium* (or other important pathogens) under field conditions with emphasis on variations between life-stages and species.
  - Inter-and intra-observer variation of diagnostic tests; an assessment intended to reveal sources of inconsistent results
  - Modelling the likelihood and consequences of misclassification of fish health based on existing tests.

Question 2 – Can tests that are currently used predict key outcome(s) in fish?

- Project examples
  - Determining thresholds of lipid levels predictive of reduced fecundity or survival in key Great Lake fish species.
  - Establishing the prevalence of infection with key pathogens that may predict population effects in infected populations, considering contaminant and environmental confounders.
  - Is evidence of infection evidence of future death?

Question 3- Does variation in sub-population characteristics affect the application and interpretation of diagnostic tests?

- Project examples
  - Variation in test performance in different life-stages and species
  - Impact of concurrent infections and contaminants on test performance

Question 4 – Can non-lethal tests enhance the predictive capacity of current methods for classifying health and disease status of fish?

- ✍ Project examples
  - o Development of non-lethal test methodology

Constraint #3 – Lack of systematic integrated surveillance

The current lack of data on significant determinants of outcomes and probabilities arises from two sources. First, there is a lack of ongoing evaluation of population health through surveillance. This often results in decisions being made on a political or short-term economic basis rather than biologically sound risk assessments (Stephen, 2001). Second, we fail to take advantage of the information that is available. Increasingly, surveillance systems in human and agricultural health have discovered the advantages that can be realized through integrating data from several existing sources. Significant applied research on communications, data management and information technology is needed to support this effort.

Question 1 – Can internet-based communication methods be used to regularly collect, centralize and interpret fish health data?

- ✍ Project examples
  - o Application of health informatics technology to fish health data
  - o Development of query-based data storage that integrates ecological and disease information on the same temporal and spatial scales.

Question 2 - Are specific diseases and fish health defined in a consistent manner across jurisdictions in the Great Lakes?

- ✍ Project examples
  - o Estimating the magnitude of misclassification bias that may result from variation in definitions or methods used across jurisdiction
  - o Application of participatory research methods to develop standard case definitions for health outcomes

Question 3 – Do any information collection and management systems meet current requirements for scientifically valid information useful for management purposes?

- ✍ Project examples
  - o Needs assessment of surveillance systems in the Great Lakes

Question 4 - On what spatial and temporal scales should we integrate measures of fish health and ecological variables?

- ✍ Project examples
  - o Variability in stomach contents of lake whitefish in different parts of the Great Lakes and its relationship to local availability of food sources and its correlation with energy stores over time.
  - o Gap analysis of information on movement and migratory patterns of species of interest

Constraint # 4- The variables that would be the most efficient and effective from a surveillance perspective are unknown.

> This constraint is linked to those identified above regarding identification and validation of health indices as well as the theme below on identifying determinants of disease.

theme 3: determinants of disease

Despite a desire to move beyond a disease paradigm of health, the control, eradication and avoidance of disease remains a foundation of fisheries management in the Great lakes. Coordinated regional resources should be available to assist state and local agencies in the identification, assessment, investigation, prevention and control of fish disease under culture and wild settings. These actions should include monitoring and investigating infectious and non- infectious diseases, the field study of their associated risk factors, and the evaluation of related prevention and control programs.

There are a variety of scientific issues that have infringed on our ability to observe the role of disease in wild fishes. Efforts to understand wild fish diseases are complicated by the relative lack of knowledge of the pathophysiology of many wild species (Kent and Fournie, 1993). In addition, most fish health research has been restricted to a limited number of commercially and recreationally important species kept in very homogeneous conditions. Evidence has accumulated to allow us to state that the outcome of exposure to etiological agents will not be the same for all fish. There are a number of examples of pathogens causing lethal disease in one host, but not in another. Experimental work has shown a spectrum of effects from no effect to death in a variety of species exposed experimentally to the same strain of various virulent salmonid pathogens (Kent *et al*, 1998). For example, brown trout are capable of harbouring, without any clinical signs, infectious salmon anemia virus that is lethal to Atlantic salmon (Nylund *et al*, 1995). Different strains of infectious hematopoeitic necrosis virus show different virulence for different fish species (LaPatra *et al*, 1990). The response of different flatfish species to sediment contaminants also reveals species variation (Johnson *et al*, 1998). In addition to innate differences in susceptibility, it is likely that different ecological niches influence susceptibility and result in different exposures to disease agents. However, there is very little information on how differences in life history create epidemiological differences in fish disease. It is not reasonable to assume that all species of fish in a given area are equally at risk to specific disease factors. Efforts to describe the variation in the response to key determinants of disease between different species would assist in the formulation of more informed ecosystem level risk assessments. A foundation to any effort to understand the role of disease in lake fish communities will require good descriptive studies of the ecology of specific diseases.

The next step towards prediction is the association of casual factors with outcomes. There are three ways that this can be accomplished: laboratory experiments, observational studies and theoretical models. Without a doubt, laboratory-based research will be a fundamental component of an ecological approach to fish health. Laboratory experiments provide investigators direct control over many of the conditions of the experiment, and thus allow them to isolate specific pathological mechanisms of disease. Because disease remains an important part of fish culture and fish culture is postulated to have an impact on the health of wild stocks, efforts will have to continue to understand fundamental mechanisms of disease such as pathophysiology (to identify opportunities for treatment) and etiology (to identify opportunities for control via immunization, hygiene or other measures). Moreover, people are increasingly turning to laboratory experiments to describe and quantify the transmission dynamics of fish diseases (Reno, 1998).

One must be cautious in the choice of experimental models used to uncover natural phenomena. The ability to extrapolate laboratory results to natural settings is reduced because of the artificial conditions of laboratory experiments. Laboratory experiments that use specific-pathogen-free animals, single-agent disease models and highly controlled environmental conditions have predominated fish disease research. This has often resulted in erroneous results. When Smith *et al* (2000) attempted to estimate the basic reproductive ratio for infectious pancreatic necrosis virus in trout through laboratory experiments, they found that the fundamental assumptions of the standard experimental approach they employed were invalid and resulted in paradoxical results. Similarly, estimates of the impacts of the salmonid leukemia virus derived from laboratory experiments grossly overestimated their effects on mortality rates of salmonids held under farmed conditions (Stephen and Ribble, 1996). Lessons learned from an examination of furunculosis in wild fish in southwestern Ontario suggest that a single-species model would fail to reveal the true epidemiology of a variety of diseases. In that case, the authors concluded that the practice of disregarding non-commercial species makes it impossible to accurately document the transmission cycle and epidemiology of diseases of commercially important salmonids (Ostland *et al*, 1987) and, thus, would prevent a complete evaluation of opportunities for prevention and control.

Thrusfield (1995) identified the following six features as factors that must be considered before a disease control or eradication campaign is initiated:

1. knowledge about the cause of the disease, its transmission and maintenance, including the host range and nature of the host/parasite relationship
2. veterinary infrastructure
3. diagnostic feasibility
4. adequacy of the surveillance
5. stakeholders' viewpoints
6. impacts/costs of the disease (ecological and economic)

A number of these elements have been addressed in other proposed research themes. However, there has been less emphasis on the first and last point.

The key questions associated with theme #3 are:

1. What is the population ecology of infectious and parasitic diseases of Great lake fishes?
2. How do multiple etiologic agents or causal mechanisms (including anthropogenic variables) affect the manifestation of disease?
3. What is the economic and ecological cost: benefit ratio of disease control programs?

Constraint #1- Lack of knowledge of the transmission dynamics of important fish pathogens in cultured and wild settings

An understanding of the methods by which a pathogen/parasite is introduced, established, maintained and disseminated is basic to an understanding of disease control. A variety of overlapping host/parasite relationships affect transmission dynamics under natural settings. However, most of our understanding of fish disease has been derived from single-species, single-pathogens experiments in laboratory settings. It is unlikely that such studies will reveal all opportunities for intervention to modify disease frequency and impact.

Question 1 – Do existing models of infectious and parasitic disease dynamics apply to wild fish populations?

- ✍ Project examples
    - Theoretical modeling of inter-specific transmission dynamics of key salmonid pathogens
    - Laboratory mesocosm-based experiments manipulating fish and pathogen population dynamics

Question 2 – What are the roles of non-salmonids species in the maintenance and distribution of important salmonid pathogens?

- ✍ Project examples
    - Descriptive epidemiology of multi-species transmission systems for key pathogens and parasites
    - Correlation of specific life history strategies with the prevalence and abundance of key pathogens

Question 3 – How do environmental stressors affect host characteristics in terms of disease susceptibility, period of infectiousness and opportunities to transmit infectious agents?

- ✍ Project examples
    - What are the effects of climate change on disease ecology in the Great Lakes?
    - Physiological mechanisms of contaminant-associated immunomodulation.
    - Modelling the disease impacts of demographic changes associated with stocking practices.
    - What is the impact of contaminant or nutritional associated immunomodulation on the epidemiology of important infectious and parasitic diseases of fish?

Question 4 – How do ecological and anthropogenic selective factors affect key aspects of host-parasite relationships?

- ✍ Project examples
    - Health impacts of genetic selection associated with disease culling of broodstock based on infection status.
    - Role of monoculture and disease control methods (e.g. vaccination) as selection pressures affecting pathogen/parasite infectivity and virulence.

Question 5 - Are different species of fish in the Great Lakes in close enough proximity at susceptible life stages to enable the transmission of key pathogens?

- ✍ Project examples
    - Metapopulation interaction of fish hosts and key pathogens

- o Risk assessment of the removal of fish barriers as a means to enable increased contact between susceptible fish and the transmission of key pathogens or parasites.

Constraint #2- Uncertainty about how population management of hatchery-reared fish affects the epidemiology of disease.

Fluctuating environments and management practices such as handling, crowding, transporting, drug treatments, undernourishment, variable temperatures, and poor water quality continuously affect cultured fish. All of these factors can impose considerable stress on the homeostatic mechanisms of fish affecting their susceptibility to a wide variety of disease-causing agents. There is a dearth of data on the epidemiology of fish diseases in terms of the contribution and interactions of host, agent and environmental factors in the maintenance and dissemination of disease in populations.

There is concern that the methods for managing salmonid enhancement may, in fact, be directly or indirectly affecting disease dynamics under culture and wild conditions. Pathogen magnification and dissemination, genetic effects and susceptibility of competitive interactions have all been hypothesized as mechanisms through which salmonid enhancement can affect diseases in wild stocks. However, there is very little information on how decisions made at enhancement facilities can affect disease manifestation in cultured stocks and risks to wild stocks.

Question 1 – How do we determine if hatchery practices affect the prevalence, abundance and impacts of key fish pathogens?

- ✍ Project ideas
  - o Development of clinical trial methods for cultured fish.
  - o Analysis of inter-agency surveillance data on disease outcomes and hatchery disease management practices
  - o Critical review of international literature on fish population disease control: Needs, gaps and opportunities

Question 2 – What are the abiotic factors limiting disease transmission and manifestation?

- ✍ Project ideas
  - o Impacts of hatchery design on transmission dynamics
  - o Abiotic limits on microbial ecology of key pathogens, including the use of disinfectants and chemotherapeutic agents

Question 3 – How do interactions between released enhanced stocks and wild fishes affect disease transmission and susceptibility?

- ✍ Project examples
  - o Behavioural ecology of released enhanced fish with an emphasis on intra- and inter-specific interactions and on the effects of infection or disease on post-release behaviour.

Question 4 - What is the microbial ecology of key pathogens and parasites?

- ✍ Project examples

- What are the primary strategies for maintenance of pathogens in culture facilities and in wild settings?
- What are the primary mechanisms for extension of the range of disease-causing agents?

Constraint #3 – Lack of capacity to identify high risk groups and conduct comprehensive risk: benefit analysis

Disease control programs need to be well designed from an ecological and economic viewpoint. There has been significant financial commitment to managing specific hatchery associated disease without the benefit of risk: benefit analyses. Each action taken at the hatchery or decisions made regarding fish translocations all result in trade-offs in terms of availability of other economic resources or ecological effects. Fisheries managers and aquaculturists often view disease control policies to be prohibitive and an impediment to reaching management objectives. Fish health managers can, therefore, feel political pressure to modify their plans to reach other management objectives. In the absence of ecologically and economically sound assessments of risks and benefits of disease management actions, such an impression will be hard to dispel.

Question 1: How do we recognize disease problems that are urgent matters?

- ✍ Project examples
  - Case series of disease outbreaks to model predictive factors of economically significant impacts, including costs of disease control.
  - Epidemiological features of diseases or populations predisposed to severe impacts of disease agents
  - To treat, cull, vaccinate or do nothing: predictive models of disease control options for fish reared for stocking.
  - Impacts of contaminants on disease susceptibility: Identifying high-risk groups.

Question 2: What is the best way to compare health benefits and risks with other management objectives?

- ✍ Project examples
  - Methods for integrated health risk assessment
  - Economic analysis of disease and associated control

theme 4 - research development and support

It is unreasonable to assume that the current research capacity, expertise and infrastructure will support new directions in fish health. Therefore, the GLFC is encouraged to dedicate funds each year to support the development of highly qualified individuals, the generation of collaborative research programs and the support needed for regular surveillance and assessment of fish health.

Areas included for funding in this area includes:

1. Fellowships for graduate training in fish population health

2. Pre-planning workshops for groups developing inter-disciplinary research projects
3. Contingency funds to support outbreak investigation unit(s) for the Great Lakes Basin
4. Yearly support for centralized surveillance unit dedicated to acquiring passively generated data and preparing annual fish health report cards.
5. Workshops on “new approaches” such as the development of health indices and methods for integrating disease and ecological data.

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Acknowledgements

The authors would like to acknowledge the important input from the workshop participants as well as the editorial input of Drs. Erin Sifton (Centre for Coastal Health) and Denise Belanger (University of Montreal).