Fish Community Objectives for Lake Superior

Public Discussion Draft

March, 2001

This public discussion draft of the Fish Community Objectives for Lake Superior is prepared pursuant to provisions of *A Joint Strategic Plan for Management of Great Lakes Fisheries* by the Lake Superior Committee, representing Minnesota, Wisconsin, Michigan, Ontario, the Great Lakes Indian Fisheries Commission, and the Chippewa Ottawa Resource Authority.

Preface

> *"The Sacred Shell rose up out of the water and told the people that this was the place they had been searching for. Here, the Waterdrum made its seventh and final stop on the migration. The Sacred Fire was carried here and here it burned brightly.* (The Mishomis Book, Edward Benton-Banai)

Ojibwe teachings tell of the long migration that the Ojibwe people undertook guided by the Sacred Megis Shell to their ultimate destination, Madeline Island in Lake Superior. It was along the shore of Lake Superior that the people found the precious food, manoomin (wild rice), a land of beauty and abundance, and it became their homeland. Today it is the responsibility of all people to protect this great gift and resource, which nourishes us both spiritually and physically.

Those of us that work day-to-day on issues related to Lake Superior probably do not reflect often enough on this unique and magnificent resource. By virtue of its great size and geographic position, Lake Superior creates its own microenvironment, distinctly influencing the flora and fauna that fall within its reach. In the context of nature's beauty, diversity, power, and value, Lake Superior stands alone. As you read of the lake's unparalleled statistics, listen to the lore, and travel its rugged, mostly undeveloped shoreline, it is easy to become captivated. It is also easy to imagine why the Native people and early European explorers so revered and respected this Great Lake.

Although managing Lake Superior fisheries has been, and will continue to be, a challenging endeavor, the ultimate challenge may rest in our ability to preserve the environment on which the fisheries depend. For despite its relative isolation, the lake's great size and pristine nature makes it exceptionally vulnerable to human activities. Restoration and protection of near-shore habitats, achievement and maintenance of water and air quality standards, and rehabilitation of native aquatic species are some of the larger goals which must be pursued to support healthy and stable fish communities. In this respect, achievement of our fish community and habitat objectives will serve as an important measure of our progress toward rehabilitating and protecting this unique and fragile ecosystem.

To achieve our common goal of a healthy Lake Superior, cooperative action among governments, interest groups, and concerned citizens from many disciplines will be required. If we are successful, future revisions of Fish Community Objectives for Lake Superior will largely reflect a desire to simply maintain and preserve the existing fish community and the environment on which it depends.

Table of Contents

Introduction

The Lake Superior fish community and our knowledge regarding its structure and function have changed substantially over the past decade. Recognizing this caveat [the word this by itself is vague], and recognizing the central importance of habitat protection, the Lake Superior fishery management agencies initiated an effort to update their vision for the Lake Superior fish community. This document is a product of that effort. It replaces the original *Fish Community Objectives for Lake Superior* (Busiahn 1990).

Changes in the Lake Superior fish community and our knowledge of the lake converge around three themes. First, the fish community is reverting to a more natural state, resembling historical conditions, requiring less management intervention and control. Second, success in rehabilitating lake trout and the recovery of many lake herring populations have allowed management attention to shift toward depleted species in embayment and tributary habitats, which are more likely to be limited by quantity and quality of habitat. Third, the fish community has been permanently altered by non-indigenous nuisance species, and remains at risk from further introductions. For example, progress in restoring the lake and its native species rests upon successful control of sea lampreys, which requires continuous, expensive intervention by managers. This document reflects these themes in its emphasis on natural reproduction, habitat protection, and prevention of additional introductions of non-indigenous species.

The development of fish community objectives for each of the Great Lakes is mandated in *A Joint Strategic Plan for Management of Great Lakes Fisheries* (Great Lakes Fishery Commission 1997). That document (referred to here as the Strategic Plan) was adopted in 1981 and revised in 1986 and 1997. It represents a commitment to cooperative management on the Great Lakes by all state, federal, tribal, and provincial agencies involved in the management of Great Lakes fisheries. As required by the Strategic Plan, these fish community objectives have been adopted by consensus of the Lake Superior Committee (LSC), representing the Wisconsin Department of Natural Resources, the Michigan Department of Natural Resources, the Minnesota Department of Natural Resources, the Ontario Ministry of Natural Resources, the Chippewa Ottawa Resource Authority, and the Great Lakes Indian Fish and Wildlife Commission.

This document reflects the "Ecosystem Approach to Fisheries Management Strategy" articulated in the Strategic Plan:

> *The Parties must exercise their full authority and influence in every available arena to meet the biological, chemical, and physical needs of desired fish communities*

This concept was added to the Strategic Plan in 1997 in recognition of the fact that actions outside the immediate control of the agencies represented on the LSC can have profound impacts on fish communities. The revised Strategic Plan called for the establishment of an ongoing dialogue between Lake Committees and the various environmental agencies. This document acknowledges the ecosystem approach strategy by specifically addressing habitat and water quality issues, and by promoting coordination with the Binational Program to Restore and Protect the Lake Superior Basin (Lake Superior Binational Program 1998).

This document is intended to provide a framework for future decision-making. It is not a management plan. Specific management strategies developed to meet the various objectives identified here will be determined within each management jurisdiction by agencies working with interested citizens. The vast array of biological, political, and socio-economic issues involved in the management of a complex ecosystem like Lake Superior makes consensus-based management challenging. In addition, an incomplete understanding of the Lake Superior ecosystem, coupled with the likelihood that the fish community will continue to change, makes predicting the fish community's response to various management actions imperfect and, sometimes, contentious. This document will assist the agencies and the interested public to develop management strategies by promoting a common understanding on how the Lake Superior ecosystem functions and, as well, by providing a unified direction to guide many management practices. This document will also serve as a mechanism to focus attention on the major issues facing Lake Superior fisheries and to communicate those priority issues to the governments, stakeholders, and the general public. This document is intended to be viewed in its entirety; much of the rational used in formulating the individual objectives is woven throughout the document.

As an expression of our increased knowledge and experience with lakewide fisheries management, *Fish Community Objectives for Lake Superior – 2000* represents a timely evolution from the original version. In recent years, agency biologists have jointly developed comprehensive research and assessment strategies, data exchange protocols, and cooperative planning processes. These advances will provide better measures to gauge progress toward achievement of the objectives, and help refine the objectives in the future. Recent efforts to coordinate with environmental organizations have also been fruitful, further encouraging fishery and environmental interests to work toward a healthy and productive Lake Superior. While this document represents current expectations and desires for the Lake Superior fish community, we anticipate future revisions will be needed as the fish community changes or as new information becomes available. Comprehensive reports on progress toward achieving the objectives (state-of-the-lake) will be given at 5-year intervals.

Description of Lake Superior

Although Lake Superior is the least altered of the Great Lakes, the fish community, fish habitats, and the surrounding watershed have been significantly altered. Management actions have restored lake trout and suppressed sea lampreys, and today important sport and commercial fisheries are active in all jurisdictions, but many challenges remain.

Physical characteristics

Lake Superior is large and its waters are clear, cold, and unproductive. It has the largest surface area of any lake in the world, water transparency can reach 23 m, and the mean annual water temperature of approximately 3.6^{o} C is the lowest among the Great Lakes (Bennet 1978). Its high water clarity reflects extremely low biological productivity (Vollenweider et al. 1974), which is a consequence of low water temperatures, low levels of organic pollution, a narrow littoral zone, and low levels of dissolved minerals. Most of Lake Superior's relatively small drainage area is composed of igneous rock that is resistant to weathering, so only small quantities of minerals are dissolved into the incoming stream flow. The mineral composition of the water is similar to rainwater (Matheson and Munawar 1978), and has remained relatively constant for the past 80 years.

Table 1. Physical attributes of Lake Superior (Anonymous 1995)

Length	563 km
Breadth	257 km
Average depth	147 m
Maximum depth	406 m
Volume	12,000 km^3
Surface area	82,100 km^2
Drainage area	127,700 km^2
Shoreline length (including islands)	4,385 km
Elevation	183 m
Outlet	St. Marys River (to Lake Huron)
Retention/replacement time	191 years

The geological and climatic factors that have created this unique water body have also helped to preserve it. Because of the cool climate and poor soils, most of the basin is sparsely populated and heavily forested, with little agriculture, and Lake Superior has not suffered from high nutrient loadings or industrial pollution to the same extent as the other Great Lakes.

Ecological structure of the fish community

The fish community of Lake Superior occupies three major trophic levels each having its own species complex (Table 2). Energy captured from sunlight by phytoplankton flows upward from one trophic level through a complex food web. In general, biomass production decreases approximately 10-fold from a lower trophic level to the next higher level. The most sought-after sport fishes of Lake Superior - lake trout and Pacific salmon - are top-level predators, and therefore represent only a small part of the Lake's energy production.

Table 2. Ecological roles of important Lake Superior fish species

Ecological role as adults	Species
planktivore - diet predominantly zooplankton or phytoplankton	lake herring
	bloater
	rainbow smelt (non-native)
benthivore - diet predominantly macro invertebrates	kiyi
	lake whitefish
	brook trout
	ninespine stickleback
	slimy sculpin
	deepwater sculpin
	lake sturgeon
piscivore - diet predominantly fish	sea lamprey (non-native)
	coho salmon (non-native)
	chinook salmon (non-native)
	lake trout
	rainbow trout (non-native)
	brown trout (non-native)
	burbot
	walleye

The low productivity of Lake Superior, in comparison with the other Great Lakes, is reflected in its lower primary production estimates and historical fish yields (Table 3). Therefore, expected fish yields from the current fish communities will be much lower for Lake Superior than for the other Great Lakes. During 1916-40, a period of high and stable fish yields, Lake Superior produced an average annual yield of 0.8 pounds per acre, which is probably near or above the maximum sustainable level. Current annual yield is about 0.4 pounds per acre, reflecting lower catches of lake herring, which dominated historical yields.

Table 3. Primary production estimates (Vollenweider et al. 1974) and average annual fish yields during the 15 year period of maximum commercial harvest Matuszek 1978, Baldwin et al. 1979 in the Great Lakes.

	Primary production ($g/m^2/yr$)	Fish yield (g/h)
Lake Erie	240-250	9710
Lake Ontario	180-190	1240
Lake Michigan	140-150	2230
Lake Huron	80-90	2090
Lake Superior	40-50	1190

Changes in the Fish Community

Lake Superior is the least altered of the Great Lakes, and yet the lake, its watershed, and its fishery have been significantly degraded. Recovery has been incomplete. The following describes Lake Superior and its fisheries at two points in the past, and compares these descriptions to current conditions.

Prior to European settlement

Prior to the mid-1800s, the fish community of Lake Superior had evolved for nearly 10,000 years since deglaciation. The indigenous fish community of the lake and its tributaries included over 70 species, some with unique locally adapted forms. At the time of European settlement, lake trout, the top predator, were present throughout the lake over a wide range of depths. Especially prominent were two deepwater forms of the lake trout called humpers and siscowets. Lake whitefish primarily occupied water less than 100 m deep, a small part of the total surface area. Planktivorous species such as lake herring and deepwater ciscoes (*Corregonus* spp.) occupied most of the water column in the pelagic zone, and provided a food source for lake trout. Benthic habitats were occupied by sculpins (*Cottus* and *Myoxocephalus* spp.), sticklebacks (primarily *Pungitius pungitius*), burbot, suckers (*Catostomus* spp.) and pygmy whitefish. Rivers, bays and coastal waters were occupied by brook trout, walleye, lake sturgeon, yellow perch, and northern pike. Hay-Chmielewski and Whelan (1997) estimated that Lake Superior supported 27 pounds/acre of lake sturgeon in near-shore waters less than 40 feet deep prior to 1870. Roosevelt (1865) found an “abundance of [brook] trout, averaging above two pounds, [along] the entire rocky shore of the lake, along both coasts...”. Arctic grayling, now extirpated from the watershed, were present in tributaries (Hubbs and Lagler 1964). Two large-bodied zooplankters, *Mysis relicta* and *Diporiea affinis*, were major components of this food web.

The offshore and near-shore open waters were characterized by a simple food web, in which lake herring fed on zooplankton and were in turn eaten by lake trout, which occupied the offshore zone during the growing season. Deepwater ciscoes and deepwater sculpin were the primary prey of siscowet lake trout in the offshore zone. A large quantity of energy was accumulated as biomass in lake herring and lake trout. Reproductive rates of these fish were low and growth was slow.

Human impacts on the fish community were probably minimal. Native Americans used gill nets made with strands of willow bark. They fished from birchbark canoes in summer and fall, and through ice in winter (Waters 1987). They also baited hooks and speared by torchlight, but the gill net provided the bulk of their catch.

Period of maximum degradation (1960s)

Lake Superior experienced dramatic changes caused by the activities of the burgeoning human population. The lake and its fisheries reached its point of maximum degradation around the 1960s, before beginning a trajectory of recovery. Many factors contributed to the degradation.

Commercial fishing began in the 1830s, and increased in intensity over the next century. Poorly controlled fishing by "aggressive and enterprising commercial fisheries" produced the destabilizing effects of intense size-selective predation (Lawrie 1978). All exploited species were affected, including lake trout, lake sturgeon, lake herring, lake whitefish, and deepwater ciscoes, and some became rare. Sport angling was a major factor in the early and rapid decline of the easily caught brook trout in the near-shore waters (Roosevelt 1865).

Destruction and degradation of habitat were severe, especially in bays and tributaries. The deposition of woody debris from sawmill operations “ruinously affected” spawning sites for sturgeon, lake whitefish, brook trout, and other species (Lawrie 1978). Logging in the Lake Superior watershed caused erosion and sedimentation, as well as higher temperatures and more variable flows in tributary streams. Dams blocked access to spawning sites, and changed downstream flows in spawning streams. Paper mill waste blanketed spawning habitat. Toxic contaminants (heavy metals and organic compounds) entered the lake from point sources and aerial deposition, and caused widespread low-level contamination of fishes. Mining, agriculture, urban development, and road and railroad construction all affected adjacent fish habitat.

The fish community was also greatly affected by non-indigenous species. The expansion of waterborne commerce and, especially, the creation of the Welland Canal and the St. Lawrence Seaway, provided entry routes for numerous non-indigenous species (Mills et al. 1993). Sea lamprey reached Lake Erie and the upper Great Lakes via the Welland Canal. They colonized Lake Superior in the 1940s, and by the late 1950s had, in conjunction with fishing, nearly destroyed the lean lake trout population (Pycha and King 1975; Lawrie and Rahrer 1973). Non-indigenous species were also intentionally introduced to provide or enhance sport and commercial fishing opportunities. Sport fishing opportunities have been diversified by introduced Atlantic salmon, brown trout, and Pacific salmon (rainbow trout, chinook salmon, coho salmon, pink salmon. The effects of these species on the ecosystem have been difficult to assess. Rainbow smelt, introduced into the Lake Michigan watershed in 1912, colonized Lake Superior during the 1930s and 1940s, and by the 1950s had largely replaced lake herring and other coregonids as the major lake trout prey item in the near-shore waters (Van Oosten 1937; Beckman 1942; Dryer et al. 1965; Selgeby et al. 1994). The effect of this displacement was enormous as lake herring had channeled energy to top-level predators throughout the lake whereas smelt were accessible only to near-shore predators. The behavior and distribution of lake trout may have changed to reflect the distribution of their major prey.

This period reflects a very unstable, rapidly changing fish community that had limited prospects for long-term sustainability. Lake trout and brook trout populations were reduced overall, and many local populations of these species were eliminated. Lake herring and deepwater cisco populations were greatly reduced, and one formerly abundant species of deepwater cisco became rare. Populations of lake sturgeon and walleye, once abundant in the bays, were virtually eliminated from some areas.

Current conditions

The present status of the fish community in Lake Superior is the closest to the desired condition that it has been since sea lamprey control began in the early 1960s. Several reports have documented the progress of recovery in the Lake Superior fish community (MacCallum and Selgeby 1987; Hansen (1990, 1994, 1996); Hansen et al. (1995). Critical factors in the recovery include the suppression of sea lamprey; the regulation of fisheries by provincial, state, and tribal governments; the stocking of lake trout; improved recruitment of lake herring; abatement of pollution; a lessening of habitat destruction; and reforestation.

Recovery of lake trout, the most economically valuable species in the historical catch, has progressed to the level where agencies believe that supplemental stocking is no longer required in most areas of Lake Superior (Hansen et al. 1995; Schreiner and Schram 1997). Lake herring, which made up the bulk of the historical commercial catch, produced a number of very abundant year classes in the late 1980s following severe depletion during the 1960s and 1970s. However, year class strength still remains extremely variable (Selgeby et al. 1994; Bronte et al. in review). Rainbow smelt abundance has declined dramatically from the high levels reached in the 1970s. Introduced brown trout and all of the Pacific salmon species have become naturalized in Lake Superior. None of the management agencies currently stock coho or pink salmon. Chinook salmon stocking continues but some of the highest stocking levels (1988-90) were found to contribute only 25% to the lake-wide sport fishery for that species (Peck et al. 1999). Rainbow trout, brown trout, and splake are stocked in some locations to supplement natural reproduction or enhance sport fisheries. Some near-shore fish populations, especially of lake sturgeon (Slade and Auer 1997), walleye (Hoff 1996), and brook trout (Newman and DuBois 1997), remain below historical levels, but rehabilitation efforts are being pursued by most management agencies.

State and tribal management agencies are using long-term assessment information and newly developed models to establish harvest controls for commercial and sport fisheries, thereby reducing the chances of over-fishing. Bioenergetics models have recently been applied to portions of Lake Superior (Negus 1995; Ebener 1995), and are expected to provide a better understanding of predator-prey dynamics, fish community function, and future information needs. Lake-wide simulation models (ECOPATH and ECOSIM) have been applied to the Lake Superior fish community, and strategies that may impact achievement of the Fish Community Objectives are being explored (Kitchell et al, 2000).

Non-indigenous species have had perhaps the greatest irreversible effect on Lake Superior. Sea lamprey continue to kill thousands of lake trout and rainbow smelt still comprise a significant portion of the near-shore forage. Ruffe and round gobies have colonized some areas, with the potential to negatively impact the near-shore coolwater fish community.

Fish habitat, with notable exceptions, is generally good. Impairments to water quality are mostly found in embayments and tributaries near mining and logging industries, resulting in the identification of eight Areas of Concern (International Joint Commission 1994) in the Lake Superior basin. Lake Superior also receives inputs of atmospheric pollutants such as PCBs and DDT originating outside the Lake Superior basin (Suns et al. 1993; Swain 1978; Eisenreich and Strachan 1992). Some climatologists anticipate that the climate of the basin in the next century will be warmer by 2-4°C. Models indicate that lake levels could decline between 0.2 and 0.5 m (Magnuson et al. 1997), while near-shore epilimnion temperatures could rise between 1.8^{o} and 5.7^{o} C for the July-September period (Hill and Magnuson 1990). Tributary streams, important for the spawning of many fishes, remain significantly degraded by activities in the watershed, including logging, agriculture, mining, and hydropower dams.

Goals and Guiding Principles

The guiding principles listed below support previously established goals of the Strategic Plan (as amended in 1997), the Great Lakes Water Quality Agreement (GLWQA) of 1978 (as amended in 1987), and the Binational Program's Aquatic Community Objective (Lake Superior Binational Program 1998).

The Strategic Plan provides a common goal statement for the management of Great Lakes fisheries that serves as a fundamental concept for Lake Superior:

> *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 the needs identified by society for: wholesome food, recreation, cultural heritage, employment and income, and a healthy aquatic ecosystem.*

The GLWQA, adopted by the International Joint Commission, contains an important goal related to water quality that must be achieved and maintained to assure healthy fish communities. Fishery management agencies on Lake Superior reaffirm their support for the GLWQA goal:

> *To restore and maintain the chemical, physical, and biological integrity of the waters of the Great Lakes basin ecosystem.*

Finally, the Binational Program has adopted the following overall objective for the aquatic community of Lake Superior:

> *Lake Superior should sustain diverse, healthy, reproducing and self-regulating aquatic communities closely representative of historical conditions.*

Consistent with the goals developed by the above-named organizations, the Lake Superior fishery management agencies adopts the following fish community goal:

> *To rehabilitate and maintain diverse, healthy, reproducing and self-regulating fish communities composed largely of indigenous species, that are sustainable and ecologically efficient.*

Along with agreement on the overall goals, complex fishery management requires agreement on specific principles to guide policies and programs. The combined forces of fisheries science, management experience, and public input have led to the development of a number of widely accepted management concepts that are essential for establishing a consistent, cooperative management approach on Lake Superior. The Lake Superior Committee adopts the following principles as a guide for formulating management policy and fish community objectives:

X **Fish habitats must be protected**

Healthy fish communities require diverse and abundant physical habitats, including clean water.

X **Lake productivity is limited**

The numbers and species of fish that can be supported by a healthy Lake Superior ecosystem are limited. Healthy, naturally reproducing fish communities that support fisheries can only be sustained by managing the entire ecosystem within the bounds of its biological productivity.

X **Naturalized species are part of the ecosystem**

Non-indigenous species, like Pacific salmon, that are now self-sustaining are likely to remain forever, and should be considered part of the fish community. Desirable species should be managed for sustainability, while detrimental species should be suppressed.

X **Further introductions of non-indigenous species must be prevented**

Non-indigenous species, especially sea lamprey, have harmed the Lake Superior fish community. Others, including ruffe and gobies, may also prove damaging. Further introductions must be prevented.

X **Fish and fisheries are culturally important**

Fisheries are a precious cultural heritage, therefore, the social, cultural, and economic benefits and costs to society, both present and future, are important considerations in making sound management decisions.

X **Unexploited fishes are also important**

All fish species, not just those that are exploited by fisheries, are important to the integrity of the fish community. Unfished species complete the network of ecological stability required to support fish communities, and some represent unique physical adaptations to the deepwater habitat of Lake Superior.

X **All citizens have a stake in Lake Superior fisheries**

Citizens, whether engaged or not in fishing, have an interest and a role in management decisions that affect these resources.

X **Management must be based on science**

Scientific information will help society make good fisheries management decisions. It is understood, however, that given our limited tools and resources, management decisions must often be made based on incomplete knowledge. Other sources of information, including traditional knowledge, are valuable.

- X **Management must be coordinated among agencies**

  Lake Superior fisheries management agencies must share information, work toward consensus, and be accountable for their management actions.

- X **Our ability to manage these fish communities is limited**

  Because knowledge is limited and because this ecosystem is influenced by forces outside our control, our ability to control the fish communities of Lake Superior will always be limited.

- X **Preservation of native species is of the highest concern**

  Those native species that are presently abundant should be maintained, and those that are depleted should be protected and enhanced.

- X **Genetic diversity and fitness must be maintained**

  Management agencies have a responsibility to maintain genetic diversity of fish through protection of individual populations, and care in the selection and stocking of particular strains of fish species already present.

Fish Community Objectives

Achievement of the goals and objectives described in this document requires emphasis on habitat restoration and protection, particularly for those fish that rely on tributary, embayment, and near-shore habitats. Achievement and maintenance of good water-quality is essential to support fish community objectives, but also to ensure achievement of the Strategic Plan's goal of healthy, self-sustaining fish populations and of wholesome food. It is important, therefore, that habitat and water quality concerns are adequately pursued so they do not impede achievement of the goals and objectives described in this document. In recognition of the importance of habitat, a separate habitat objective is described, followed by broad objectives for individual fish species or species groups.

Given our limited ability to manipulate the Lake Superior fish community or predict its future, the following objectives encompass broad ecological concepts that provide the framework for development of specific fisheries management plans and strategies. The Lake Superior Committee also recognizes that much progress has been made in rehabilitating some Lake Superior fish communities. Therefore, maintenance and protection of existing conditions or trends is emphasized for those situations.

In describing fish community objectives, we also recognize these realities:

- The abundance and composition of fish in a community are strongly influenced by habitat features (e.g., lake area, depth, and thermal characteristics) that are beyond human control.

- Only a few options exist for influencing the fish community structure in Lake Superior, and fishery managers will likely focus much of their attention on these possibilities. The primary means by which managers can significantly manipulate the Lake Superior fish community are regulation of harvest, stocking fish, habitat protection and enhancement, and suppression of nuisance species (e.g., sea lamprey).

- Management actions are inexact. Effects of management action often cascade to species well beyond those targeted, and those effects can have different time scales for different species. Short-term responses can be deceptive and long-range prediction can prove difficult.

- Species invasions (e.g., sea lamprey and ruffe) often result in substantial and unpredictable perturbations in the fish community. Such perturbations make management planning and quantification of objectives difficult.

- Fish community objectives for an entire lake cannot be taken to a high level of exactness - they are reasoned expectations. Management initiatives aimed at achieving objectives will continue to have a large experimental component, and the time frame needed to meet some objectives will be measured in decades.

Habitat

Objective: Achieve no net loss of the productive capacity of habitat supporting Lake Superior fishes. Where feasible, restore habitats that have been degraded and have lost their capacity for fish production. Reduce contaminants so that all fish are safe to eat. Develop comprehensive and detailed inventories of fish habitats.

The Strategic Plan calls upon the Lake Committees to identify the habitat needs for desired fish communities, and to work with other ecosystem initiatives, such as the Binational Program, in this area. A great deal is known about the specific requirements of individual species and Koonce et al. (1999) have proposed a methodology for identifying and classifying the habitats most important for sustaining not only individual species, but a desired fish community as a whole. However, at present the habitat needs of individual Lake Superior fish species or of the desired fish community have not been quantified.

The identification, restoration, and protection of important habitat for all species living in the Lake Superior basin is a primary objective of the Binational Program. Past or ongoing efforts in this area are the Atlas of the Spawning and Nursery Areas of Great Lakes Fishes (Goodyear et al. 1982), Habitat 2001 (Graham and Iwachewski 1997), A Summary of Important Habitat Conditions in the Lake Superior Basin (Wisconsin Department of Natural Resources 1996), proceedings of a workshop on environmental objectives (Koonce 1994), and the identification of aquatic biodiversity investment areas (ABIA's) through the State of the Lake Ecosystem Conference (SOLEC) process (Chow-Fraser and Albert 1998; Koonce et al. 1998). Future work to develop habitat objectives essential to achieving fish community objectives will be assisted by the newly formed Great Lakes Fish Habitat Conservation Committee, formed by the Great Lakes Fishery Commission.

Habitat can be classified into four zones in Lake Superior, each with a characteristic fish assemblage:

- offshore (>80 m deep)
- near-shore (0-80 m deep)
- embayments (harbors, estuaries and bays subject to seiches)
- and tributary reaches not subject to seiches.

Any categorization of this sort is somewhat arbitrary, but useful in describing and understanding this vast and diverse body of water. There is much interchange of material and energy among the zones due to currents, upwellings, and movements of fish and other organisms. Each of these habitat zones is subject to distinct stresses, which have been identified in the LAMP (Lake Superior Binational Program 2000).

The offshore habitat makes up the largest share of Lake Superior and contains nearly all of the spawning and feeding habitat for siscowet lake trout, humper lake trout, deepwater ciscoes, and deepwater sculpins. Seventy-seven percent of the surface area of Lake Superior is considered offshore habitat. The offshore fish community is relatively simple and composed almost solely of pelagic adult lean lake trout, siscowet lake trout, burbot, Pacific salmon, sea lamprey, deepwater ciscoes, lake herring, and deepwater sculpins.

Roughly 23% of Lake Superior's surface area is near-shore habitat. Most of the important and critical habitat for lean lake trout, lake herring, and lake whitefish are found in the near-shore zone (Figure 1). This zone is also used by Pacific salmon. The near-shore habitat has a greater diversity of fish species than the offshore habitat. This fish community is composed mainly of lean lake trout, siscowet lake trout, humper lake trout, burbot, Pacific salmon, brown trout, lake herring, lake whitefish, round whitefish, rainbow smelt, lake sturgeon, nine-spine sticklebacks, pygmy whitefish, deepwater ciscoes, slimy and deepwater sculpins, trout perch, and longnose and white suckers. This zone supports the major sport and commercial fisheries in Lake Superior.

The fish communities occupying the embayment habitats are richer than those in the offshore and near-shore habitats because Lake Superior's embayments are warmer, more productive, and more physically diverse than other parts of the lake. Embayments support most of the species that live in the near-shore and offshore habitats, but also support warm and cool water fish species such as walleye, smallmouth bass, yellow perch, rock bass, northern pike, trout-perch, lake sturgeon, brook trout, nine-spine sticklebacks, johnny darters, emerald shiners, longnose dace, sand shiners, bullheads, carp, and redhorse suckers.

Approximately 3,300 km of tributaries are available to Lake Superior fishes. Many fish that live in the embayment, near-shore, and offshore habitats spend part of their life in tributaries, but the dominant fish community of tributaries includes walleye, brook trout, burbot, lake sturgeon, Pacific salmon, longnose and white suckers, redhorse suckers, mottled sculpin, bullheads, sea lamprey, and many species of minnows. Tributaries provide critical habitat for lake sturgeon, walleye, brook trout, brown trout, rainbow trout and other Pacific salmon, and sea lamprey. Rainbow trout and brook trout are found in more tributaries of Lake Superior than the other species listed here, while lake trout and lake whitefish are uncommon.

Some populations of Lake Superior fish are currently limited by habitat; others are not. Presently, the following populations are not limited by habitat:

- All lake-spawning populations of lake trout, lake herring, lake whitefish, deepwater ciscoes, and round whitefish.
- Salmonines, other than lake trout, that spawn in Lake Superior and live in the offshore, near-shore, or embayment habitats. Salmonines that spawn or live in tributaries could be limited by habitat loss.
- Rainbow smelt, sculpins, trout perch, pygmy whitefish, and nine-spine stickleback populations that spawn in Lake Superior.

In contrast, the following fish populations have been affected by habitat loss in the Lake Superior basin, and achievement of fish community objectives may not be possible under current habitat conditions:

- Lake trout stocks that spawn in eastern Ontario tributaries of the lake.
- The lake whitefish stock that historically spawned in the St. Louis estuary. This stock of lake whitefish was extirpated over 100 year ago because of habitat destruction.

- Brook trout, brown trout and Pacific salmon stocks that spawn in tributaries.
- Walleye and lake sturgeon stocks that spawn in tributaries.
- Yellow perch, northern pike, and smallmouth bass.
- Rainbow smelt stocks that spawn in tributaries.

The principal stresses to habitats in Lake Superior include atmospheric deposition of contaminants, dams of all kinds, industrial effluents and waste, wetland dredging and filling, non-point source pollution, shoreline development, and land-use practices leading to increased runoff and erosion. Specific stresses and affected species are listed in Table 4. Generally, loss of habitat is an issue only in the tributary and embayment habitat zones of Lake Superior, but discharges of mine chemicals and tailings have degraded a few local areas of the near-shore habitat zone along the Minnesota and Michigan shoreline and atmospheric deposition of contaminants has degraded all habitat zones lakewide. Habitat in the offshore and near-shore zones in Lake Superior is probably in sufficient quantity and quality to allow achievement of the fish community objectives described below, but the tributary and embayment zones do not have sufficient amounts of suitable habitat to allow achievement of fish community objectives.

Table 4. Stresses to fish habitat and the affected species at specific sites around Lake Superior.

Site	Environmental Stress	Affected Species
Whitefish Bay	dredging of spawning grounds	eggs of lake whitefish
Batchawana Bay	removal of aquatic vegetation	yellow perch, smallmouth bass, cyprinids
Current River	removal of spawning substrate	walleye
Montreal River	hydroelectric peaking dam	eggs of walleye & lake trout
Nipigon Rier	hydroelectric development	all life stages of brook trout
Peninsula Harbor	mercury contamination from pulp mill	all species
Terrace Bay	wood fiber effluent from mill	eggs of lake trout
Thunder Bay	urban development and loss of wetlands	walleye, yellow perch
Kaministiquia River	low water quality from wood and chemicals	all species
St. Louis River	hydroelectric dams, breakwalls, industrial effluents, vessel discharge, loss of wetlands	walleye, sturgeon, perch, northern pike, lake whitefish
North & South Entry	mine tailings, loss of wetlands	lake trout, lake whitefish
Ontonagon River	hydroelectric development, loss of wetlands, industrial effluents	walleye, sturgeon, salmonines
Sturgeon River	hydroelectric development, industrial effluents	walleye, sturgeon
L’Anse Bay	loss of wetlands	yellow perch
Bete Gris Bay	loss of wetlands	yellow perch, walleye, northern pike
Huron Bay	loss of wetlands	yellow perch
Falls River	industrial effluents	all species
Dead River	industrial effluents, hydroelectric dams	all species
AuTrain River	hydroelectric dams	anadromous species

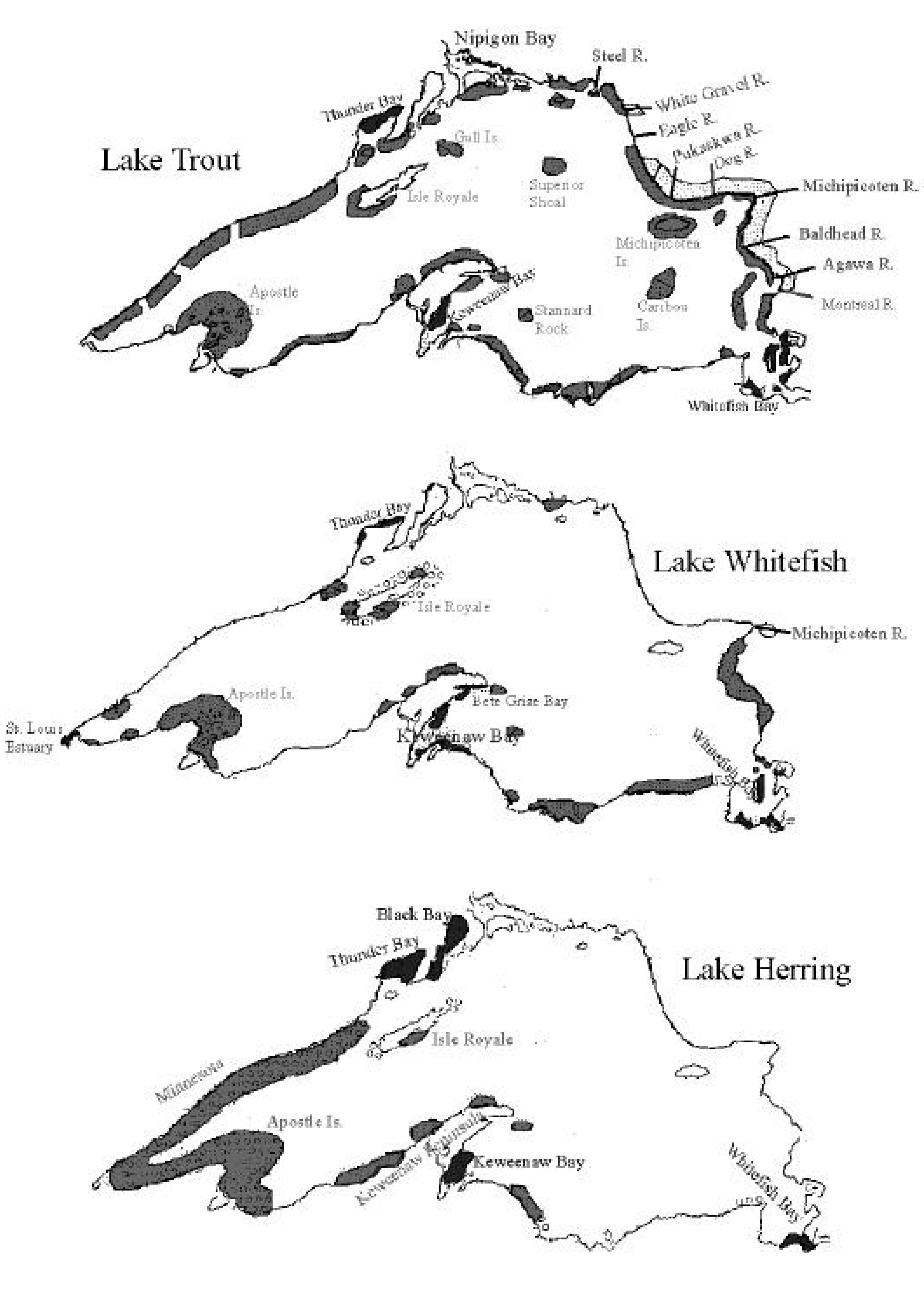

Fig. 1. Locations of known historic lake trout, lake whitefish, and lake herring spawning grounds in Lake Superior (from Coberly and Horral 1980; Goodier 1981; Goodyear et al. 1982). Lake whitefish nursery grounds are shown surrounding Isle Royale.

Prey Species

Objective: A self-sustaining assemblage of prey species at population levels capable of supporting populations of desired predators and a managed commercial fishery.

The prey fish assemblage of Lake Superior is comprised mostly of lake herring, three species of deepwater ciscoes (primarily bloater), slimy and deepwater sculpins, ninespine sticklebacks, and rainbow smelt (Lawrie 1978).

Historically lake herring was the dominant prey fish in Lake Superior (Dryer et al. 1965). They supported lake trout populations and composed most of the commercial fishery landings (Baldwin et al. 1979). Populations of lake herring declined drastically in U. S. waters during the mid 1960s. The collapse has been attributed to overfishing (Selgeby 1982), and to predation by and competition with rainbow smelt (Anderson and Smith 1971). Rainbow smelt became abundant during the 1930s, 1940s, and 1950s and were the main component of the near-shore prey community until the early 1980s when a significant decline was observed in U. S. waters (MacCallum and Selgeby 1987; Selgeby et al. 1994). Rainbow smelt densities have remained low for the past 17 years and are not expected to recover to former levels. Though recruitment of rainbow smelt has remained relatively stable, predation limits the number of fish living beyond age 4 (Bronte and Hoff 1997). Recent surveys in Ontario waters indicate that densities there are much higher and mortality lower than in U. S. waters. Even though rainbow smelt densities are depressed, this fish still composes a large portion of the diets of near-shore predators (Conner et al. 1993; Bronte et al. 1996; Gallinat and Bronte 1996).

Lake herring began to recover in Lake Superior in 1978 with recruitment of the 1977 year class, and densities increased further in the 1980s because of large years classes produced in 1984, 1988, 1989, and 1990 (Selgeby et al. 1994). Moderate to large parental stock sizes have been present since the late 1980s, but their progeny were few. Some of the weakest year classes have been produced under the highest stock sizes, suggesting a density-dependent effect on survival of young. Similar patterns in recruitment across jurisdictions and the contrast between recruitment events also suggest some lakewide, density-independent factor(s) may be important to recruitment rather than just total egg deposition. Despite the abundance of parental stocks, recruitment from 1991 to 1998 has been poor, resulting in an 80% reduction in biomass since a peak was reached in 1990 (Hoff and Bronte 1998). Adult lake herring are now too large to be consumed by any but the largest predators. The low biomass of both rainbow smelt and lake herring has resulted in a shift of predation to sculpins, ninespine sticklebacks, terrestrial insects, and other previously underutilized food resources, emphasizing the importance of these species as a reserve forage base.

Management agencies are limited in what can be done to affect change in Lake Superior's prey fish populations, although agencies can minimize mortality on spawning populations of lake herring by continuing to limit commercial harvest. Predation cannot be controlled, because populations of lake trout, salmon, and other predators are maintained primarily by natural reproduction. Current fisheries for bloaters and rainbow smelt remove only a fraction of the biomass, so elimination of fishing would not cause significant increases in biomass or recruitment of these populations. Stocking prey species is not an option, as the biological, financial, and logistical requirements to make an impact are beyond agency capabilities. There are no recognized habitat-related impediments to lake herring recruitment. Habitat loss in tributaries may be a problem for small populations which are of minor importance.

Lake Trout

Objective: Achieve and maintain genetically diverse self-sustaining populations of lake trout that are similar to those found in the lake prior to 1940, with lean lake trout being the dominant form in near-shore waters, siscowet lake trout the dominant form in offshore waters, and humper lake trout a common form in eastern waters and around Isle Royale.

Lake trout management is guided by *A Lake Trout Restoration Plan for Lake Superior* (Hansen 1996). Lake trout were, and continue to be, the dominant predator in Lake Superior. At least three forms of lake trout have been recognized in the lake; leans, siscowets, and humpers, although up to 12 morphological variants have been reported (Goodier 1981). Lean lake trout are the most commonly recognized form, and along with siscowet lake trout, are the dominant predator in near-shore waters less than 80 m deep and over shallow offshore reefs. Siscowet lake trout inhabit mainly the offshore waters deeper than 80 m, but they are also common in all near-shore waters. Humpers are the least abundant of the three forms of lake trout and live primarily on deep, offshore underwater reefs around Isle Royale and in the eastern waters of the lake around Caribou Island. These three forms of lake trout are distinguished from each other by differences in shape of the snout and body, fat content, size of the eye, and thickness of the abdominal wall (Lawrie and Rahrer 1973; Burnham-Curtis 1993). The current lake trout rehabilitation plan for Lake Superior calls for the development of specific objectives for each of the three lake trout forms.

All three forms of lake trout were represented in the historic commercial harvest that averaged 1.8 million kg during 1929-1943, the time period just before the collapse of lean lake trout populations began. Lake trout populations were believed to be stable during 1929-1943, but recent analysis of historic commercial catch data suggests that populations were declining in several areas of Lake Superior during this time period (Bronte 1998, Wilberg 2000). Analysis of historical commercial catch data indicates that the lean form of lake trout composed the bulk of the historic harvest, but the proportion of each form of lake trout represented in the historic yields varied among locations of the lake. Lean lake trout composed 87% of the historic harvest from Wisconsin waters (Swanson et al. 1994) and 75% in Michigan waters (Bronte 1998). Thus siscowet lake trout and humper lake trout could have composed 20% or more of the historic yield from Lake Superior (Bronte 1998). Fishery management agency efforts to rehabilitate lake trout populations in Lake Superior have focused on the lean form during the last 40 years. Siscowet lake trout are currently the most abundant form of lake trout in Lake Superior, and surveys in 1996 and 1997 indicate that they are expanding their distribution into near-shore waters and outnumbering lean lake trout in some areas (Lake Superior Technical Committee, unpublished data; Bronte et al. in press).

Impediments to fully achieving and maintaining the lake trout objective include sea lamprey predation, fishing mortality, and habitat loss or degradation in tributaries. Sea lampreys continue to kill significant numbers of lake trout. They may have accounted for 31% of the total number of lake trout killed by all sources in U. S. waters of Lake Superior in 1990-1992 (Hansen 1994). On a lakewide basis, exploitation is not excessive (Hansen 1994). Habitat loss or degradation is an impediment to lake trout rehabilitation only in isolated areas of Lake Superior. Fortunately, much of the near-shore and most of the offshore habitat of lake trout is unchanged from historic times, and is not an impediment to lake trout restoration; however, habitat impairment may be an impediment to lake trout recovery in some embayments and tributary habitats. There is concern that hydroelectric peaking operations on the Montreal River in eastern Ontario waters may be affecting spawning activity and survival of lake trout eggs. Wood fiber effluent from paper mills may be affecting survival of lake trout eggs in Terrace Bay, Ontario. Atmospheric deposition of chemicals does affect the consumption of lake trout by humans, but the affect of these chemicals on achieving the lake trout objective for Lake Superior is still being debated and examined within the scientific community.

Nearly the entire lake is important habitat for lean, siscowet, and humper lake trout (Coberly and Horrall 1980; Goodier 1981; Goodyear et al. 1982). In offshore areas, important spawning habitat is found on Gull Islands, Superior Shoal, Stannard Rock, Caribou Island, Michipicoten Island, and in eastern Ontario waters. Lake trout spawning grounds are found throughout the near-shore waters and amount to roughly 140,000 ha in U. S. waters alone. There are 337 sites in Lake Superior where lake trout historically spawned, and 9 tributaries to eastern Ontario waters of Lake Superior that lake trout historically ascended to spawn.

Lake Whitefish

Objective: Maintain self-sustaining populations of lake whitefish at an abundance that can sustain commercial fish harvests within the range observed during 1990-1999.

Lake whitefish populations in Lake Superior were reduced in the early part of the 20^{th} century, possibly as a consequence of progressive elimination of discrete stocks (Lawrie and Rahrer 1972), and/or habitat degradation from the deposition of woody debris in rivers and embayments. Currently whitefish populations are believed to be stable, with harvest during 1990-1996 ranging between 1023 and 3235 metric tons annually (Bronte et al. in press). This species has been described as resilient to exploitation (Smith 1972, Healey 1975), and since 1983 lake whitefish populations have recovered to the point where commercial harvests have been in excess of 1,000 tons annually. Lake whitefish in Lake Superior do not contain contaminants at levels found in larger predatory species. Lake whitefish exhibit homing to spawning grounds (Walker et al. 1993), and movements are typically within 40 km of the spawning grounds, resulting in the creation of distinct stocks.

In Lake Superior, lake whitefish spawn in early November over coarse sand or rubble in shallow water. Spawning habitat occurs throughout the lake over this type of substrate in embayments and the near-shore habitat zones. Early reports also indicated the existence of river-spawning populations, such as those in the St. Mary’s River rapids above the control gates, the St. Louis River in the U.S., and the Michipicoten, Dog, and Kaministikwia rivers in Ontario (Lawrie and Rahrer 1972).

We do not know the quantities of the various habitats required to support the desired lake whitefish populations, but it is possible to describe their habitat needs qualitatively. The offshore habitat zone appears not to be important to the species. Near-shore areas are used by adult lake whitefish for foraging and as spawning grounds. Embayments and the near-shore areas also provide habitat for developing larvae and juveniles. Even streams - at least those that can be identified historically as having spawning runs - are important spawning habitat, as are shallow areas with gravel bottoms.

Commercial fishing is currently the major source of mortality for adult lake whitefish in Lake Superior. Sea lamprey can kill lake whitefish, and significantly reduce lake whitefish populations, but wounding rates in Lake Superior are currently low. Lake whitefish have rarely been found in the diet of salmonine predators in Lake Superior (Conner et al. 1993; Lake Superior Technical Committee, unpublished data).

Walleye

Objective: Maintain, enhance, and rehabilitate self-sustaining populations of walleye and their habitat over their historical range.

The status of walleye in Lake Superior and its tributaries has been summarized by the Lake Superior Technical Committee (Hoff 1996), and the Lake Superior Committee has endorsed a walleye rehabilitation plan for Lake Superior (Hoff 1998). Walleye were important in regional fisheries in large bays, estuaries, and rivers of Lake Superior, and were likely important predators in the fish communities of these systems. Historically, the largest populations of walleye were found in Black Bay (Ontario) and the St. Louis River (Minnesota and Wisconsin) and its embayment. Walleye in the St. Louis River are already considered rehabilitated. Walleye are currently found in about 79 tributaries and in most bays on Lake Superior.

Achievement of the fish community goal for walleye will depend upon sufficient and usable habitat. Survival of walleye populations is linked to habitat in embayments and tributaries, which are the most impacted habitats in the lake.

Impediments to achieving the walleye goal include fishing-induced mortality and habitat degradation, including poor water quality. These stresses have affected walleye populations in every major bay and tributary of Lake Superior. Excessive fishing mortality has been identified as a limiting factor on stocks of walleye living in most of the major tributaries. Winter navigation and shipping have negatively affected walleye populations in the upper St. Mary’s River by causing sedimentation of walleye spawning and nursery areas, and loss of submergent and emergent vegetation in nursery habitat near commercial shipping channels. Habitats of walleye have been degraded by logging and agricultural practices, river bank erosion, wetlands development, hydropower development, and sedimentation in Huron Bay, the Ontonagon River, the St. Mary’s River, Goulais Bay, Nipigon Bay, and Thunder Bay. Poor water quality has limited the walleye in parts of the St. Louis River. Toxic contaminants in walleye have produced advisories regarding consumption of walleye in many bays of Lake Superior.

Lake Sturgeon

Objective: Rehabilitate and maintain spawning populations of lake sturgeon that are self-sustaining throughout their native range.

The status of lake sturgeon has been summarized by the Lake Superior Technical Committee (Slade and Auer 1997), and the Lake Superior Committee has endorsed a lake sturgeon rehabilitation plan for Lake Superior (Auer 1999). The lake sturgeon is the only species of sturgeon indigenous to the Great Lakes. It is also the largest and longest-lived fish in the basin. Sturgeon are distributed throughout the Lake Superior basin with concentrations found near tributaries where the species spawns. At least 17 tributaries within the Lake Superior basin were known (based on catches made by Native Americans that were documented by 17th century explorers to the Lake Superior region) to contain spawning concentrations of lake sturgeon (Slade and Auer 1997). Lake sturgeon populations likely began to decline prior to the first records of commercial catch in the late 1880s due to the combined affects of pollution from sawmills, log drives on spawning tributaries, and incidental catch in commercial fisheries for other species. In the late 1920s, hydroelectric dams were constructed on several tributaries used for spawning by lake sturgeon, and industrial development on other tributaries further destroyed lake sturgeon spawning and rearing habitat.

Currently, nine tributaries to Lake Superior are known to support self-sustaining populations of lake sturgeon: Sturgeon, Bad, Big Pic, Black Sturgeon, Goulais, Gravel, Kaministiquia, Michipicoten, and Nipigon rivers. Populations in all nine tributaries are reduced from historical levels of abundance, but they appear to be recovering. Lake sturgeon abundance in the St. Louis River estuary and along the south shore of Lake Superior has been increasing since 1988. An increase in abundance of lake sturgeon in western Lake Superior waters has been attributed to stocking of fingerling lake sturgeon in the St. Louis River embayment, and the population of juveniles in the area is stable (Slade and Auer 1997; Schram et al. 1999).

This objective will be considered achieved when at least 1,500 adult lake sturgeon, with equal numbers of males and females, and representing 20 year classes, spawn in each of the important tributaries. These adult fish should produce annual evidence of reproduction that can be measured by collecting viable eggs and age 0-5 lake sturgeon in tributaries. Impediments to achievement of this objective may include excessive sport and commercial harvests, mortality during sea lamprey control activities, habitat destruction, and dams.

Most of the impediments to achieving the objective for lake sturgeon occur in embayment and tributary habitats. Stresses to the embayment habitat include dredging, break-walls, vessel discharges, industrial discharges, and filling of wetlands and sloughs, and affect all except the egg stage of lake sturgeon in all the bays around Lake Superior. Alterations of tributary habitat affect all life stages of lake sturgeon from the egg to adults.

Brook Trout

Objective: Maintain widely distributed, self-sustaining populations in as many of the original, native habitats as is practical.

The status of brook trout in Lake Superior has been summarized by the Lake Superior Technical Committee (Newman and DuBois 1997), and a rehabilitation plan has been endorsed by the Lake Superior Committee (Newman et al. 1998). A large anadromous or lake dwelling form of brook trout, called coasters, was historically widespread and common in the very near-shore waters of Lake Superior. Brook trout provided a highly valued and productive fishery along shoreline areas of the lake, and in tributaries with spawning populations. These lake-run brook trout were known to inhabit at least 106 streams tributary to Lake Superior (Newman and DuBois 1997). Populations were extirpated rapidly during the 1880s and by the end of the 1920s fishing and habitat degradation reduced them to just a handful of viable populations. Contemporary lake-run populations of brook trout are found in remote areas including populations around Isle Royale and in the Cypress, Big Gravel, and Little Gravel rivers in Ontario. The Nipigon River in Ontario contains the most robust population in the Lake Superior basin.

Because very little is known about the ecology of brook trout in Lake Superior, specific strategies to achieve the goal should be flexible. Restrictive harvest regulations, stocking of hatchery-reared fish, and habitat restoration may be needed to restore them.

The lakewide brook trout rehabilitation plan (Newman et al. 1998) adopted in 1999 lists the following objectives:

- Populations will be self-sustaining and capable of coexisting with naturalized salmonines.
- Populations will be geographically widespread, inhabiting areas that historically held viable populations, given that tributary and lake habitat conditions in these areas are still suitable or can be restored.
- Populations will be comprised of six or more age groups, including at least two spawning year classes of females, and will be sufficiently large to ensure viable gene pools.
- Populations will exhibit genetic profiles consistent with those of populations currently inhabiting the Lake Superior basin.
- Essential habitats in tributaries will be protected and, where necessary, rehabilitated.
- Populations will be capable of supporting managed fisheries.

Protection of tributary habitat is essential for achieving the brook trout goal because habitat is currently an impediment to achieving the goal for brook trout. Hydroelectric development and operation, barrier dams, land-use practices, timber harvesting, and sedimentation all contribute to the loss of habitat for brook trout. Additional impediments to brook trout in Lake Superior may be splake and/or naturalized salmonines that occupy tributary habitat during their life cycle (Newman et al. 1998).

Pacific Salmon, Rainbow Trout, and Brown Trout

Objectives: Manage populations of Pacific salmon, rainbow trout, and brown trout that are predominately self-sustaining, but that may be supplemented by stocking that is compatible with restoration and management goals established for native fish species.

Non-indigenous top predators currently living in Lake Superior include rainbow trout, brown trout, chinook salmon, coho salmon, splake, pink salmon, and Atlantic salmon. Also, splake (a lake trout x brook trout hybrid) is present. The annual yield of these species accounts for 15-20% of the total harvest of all salmon, trout, and chars (lake trout and brook trout) from Lake Superior. All of these species are sustained primarily by natural reproduction, except splake which is not thought to reproduce in the wild. Stocking of coho salmon has been discontinued throughout the lake, yet coho salmon continue to be an important sport fish and spawn in at least 79 Lake Superior tributaries. Returns of chinook salmon to sport fisheries in the areas where they were stocked have declined (Schreiner 1995). A recent study by the Lake Superior Technical Committee found that naturally reproduced chinook salmon made up over 75% of the sport harvest of this fish from Lake Superior (Peck et al. 1999). Pink salmon were accidentally stocked in Lake Superior, but became established and have colonized spawning streams around the whole lake. Rainbow trout, naturalized in over 200 of 1,525 Lake Superior tributaries, are probably the most successful Pacific salmon.

Non-indigenous salmon and trout depend upon tributaries to Lake Superior for reproduction and rearing of juveniles, and have developed self-sustaining populations throughout the lake. Hydroelectric development limits the amount of tributary habitat available to salmon and trout for spawning, while also producing erratic flow regimes that depress survival of eggs and diminish the amount of protective cover available to juveniles. Forestry and agricultural practices often increase stream temperatures and sedimentation in tributaries. After emigration from streams, salmon and trout are found throughout the near-shore areas of Lake Superior, where they feed extensively on terrestrial insects, smelt, and young lake herring (Conner et al. 1993). Splake are stocked in some areas of the lake to provide a sport fishery.

The use of non-indigenous predators has led to concerns regarding the potential for introducing pathogens. Fish health concerns in the Great Lakes are addressed by the Fish Health Committee of the Great Lakes Fishery Commission. Guidance regarding the control of fish diseases and the minimization of the risk of introducing pathogens is contained in two documents, *Great Lakes Fish Disease Control Policy* (Hnath 1993) and *Model Program* and *Protocol to Minimize the Risk of Introducing Emergency Disease Agents with Importation of Salmonid Fishes From Enzootic Areas* (Horner and Eshenroder 1993). Management agencies on the Great Lakes have, acting through the Council of Lake Committees, adopted a *Procedures for Consultation*, to be followed when any jurisdiction wishes to introduce any species into the Great Lakes basin (Council of Lake Committees 1992).

The effect of competition and/or predation by stocked and wild salmon and trout on lake trout and brook trout remains a concern for management agencies (Lake Superior Lake Trout Technical Committee 1986; Busiahn 1990), but that concern does not apply to the offshore waters of the lake. If salmon and trout are depressing lake trout or brook trout populations, these effects would occur in the near-shore zone where introduced salmon and trout are most abundant. Non-indigenous salmon and trout, however, may compete with lake trout or brook trout in tributaries.

Sea Lamprey

Objective: Suppress sea lampreys to population levels that cause only insignificant mortality on adult lake trout.

The sea lamprey, a parasitic fish from the Atlantic Ocean first seen in Lake Superior in 1938, has been suppressed to less than 10% of pre-control population levels mainly through the application of a lampricide (TFM) in tributaries (Figure 2). TFM applications, begun in 1958, undoubtedly saved inshore and likely some offshore lake trout populations from extirpation and set the stage for lake trout recovery to near pre-control numbers in most areas of the lake. Despite persistent suppression, sea lampreys remain a significant source of mortality on lake trout. During the 10-year period from 1985 to 1994, sea lampreys accounted for 16% of the annual mortality on lake trout. If suppression could be increased, more lake trout would be available for harvest and reproduction.

The management objective for sea lampreys is to suppress populations until annual lamprey-induced adult lake trout mortality is essentially insignificant (< 5%). This objective is clearly desirable, but intensified control efforts with TFM are unlikely to achieve it. All of the major lamprey-producing tributaries are presently being treated. Model projections of sea lamprey abundance against treatment costs indicate that more stream treatments will yield only small benefits (Figure 3). With new methods of application, however, the same level of suppression is being achieved with 25% less TFM. Now that granular Bayluside has been reformulated, sea lamprey-infested areas outside of river mouths can be effectively treated. The extent of those infestations is currently being assessed and methods to inventory lentic habitats are being developed (Fodale et al. in review).

Alternative methods of control offer the best prospects for gains in suppression. More barriers that block adult sea lampreys from their spawning grounds can be constructed. The top five sites for barriers are the Goulais (Ontario), the Betsy and Two Hearted (Michigan), and the Bad and Iron Rivers (Wisconsin). Well-placed barriers can reduce the need for lampricide treatments, but improved designs are needed to minimize affects on non-target fishes. Introduction of sterilized male sea lampreys is currently being researched in Lake Superior, and early results indicate that sterile males compete with normal males and impede reproduction. The supply of males for sterilization, however, is inadequate to meet pressing needs elsewhere and to supply operational numbers for Lake Superior.

The objective of reducing sea lamprey populations in Lake Superior to ecological insignificance is unlikely to be fully achieved until new control technologies are available for implementation. Of the candidate technologies being researched, pheromone-based control is the most promising, but it needs more development before it can be field-tested. Other approaches being researched are now only at a conceptually attractive stage. Moving a candidate technology from a promising concept to operational feasibility can take 6-10 years if major bottlenecks are not encountered and funding is adequate. Therefore, achievement of the management objective of ecological insignificance for sea lampreys is promising, but it will be challenging and require a long-term commitment of time and money.

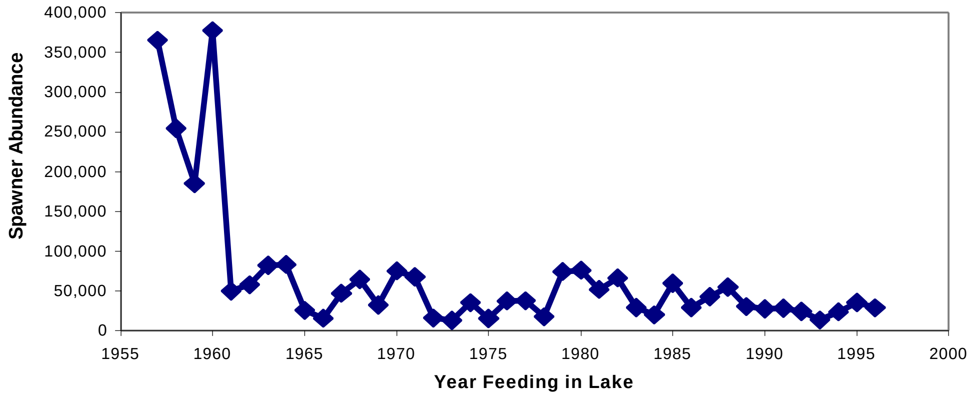

Fig. 2. Abundance of parasitic-phase sea lamprey in U.S. waters of Lake Superior.

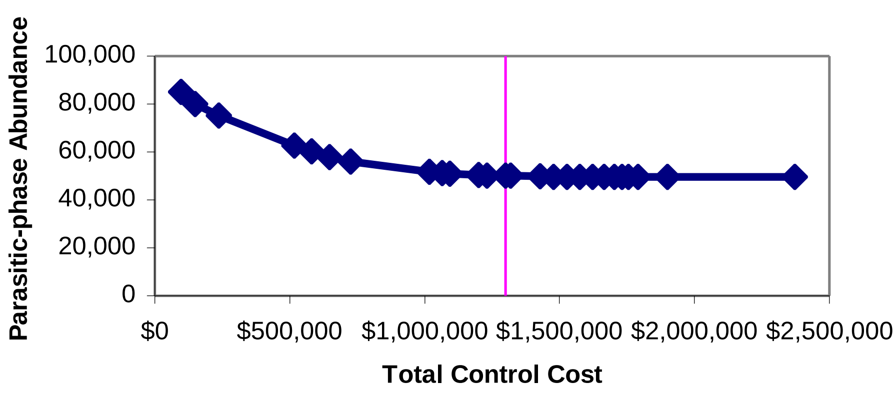

Fig. 3. Abundance of parasitic-phase sea lampreys in relation to costs of stream treatments in Lake Superior. Vertical line shows costs of the 1997 program.

Nuisance Species

Objective 1: Prevent the introduction of any non-indigenous aquatic species that is not currently established in Lake Superior.

Objective 2: Prevent or delay the spread of non-indigenous nuisance species, where feasible.

Objective 3: Eliminate or reduce populations of non-indigenous nuisance species, where feasible.

Since the 1800s at least 139 non-indigenous aquatic organisms, including 25 species of fish, have become established in the Great Lakes (Mills et al. 1993). Of the 96 fish species present in Lake Superior and its tributaries, 16 are non-indigenous (Appendix Table 4). The rate of introductions has increased; nearly a third of the non-indigenous species were introduced into the Great Lakes since the opening of the St. Lawrence Seaway in 1959. The most common mechanisms for entry into the Great Lakes are unintentional releases and ships ballast. The effects of established and abundant non-indigenous species may be instability and unpredictability in previously stable ecosystems, and a loss of diversity in biotic communities (Mills et al. 1993).

The ecological and economic impacts of non-indigenous nuisance species have been enormous. The sea lamprey has cost hundreds of millions of dollars in losses to fisheries and in costs of control, in addition to the depletion or extirpation of lake trout populations. Ruffe colonized the St. Louis River in the 1980s (Pratt et al. 1992) and became very abundant in some western embayments, raising concerns about competition with native species (Ruffe Task Force 1992; Bronte et al. 1998). Zebra mussels and round gobies have affected the other Great Lakes and may yet have local effects in Lake Superior bays and harbors.

Management agencies are hampered by a lack of technology for controlling aquatic nuisance species once they become established. The integrated pest management approach advocated by Marsden (1993) and others requires a set of management tools from which to choose. By and large, these tools do not exist for most aquatic pests. An economic injury analysis is ill suited to common property resources and non-economic values such as biodiversity. Research and development leading to new analytical and management tools are needed for an adequate response to non-indigenous aquatic nuisance species (Busiahn 1993).

Species diversity

Objective: Protect and sustain the diverse community of indigenous fish species not specifically mentioned earlier (e.g., burbot, minnows, yellow perch, northern pike, and suckers). These species add to the richness of the fish community and should be recognized for their ecological importance, and cultural, social, and economic values.

Lake Superior contains a fish community composed of 86 species, 70 of which are indigenous (Appendix Table 4). Most of these species are not specifically identified in this document because they are typically considered to be of lesser importance in the management of recreational and commercial fisheries. However, each species is recognized as having an important ecological role and, therefore an intrinsic value. The loss of populations of all native species should be prevented and those species that have been depleted or lost should be restored, where feasible.

Some of these species are of uncertain status as little effort is expended to assess trends in their lake wide distribution or population status (i.e., minnows). Others may be considered rare, threatened, or endangered. Some of these species are of economic value, while others are noted mostly for their intrinsic value and integrative function with the fish community. As prey and predators, they act as energy vectors and provide balance and stability.

Specific objectives for the lower profile indigenous species are difficult to develop, but these species should be self-sustainable and protected. Management and protection of these species can be accomplished by

- protecting and rehabilitating habitat, particularly near-shore habitat, to provide adequate conditions for the diversity of native fishes,
- regulating harvests (for example, bag limits for yellow perch and bait-fish harvest control),
- preventing further unintentional introductions of non-indigenous aquatic species, and where feasible, controlling aquatic nuisance species, and
- collecting baseline population data on abundance and distribution that will allow for detection of any serious population fluctuations or declines.

.

Literature Cited

Anderson, E. D., and L. L. Smith, Jr. 1971. Factors affecting abundance of lake herring (*Coregonus artedii* LeSuer) in western Lake Superior. Transactions of the American Fisheries Society 100:691-707.

Anonymous 1995. Great Lakes Atlas. Environment Canada and U.S. Environmental Protection Agency, 1995 Government of Canada Toronto, Ontario and United States Environmental Protection Agency, Great Lakes National Program Office, Chicago, Illinois. Third Edition.

Auer, N.A. 2000. A lake sturgeon rehabilitation plan for Lake Superior. A draft report prepared for the Lake Superior Committee by the Sturgeon Subcommittee.

Baldwin, N. S., R. W. Saalfeld, M. A. Ross, and H. J. Buettner. 1979. Commercial fish production in the Great Lakes 1867-1977. Great Lakes Fishery Commission Technical Report No. 3, Ann Arbor.

Beckman, W. C. 1942. Length-weight relationship, age, sex ratio, and food habits of the smelt (*Osmerus mordax*) from Crystal Lake, Benzie County, Michigan. Copeia 2:120-124.

Bennet, E. B. 1978. Characteristics of the thermal regime of Lake Superior. Journal of Great Lakes Research 4:310-319.

Bronte, C.R. 1998. Evaluation of historic lake trout harvests from Lake Superior, pages ???. *In* ??? [ed.] Lake Superior Committee Annual Meeting (Minutes). March 17-18, 1998. Great Lakes Fishery Commission, Ann Arbor.

Bronte, C.R.,and M. H. Hoff. 1997. Population status and trends for Lake Superior forage fishes, 1978-96. Minutes of the Lake Superior Committee Meeting, March 19-20, 1997, Great Lakes Fishery Commission, Ann Arbor.

Bronte, C.R., M.P. Ebener, D.R. Schreiner, D.S. Devault, M. Petzold, C. Richards, and D.A. Jensen. A case history of the fish community of Lake Superior, 1970-2000.

Bronte, C.R., L.M. Evrard, W.P. Brown, K.R. Mayo, and A.J. Edwards. 1998. Fish community changes in the St. Louis River estuary, Lake Superior, 1989-1996: is it ruffe or population dynamics? Journal of Great Lakes Research 24: 309-318.

Bronte, C.R., M.P. Gallinat, M.C. Donofrio, M.P. Ebener, S.T. Schram, R.G. Schorfaar, and D. R. Schreiner. 1996. Results of the interagency asessment of the diet of lake trout in Lake Superior, 1991-1994. Minutes of the Lake Superior Committee, March 28-29, 1995,Great Lakes Fishery Commission. Ann Arbor.

Burnham-Curtis, M. K. 1993. Intralacustrine speciation of *Salvelinus namaycush* in Lake Superior: an investigation of genetic and morphological variation and evolution of lake trout in the Laurentian Great Lakes. Ph.D. thesis. University of Michigan, Ann Arbor.

Busiahn, T. R. 1990. Fish community objectives for Lake Superior. Great Lakes Fishery Commission Special Publication 90-1.

Busiahn, T.R. 1993. Can the ruffe be contained before it becomes *your* problem? Fisheries 18(8): 22-23.

Chow-Fraser, P., and D. A. Albert. 1998. Biodiversity investment areas; coastal wetland ecosystems. Discussion draft presented at SOLEC 98.

Coberly, C. E., and R. M. Horrall. 1980. Fish spawning grounds in Wisconsin waters of the Great Lakes. Marine Studies Center, University of Wisconsin - Madison, Published by the University of Wisconsin Sea Grant Institute, Madison

Conner, D.J., C.R. Bronte, J.H. Selgeby, and H.L. Collins. 1993. Food of salmonine predators in Lake Superior, 1981-87. Great Lakes Fishery Commission Technical Report 59, Ann Arbor.

Council of Lake Committees. 1992. Introductions in the Great Lakes basin; procedures for consultation. Great Lakes Fishery Commission, Ann Arbor.

Cudmore and Crossman. 2000. In review. Checklists of the fish fauna of the Laurentian Great Lakes and their connecting channels. Great Lakes Fishery Commission.

Dryer, W.R., L.F. Erkkila, and C.L. Tetzloff. 1965. Food of lake trout in Lake Superior. Transactions of the American Fisheries Society 94: 169-176.

Ebener, M. P. 1995. Bioenergetics of predator fish in the western arm of Lake Superior. A completion report to the Red Cliff Band of Lake Superior Chippewas. 60p.

Eisenreich, S.J., and W.M.J. Stracham. 1992. Estimating atmospheric deposition of toxic contaminants to the Great Lakes: an update. Environment Canada/Great Lakes Protection Fund. Burlington, CAN.

Fodale, M.F., C.R. Bronte, R.A. Bergstedt, D.W. Cuddy, and J.V. Adams. In review. Classification of lentic habitat for sea lamprey (*Petromyzon marinus*) larvae using a remote seabed classification device. Canadian Journal of Fisheries and Aquatic Sciences.

Gallinat, M.P., and C.R. Bronte. 1996. Food habits of lake trout in management units WI-2 and MI-2 in Lake Superior, 1985-1994. Minutes of the Lake Superior Committee, March 28-29, 1995, Great Lakes Fishery Commission, Ann Arbor.

Goodier, J. L. 1981. Native lake trout stocks in the Canadian waters of Lake Superior, prior to 1955. Canadian Journal of Fisheries and Aquatic Sciences 28: 1724-1737.

Goodyear, C. D., T. A. Edsall, D. M. Ormsby Dempsey, G. D. Moss, and P. E. Polanski. 1982. Atlas of the spawning and nursery areas of Great Lakes Fishes. Volume two: Lake Superior. U.S. Fish and Wildlife Service, Washington, DC FWS/OBS-82-52.

Graham, J., and E. Iwachewski. 1997. Habitat 2001; A workshop on the future of habitat restoration and protection on the upper Great Lakes.

Great Lakes Fishery Commission. 1997. A joint strategic plan for management of Great Lakes Fisheries. Great Lakes Fisheries Commission, Ann Arbor.

Hansen, M. J. (ed.) 1990. Lake Superior: The state of the lake in 1989. Great Lakes Fishery Commission Special Publication 90-3. Ann Arbor, MI.

Hansen, M.J. (ed.). 1994. The state of Lake Superior in 1992. Great Lakes Fishery Commission Special Publication 94-1, Ann Arbor.

Hansen, M. J. (ed.). 1996. A lake trout restoration plan for Lake Superior. Great Lakes Fishery Commission. Ann Arbor.

Hansen, M.J. 1999. Lake trout in the Great Lakes: basin-wide stock collapse and binational restoration. Pages 417-453 in W.W. Taylor and C.P. Ferrari, Editors. Great Lakes Fishery Policy and Management: A Binational Perspective. Michigan State University Press. East Lansing.

Hansen, M. J., and eleven coauthors. 1995. Lake trout (*Salvelinus namaycush*) populations in Lake Superior and their restoration in 1959-1993. Journal of Great Lakes Research 21(Supplement 1):152-175.

Hay-Chmielewski, E.M. and G.E. Whelan (ed.). 1997. Lake sturgeon rehabilitation strategy. Michigan Department of Natural Resources, Fisheries Division Special Report Number 18, Lansing.

Healey, M.C. 1975. Dynamics of exploited whitefish populations and their management with special reference to the Northwest Territories. Journal of the Fisheries Research Board of Canada. 32: 427-428.

Hill, D.K., and J.J. Magnuson. 1990. Potential effects of global climate warming on the growth and prey consumption of Great Lakes fishes. Transactions of the American Fisheries Society. 119:265-275.

Hnath, J.G. (ed.). 1993. Great Lakes fish disease control policy and model program (supercedes September 1985 edition). Great Lakes Fisheries Commission Special Publication. 93-1, Ann Arbor.

Hoff, M.H. (ed). 1996. Status of walleye in Lake Superior and its tributaries. A draft report prepared for the Lake Superior Committee by the Walleye Subcommittee.

Hoff, M. H. 1998. A rehabilitation plan for walleye populations and habitats in Lake Superior. A draft report prepared for the Lake Superior Committee by the Walleye Subcommittee.

Hoff, M. H., and C. R. Bronte. 1998. Population status and trends for economically and ecologically important fishes in Lake Superior, 1978-97. Minutes of the Lake Superior Committee Meeting, March 17-18, 1998, Great Lakes Fishery Commission.

Horner, R.W., and R.L. Eshenroder (ed.). 1993. Protocol to minimize the risk of introducing emergency disease agents with importation of salmonid fishes from enzootic areas. Great Lakes Fisheries Commission Special Publication. 93-1: 39-54.

Hubbs, C. L., and K. F. Lagler. 1964. Fishes of the Great Lakes region. University of Michigan Press, Ann Arbor, Michigan.

International Joint Commission. 1994. Great Lakes Water Quality Agreement, as amended by protocol. IJC 64 pp.

Kitchell, J. F. and twelve co-authors. 2000. Sustainability of the Lake Superior fish community: Analysis of interactions in a food web context. Ecosystems. 3:545-560.

Koonce, J.F. 1994. Workshop on environmental objectives; summary of proceedings. Habitat Advisory Board, Great Lakes Fishery Commission. Ann Arbor.

Koonce, J.F., C.K. Minns, and H.A.Morrison. 1998. Biodiversity investment areas in the Great Lakes basin: identification and validation. Discussion draft presented at SOLEC 98.

Koonce, J.F., C.K. Minns, and H.A. Morrison. 1999. A methadology for identifying and classifying aquatic biodiversity investment areas: application in the Great Lakes basin. Great Lakes Fishery Commission, Project Completion Report. Ann Arbor.

Lake Superior Binational Program. 2000. Chapter 8, Aquatic community. Part I: Fish and their habitat. Lake Superior Lakewide Management Plan 2000.

Lake Superior Binational Program. 1998. Ecosystem principles and objectives, indicators and targets for Lake Superior (May 4, 1998). Lake Superior Work Group of the Lake Superior Binational Program, Thunder Bay, Ontario.

Lake Superior Lake Trout Technical Committee. 1986. A lake trout rehabilitation plan for Lake Superior. Lake Superior Committee Annual Meeting. March 20, 1986. Great Lakes Fishery Commission. Ann Arbor.

Lawrie, A.H. 1978. The fish community of Lake Superior. International Association for Great Lakes Research 43:513-549.

Lawrie, A.H., and J. F. Rahrer. 1972. Lake Superior: effects of exploitation and introductions on the salmonid community. Journal of the Fisheries Research Board of Canada. 29: 765-776.

Lawrie, A.H., and J.F. Rahrer. 1973. Lake Superior: A case history of the lake and its fisheries. Great Lakes Fisheries Commission. Technical Report 19. Ann Arbor

MacCallum W. R., and J.H. Selgeby. 1987. Lake Superior revisited, 1984. Canadian Journal of Fisheries and Aquatic Sciences 44(Suppl 2): 23-36..

Magnuson, J.J., K.E. Webster, R.A. Assel, C.J. Bowser, P.J. Dillon, J.G. Eaton, H.E. Evans, E.J. Fee, R.I. Hall, L.R. Mortsch, D.W. Schindler, and F.H. Quinn. 1997. Potential effects of climate changes on aquatic systems: Laurentian great lakes and precambrian shield region. Hydrologial Processes. 2:825-871.

Marsden, J.E. 1993. Responding to aquatic pest species: control or management? Fisheries 18(1): 4-5.

Matheson, D.H. and M. Munawar. 1978. Lake Superior basin and its development. Journal of Great Lakes Research 4: 249-263.

Mills, E.L., J.H. Leach, J.T. Carlton, and C.L. Secor. 1993. Exotic species in the Great Lakes: a history of biotic crises and anthropogenic introductions. Journal of Great Lakes Research 19(1): 1-54.

Negus, M. T. 1995. Bioenergetics modeling as a salmonine management too applied to the Minnesota waters of Lake Superior. North America Journal of Fisheries Management. 15:60-78.

Newman, L. E., and R. B. DuBois. 1997. Status of brook trout in Lake Superior. Prepared for the Lake Superior Technical Committee by the Brook Trout Subcommittee. Great Lakes Fishery Commission. Ann Arbor.

Newman, L.E., R.B.DuBois, and T. N. Halpern. [eds.]. 1998. A brook trout rehabilitation plan for Lake Superior. Great Lakes Fishery Commission. Ann Arbor.

Peck, J. W., Thomas S. Jones, W. R. MacCallum, and S.T. Schram. 1999. Contribution of hatchery-reared fish to chinook salmon populations and sport fisheries in Lake Superior. North American Journal of Fisheries Management. 19:155-164.

Pratt, D.M., W.H. Blust, and J.H. Selgeby. 1992. Ruffe, *Gymnocephalus cernuus*: newly established in North America. Canadian Journal of Fisheries and Aquatic Sciences 49: 1616-1618.

Pycha, R.L., and G. R. King. 1975. Changes in the lake trout population of southern Lake Superior in relation to the fishery, the sea lamprey, and stocking, 1950-70. Great Lakes Fishery Commission Technical Report 28. Ann Arbor.

Roosevelt, R.B. 1865. Superior Fishing. Originally published by G.W. Carleton. Minnesota Historical Society Press, St. Paul, 1985. 310 p.

Ruffe Task Force. 1992. Ruffe in the Great Lakes: a threat to North American Fisheries. Great Lakes Fishery Commission., Ann Arbor.

Schram, S.T., J. Lindren, and L.M. Evrard. 1999. Reintroduction of lake sturgeon in the St. Louis River, western Lake Superior. North American Journal of Fisheries Management. 19:815-823.

Schreiner, D.R., [ed.] 1995. Fisheries management plan for the Minnesota waters of Lake Superior. Minnesota Department of Natural Resources, Division of Fisheries and Wildlife, Section of Fisheries Special Publication No. 149.

Schreiner, D.R., and S. T. Schram. 1997. Lake trout rehabilitation in Lake Superior: Maintaining our progress. Fisheries. 22:12-14.

Selgeby, J. H. 1982. Decline of lake herring (*Coregonus artedii*) in Lake Superior: an analysis of the Wisconsin herring fishery. Canadian Journal of Fisheries and Aquatic Sciences 39:554-563.

Selgeby, J. H., C. R. Bronte, and J. W. Slade. 1994. Forage species. Pages 53-62 *In* M. J. Hansen, editor. The State of Lake Superior in 1992. Great Lakes Fishery Commission Special Publication 94-1. Ann Arbor.

Slade, J. W., and N. A. Auer. 1997. Status of lake sturgeon in Lake Superior. A report prepared for the Lake Superior Technical Committee by the Lake Sturgeon Subcommittee.

Smith, S.H. 1972. Factors of ecological succession in oligotrophic fish communities of the laurentian Great Lakes. Journal of the Fisheries Research Board of Canada. 29: 717-730.

Suns, K.R, Hitchin, G.G., and D. Toner, 1993. Spatial and temporal trends of organochlorine contaminanst in spottail shiners from selected sites in the great lakes (1975-1990). Journal of Great Lakes Research 19(4):703-714.

Swain, R.W., 1978. Chlorinated organic residues in fish, water, and precipitation from the vicinity of Isle Royale, Lake Superior. J. Great Lakes Research (4):(3-4):398-407.

Swanson, B., M. Halverson, and S. Fischer. 1994. Historical lake trout catch for Wisconsin waters of Lake Superior, 1936-41, pages 135-139. *In* K. Wright, editor, Lake Superior Committee Annual Meeting. March 22-23, 1994. Great Lakes Fishery Commission. Ann Arbor.

U.S. Fish and Wildlife Service. 1995. Great Lakes Fishery Resources Study. Report to Congress pursuant to the Great Lakes Fish and Wildlife Restoration Act, P.L. 101-537. Washington D.C.

Van Oosten, J. 1937. The dispersal of smelt, *Osmerus mordax* (Mitchill) in the Great Lakes region. Transactions of the American Fisheries Society 66:160-171.

Vollenweider, R.A., M.Munawar, and P.Stadelmann. 1974. A comparative review of phytoplankton and primary production in the Laurentian Great Lakes. Journal of the Fisheries Research Board of Canada 31: 739-762.

Walker, S. H., M.W. Prout, W.W. Taylor, and S. R. Winterstein 1993. North American Journal of Fisheries Management. 13:73-85.

Waters, T. F. 1987. The Superior North Shore. University of Minnesota Press, Minneapolis. 361 p.

Wilberg, M. 2000. Historic and modern lake trout abundance, effects of fishing on lake trout, and dynamics of the commercial lake trout fishery in Michigan waters of Lake Superior. Masters Thesis. University of Wisconsin – Stevens Point.

Wisconsin Department of Natural Resources. 1996. A Summary of Important Habitat Conditions in the Lake Superior Basin. PUBL-WT-472 96. Bureau of Watershed Management, Wisconsin Department of Natural Resources, Madison.

Appendix

Table 1. Estimated quantity of total, spawning, and nursery habitat, and biological parameters for lake trout in each management unit in Lake Superior. Number of spawning sites taken from Coberly and Horrall (1980), Goodyear et al. (1982) and Goodier (1981), and includes present day as well as historically important areas. Spawning habitat as defined includes waters < 9.1 m deep. Average CPUE, wild fish, and mortality for U. S. and Canadian waters adjusted for area < 73 m and < 91 m deep, respectively.

									Biological parameters			
Mgt	Total habitat (ha)		No. spawning sites		Spawning habitat		Nursery habitat			Survey	Wild	Annual
unit	total	<40 fa[1]	onshore	offshore	(ha)	% area[2]	(ha)	% area[2]	Years	CPUE[3]	fish[4]	mortality[5]
US waters												
MI-1	573,003	49,645	18	2	13,600	27%	1,200	2%	1993-95	16	98%	29%
MI-2	636,599	87,786	7	0	4800	5%	1,200	1%	1996	34	87%	45%
MI-3	620,654	64,674	10	0	4625	7%	1,200	2%	1996	7	91%	41%
MI-4	622,657	132,146	15	7	15,213	12%	2,300	2%	1996	14	88%	51%
MI-5	367,935	76,385	13	0	4,290	6%	14,500	19%	1996	32	83%	42%
MI-6	761,196	74,934	7	3	36,600	49%	71,500	95%	1996	45	90%	58%
MI-7	411,881	81,697	1	5	31,300	38%	42,800	52%	1996	18	94%	54%
MI-8	179,626	176,868	2	1	14,300	8%	40,100	23%	1996	10	17%	68%
WI-1	107,408	48,513	1	0	12	0%	0	0%	1995 & 97	20	42%	36%
WI-2	400,703	231,797	12	23	7,773	3%	266,131	115%	1995 & 97	18	71%	37%
MN-1	107,723	57,185	8	0	5,700	10%	1,190	2%	1996	34	45%	45%
MN-2	173,567	7,955	9	0	400	5%	430	5%	1996	7	20%	40%
MN-3	358,789	14,899	21	0	1,200	8%	4,500	30%	1996	26	70%	45%
subtotal	5,321,741	1,104,485	124	41	139,813	13%	447,051	40%	1993-1997	21	69%	48%
Canadian waters												
1	33,366	33,046	4	2					1992-96	90		<45%
2	22,451	22,440	0	4					1992-96	47		<45%
3	10,922	9,765	1	1					1992-96	100		<45%
4	13,871	13,871	3	3					1992-96	44		
5	41,614	25,361	5	1						22		
6	46,285	5,875	3	2					1992-96	46		
7	60,139	60,139	2	0					1992-96	16		
8	4,431	3,409										
9	101,191	28,759	11	3					1992-96	37		
10	39,818	39,818	3	6								
11	35,627	31,229	1	6					1992-96	34		

Table 1. Estimated quantity of total, spawning, and nursery habitat, and biological parameters for lake trout in each management unit in Lake Superior. Number of spawning sites taken from Coberly and Horrall (1980), Goodyear et al. (1982) and Goodier (1981), and includes present day as well as historically important areas. Spawning habitat as defined includes waters < 9.1 m deep. Average CPUE, wild fish, and mortality for U. S. and Canadian waters adjusted for area < 73 m and < 91 m deep, respectively.

									Biological parameters			
Mgt	Total habitat (ha)		No. spawning sites		Spawning habitat		Nursery habitat			Survey	Wild	Annual
unit	total	<40 fa[1]	onshore	offshore	(ha)	% area[2]	(ha)	% area[2]	Years	CPUE[3]	fish[4]	mortality[5]
12	105,284	14,218	0	10					1992-96	36		
13	91,264	0										
14	27,415	2,784	0	3					1992-96	185		
15	209,058	0										
16	45632	2,192	0	4					1992-96	318		
17	119784	919										
18	67,572	17,485	9	8						110		
19	72,227	26,510	9	0					1992-96	27		
20	119,784	13,209										
21	159,712	23										
22	204,436	0										
23	99,844	10,240	8	0					1992-96	68		<45%
24	137,912	26,158	5	0					1992-96	51		<45%
25	109,766	6,347										
26	49,287	15,657	0	15						291		
27	182,150	57,232	0	3					1992-96	270		
28	88,909	43,661	10	0					1992-96	52		23%
29	79,856	10,681	0	0						280		
30	114,080	0	0	0					1992-96	229		<45%
31	90,303	51,997	2	11					1987-92	11	45%	42%
32	77,099	2,552	0	0					1992-96	273		<45%
33	131,729	90,707	4	3					1987-92	8	35%	69%
34	47,452	44,409	6	1					1987-92	7	2%	63%
subtotal	2,840,270	710,693	86	86	0	0	0	0	1992-96	61		<45%
Total	8,162,011	1,815,178	210	127	139,813	0	447,051	0				

[1]Canadian waters is < 50 fa deep.
[2]Percent of areas < 40 fa deep in U. S. waters.
[3]CPUE is fish per 1,000 ft. of survey gill net in U. S. waters and in Canada CPUE is based on commercial catches and expressed as kg/km.
[4]In MN-1, MN-2, and MN-2 is percent of fish ≤635 mm total length.
[5]Mortality rates are for ages 5-9 in 1996-97 for MI-8, whereas ages 9-12 MI-3 through MI-7.

Table 2. Estimated quantity of total, spawning, and nursery habitat, and biological parameters for lake whitefish in each management of Lake Superior. Number of spawning sites taken from Coberly and Horrall (1980), Goodyear et al. (1982) and includes present day as well as historically important areas. Spawning habitat is considered to be < 9.1 m deep. Average CPUE and mortality in U. S. and Canadian waters adjusted for area < 73 m and < 91 m deep, respectively.

									Biological parameters		
Mgt	Total habitat (ha)		No. spawning sites		Spawning habitat		Nursery habitat				Annual
unit	total	<40 fa[1]	onshore	offshore	(ha)	% area[2]	(ha)	% area[2]	Years	CPUE[1]	mortality
US waters											
MI-1	573,003	49,645	9	0	628	1%			1978-81		55%
MI-2	636,599	87,786	0	0	300	0%	700	1%	1996	160	45%
MI-3	620,654	64,674	7	0	400	1%	600	1%	1996	130	78%
MI-4	622,657	132,146	14	2	500	0%	800	1%	1996	72	73%
MI-5	367,935	76,385	2	1	18,600	24%	4,700	6%	1994-96	71	30%
MI-6	761,196	74,934	9	0	52,500	70%	37,000	49%	1996	57	50%
MI-7	411,881	81,697	1	0	13,000	16%	20,000	24%	1996	156	53%
MI-8	179,626	176,868	6	0	25,500	14%	39,500	22%	1996	93	57%
WI-1	107,408	48,513	2	0	162	0%	0	0%		20	
WI-2	400,703	231,797	4	35	8,500	4%	187,023	81%	1996	126	73%
MN-1	107,723	57,185	0	0	0	0%	0	0%			
MN-2	173,567	7,955	5	0	0	0%	7,955	100%			
MN-3	358,789	14,899	2	0	3,000	20%	0	0%			
subtotal	5,321,741	1,104,485	61	38	123,090	11%	298,278	27%		104	63%
Canadian waters											
1	33,366	33,046	1	0					1992-96	427	<45%
2	22,451	22,440	1	0					1992-96	184	
3	10,922	9,765							1992-96	102	
4	13,871	13,871							1992-96	132	
5	41,614	25,361							1992-96	129	
6	46,285	5,875							1992-96	88	
7	60,139	60,139							1992-96	88	<45%
8	4,431	3,409									
9	101,191	28,759							1992-96	140	
10	39,818	39,818									

Table 2. Estimated quantity of total, spawning, and nursery habitat, and biological parameters for lake whitefish in each management of Lake Superior. Number of spawning sites taken from Coberly and Horrall (1980), Goodyear et al. (1982) and includes present day as well as historically important areas. Spawning habitat is considered to be < 9.1 m deep. Average CPUE and mortality in U. S. and Canadian waters adjusted for area < 73 m and < 91 m deep, respectively.

Mgt unit	Total habitat (ha)		No. spawning sites		Spawning habitat		Nursery habitat		Biological parameters		
	total	<40 fa[1]	onshore	offshore	(ha)	% area[2]	(ha)	% area[2]	Years	CPUE[1]	Annual mortality
11	35,627	31,229							1992-96	74	
12	105,284	14,218							1992-96	200	
13	91,264	0									
14	27,415	2,784							1992-96	5	
15	209,058	0									
16	45,632	2,192							1992-96	0	
17	119,784	919									
18	67,572	17,485							1992-96	59	
19	72,227	26,510							1992-96	79	
20	119,784	13,209									
21	159,712	23									
22	204,436	0									
23	99,844	10,240							1992-96	143	<45%
24	137,912	26,158							1992-96	76	<45%
25	109,766	6,347									
26	49,287	15,657							1992-96	109	
27	182,150	57,232									
28	88,909	43,661							1992-96	152	<45%
29	79,856	10,681									
30	114,080	0									
31	90,303	51,997							1992-96	108	68%
32	77,099	2,552									
33	131,729	90,707	2	1					1992-96	99	39%
34	47,452	44,409	1	1					1992-96	151	36%
Subtotal	2,840,270	710,693	5	2					1992-96	131	<45%
Total	8,162,011	1,815,178	66	40	123,090	0	298,278	0		114	

[1]Canadian waters is < 50 fa deep.
[2]Percent of areas < 40 fa deep in U. S. waters.
[3]CPUE is expressed as kilograms per kilometer of gill net

Table 3. Known spawning and foraging habitat for selected fish species in Lake Superior.

Habitat zone	Species	Life stage	foraging habitat	spawning habitat
Offshore (>80 m)	Lean lake trout	juvenile	all water <91 m	Stannard Rock, Superior Shoal, Caribou Island (Fig. 1)
		non-spawning adult	all water <146 m	Stannard Rock, Superior Shoal, Caribou Island (Fig. 1)
	Siscowet	egg	all water >110 m	Caribou Island
		juvenile	all water 80 to 128 m	Caribou Island
		non-spawning adult	all water >110 m	Caribou Island
		spawning adult	all water >110 m	Caribou Island
	Humper	egg	rock substrate <60 m in offshore areas	Caribou Is., Isle Royale, & Superior Shoal (Fig. 1)
		juvenile	unknown	none
		non-spawning adult	unknown	none
		spawning adult	rock substrate <60 m in offshore areas	Caribou Is., Isle Royale, & Superior Shoal (Fig. 1)
	Lake herring	egg	unknown	unknown
		juvenile	all water 80 to 220 m	none
		non-spawning adult	all water 80 to 220 m	none
		spawning adult	unknown	unknown
	Burbot	egg	unknown	unknown
		juvenile	all water >80 m	none
		non-spawning adult	all water >80 m	none
		spawning adult	unknown	unknown
	Deepwater ciscoes	egg	all water 80 to 220 m	unknown
		juvenile	all water 80 to 220 m	none
		non-spawning adult	all water 80 to 220 m	none
		spawning adult	all water 80 to 220 m	unknown
	Scuplins spp.	egg	unknown	unknown
		juvenile	all water >80 m	none
		non-spawning adult	all water >80 m	none
		spawning adult	all water >80 m	unknown

Table 3. Known spawning and foraging habitat for selected fish species in Lake Superior.

Habitat zone	Species	Life stage	foraging habitat	spawning habitat
Near-shore (<80 m)	Lean lake trout	egg	rock substrates 0.5 to 30 m	rock substrates 0.5-30 m, DO >6mg/l in Fig. 1
		juvenile	all water 35 to 80 m	none
		non-spawning adult	all water 35 to 80 m	none
		spawning adult	rock areas 0.5-30 m	rock substrates 0.5-30 m in Fig. 1
	Siscowet	egg	unknown	unknown
		juvenile	all water <80 m	none
		non-spawning adult	water 36 to 80 m	none
		spawning adult	unknown, probably very little	unknown
	Humper	egg	rock substrate <60 m	water <60 m Caribou Is., Isle Royale, & Superior Shoal (Fig. 1)
		juvenile	offshore banks Isle Royale, Caribou Is.	none
		non-spawning adult	offshore banks Isle Royale, Caribou Is.	none
		spawning adult	rock substrate <60 m	water <60 m Caribou Is., Isle Royale, & Superior Shoal (Fig. 1)
	Lake whitefish	egg	sand to rock substrates <9 m	areas identified in Fig. 1
		juvenile	all water <73 m	none
		non-spawning adult	all water <73 m	none
		spawning adult	sand to rock substrates <9 m	areas identified in Fig. 1
	Lake herring	egg	unknown	unknown
		juvenile	all water <80 m	areas identified in Fig. 1
		non-spawning adult	all water <80 m	none
		spawning adult	all water <80 m	areas identified in Fig. 1
	Walleye	juvenile	near tributaries (Fig. 2)	none
		non-spawning adult	near tributaries (Fig. 2)	none
	Lake sturgeon	non-spawning adult	Superior to Munising (Fig. 2)	none
Harbor, bays, & estuaries	Lake whitefish	eggs	sand to rock substrates <9 m	areas identified in Fig. 1
		juvenile	all water <73 m	none
		non-spawning adult	all water <73 m	none
		spawning adult	sand to rock substrates <9 m	areas identified in Fig. 1

Table 3. Known spawning and foraging habitat for selected fish species in Lake Superior.

Habitat zone	Species	Life stage	foraging habitat	spawning habitat
	Lake herring	egg	gravel to rock substrates	Thunder, Black, Keweenaw, & Whitefish bays
		juvenile	all water	none
		non-spawning adult	all water	none
		spawning adult	gravel to rock substrates	Thunder, Black, Keweenaw, & Whitefish bays
	Brook trout	egg	upwellings areas along shore	Tobin Harbor and Siskiwit Bay on Isle Royale
		juvenile	water <15 m	none
		non-spawning adult	water <15 m	none
		spawning adult	upwellings areas along shore	Tobin Harbor and Siskowit Bay on Isle Royale
	Walleye	juvenile	bays indicated on Fig. 2	Black, Thunder, Chequamenon, & Whitefish bays, St. Louis estuary
		non-spawning adult	bays indicated on Fig. 2	none
		spawning adult	bays indicated on Fig. 2	Black, Thunder, Chequemenon, & Whitefish bays, St. Louis estuary
	Lake Sturgeon	juvenile	13 bays identified in Fig. 2	none
		non-spawning adult	13 bays identified in Fig. 2	none
Tributaries	Lake trout	egg	eastern Lake Superior tributaries	Montreal & Dog (University) rivers
		spawning adult	eastern Lake Superior tributaries	Montreal & Dog (University) rivers
	Lake sturgeon	egg	19 river identified in Fig. 2	Bad, Sturgeon, Gravel, Kaministiquia, & Nipigon rivers
		juvenile	19 river identified in Fig. 2	none
		non-spawning adult	19 river identified in Fig. 2	none
		spawning adult	19 river identified in Fig. 2	Bad, Sturgeon, Gravel, Kaministiquia, & Nipigon rivers
	Brook trout	egg	106 stream in Fig. 3	Nipigon, Current, Jackpine, Cypress, Pancake, Salmon-Trout, & Isle Royale
		juvenile	106 stream in Fig. 3	none
		non-spawning adult	106 stream in Fig. 3	none
		spawning adult	106 stream in Fig. 3	Nipigon, Current, Jackpine, Cypress, Pancake, Salmon-Trout, & Isle Royale

Table 4. Fish species list for Lake Superior based on Cudmore and Crossman (2000) and reports of possible additional species. N = native; I = introduced and reproducing; R = reported to occur but non-reproducing; P = possible occurrence, native; U = reported but unlikely occurrence.

PETROMYZONTIDAE	
Ichthyomyzon unicuspis (silver lamprey)	N
I. fossor (northern brook lamprey)	N
Lampetra appendix (American brook lamprey)	N
Petromyzon marinus (sea lamprey)	I
ACIPENSERIDAE	
Acipenser fulvescens (lake sturgeon)	N
LEPISOSTEIDAE	
Lepisosteus osseus (longnose gar)	N
AMIIDAE	
Amia calva (bowfin)	P
ANGUILLIDAE	
Anguilla rostrata (American eel)	R
CLUPEIDAE	
Alosa pseudoharengus (alewife)	I
Dorosoma cepedianum (gizzard shad)	I
CYPRINIDAE	
Couesius plumbeus (lake chub)	N
Cyprinus carpio (common carp)	I
Luxilus cornutus (common shiner)	N
Margariscus margarita (pearl dace)	N
Nocomis biguttatus (hornyhead chub)	N
Notemigonus crysoleucas (golden shiner)	N
Notropis atherinoides (emerald shiner)	N
N. buccatus (silverjaw minnow)	U
N. dorsalis (bigmouth shiner)	P
N. heterodon (blackchin shiner)	N
N. heterolepis (blacknose shiner)	N
N. hudsonius (spottail shiner)	N
N. rubellus (rosyface shiner)	P
N. stramineus (sand shiner)	N
N. volucellus (mimic shiner)	N
Opsopoeodus emiliae (pugnose minnow)	U
Phoxinus eos (northern redbelly dace)	N
P. neogaeus (finescale dace)	N
Pimephales notatus (bluntnose minnow)	N
P. promelas (fathead minnow)	N
Rhinichthys atratulus (blacknose dace)	N
R. cataractae (longnose dace)	N
Semotilus atromaculatus (creek chub)	N
CATOSTOMIDAE	
Catostomus catostomus (longnose sucker)	N
C. commersoni (white sucker)	N
Moxostoma anisurum (silver redhorse)	N
M. macrolepidotum (shorthead redhorse)	N
M. valenciennesi (greater redhorse)	N
ICTALURIDAE	
Ameiurus melas (black bullhead)	N
A. natalis (yellow bullhead)	N
A. nebulosus (brown bullhead)	N
Ictalurus punctatus (channel catfish)	N
Noturus flavus (stonecat)	N
N. gyrinus (tadpole madtom)	N
N. miurus (brindled madtom)	U
ESOCIDAE	
Esox lucius (northern pike)	N
E.masquinongy (muskellunge)	N
OSMERIDAE	
Osmerus mordax (rainbow smelt)	I
SALMONIDAE	
Coregonus artedi (lake herring)	N
C. clupeaformis (lake whitefish)	N
C. hoyi (bloater)	N
C. kiyi (kiyi)	N
C. zenithicus (shortjaw cisco)	N
Oncorrhynchus kisutch (coho salmon)	I
O. gorbuscha (pink salmon)	I
O. mykiss (rainbow trout)	I
O. tshawytscha (chinook salmon)	I
Prosopium coulteri (pygmy whitefish)	N
P. cylindraceum (round whitefish)	N
Salmo trutta (brown trout)	I
Salvelinus fontinalis (brook trout)	N
S. namaycush (lake trout)	N
S. namaycush siscowet	N
PERCOPSIDAE	
Percopsis omiscomaycus (trout-perch)	N
GADIDAE	
Lota lota (burbot)	N
ATHERINIDAE	
Labidesthes sicculus (brook silverside)	R
GASTEROSTEIDAE	
Apeltes quadracus (fourspine stickleback)	I
Culaea inconstans (brook stickleback)	N
Gasterosteus aculeatus (threespine stickleback)	I
Pungitius pungitius (ninespine stickleback)	N
COTTIDAE	
Cottus bairdi (mottled sculpin)	N
Cottus cognatus (slimy sculpin)	N
Cottus ricei (spoonhead sculpin)	N
Myoxocephalus thompsoni (deepwater sculpin)	N
MORONIDAE	
Morone americana (white perch)	I
Morone chrysops (white bass)	N
CENTRARCHIDAE	
Ambloplites rupestris (rock bass)	N
Lepomis cyanellus (green sunfish)	N
L. gibbosus (pumpkinseed)	N
L. macrochirus (bluegill)	N
Micropterus dolomieu (smallmouth bass)	N
M. salmoides (largemouth bass)	N
Pomoxis annularis (white crappie)	P
P. nigromaculatus (black crappie)	N
PERCIDAE	
Etheostoma exile (Iowa darter)	N
E. flabellare (fantail darter)	N
E. microperca (least darter)	N
E. nigrum (johnny darter)	N
Gymnocephalus cernuus (ruffe)	I
Perca flavescens (yellow perch)	N
Percina caprodes (logperch)	N
P. maculata (blackside darter)	U
Stizostedion canadense (sauger)	N
S. vitreum (walleye)	N
SCIAENIDAE	
Aplodinotus grunniens (freshwater drum)	I
GOBIIDAE	
Neogobius melanostomus (round goby)	I