OFFSHORE PREDATORS AND THEIR FISH COMMUNITY

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Establish a diverse salmonine community that can sustain an annual harvest of 2.4 million kg with lake trout the dominant species and anadromous (stream-spawning) species also having a prominent place.

The above statement from DesJardine et al. (1995) is the overarching objective for Lake Huron's offshore predators, a group comprising one native salmonine, six introduced salmonines, and one non-salmonine, the burbot. We will discuss the status of each species, and, in addition, describe the status of their prey, the status of the sea lamprey (which preys on salmonines), and the status of the double-crested cormorant, a competing predator. We further note that the envisioned yield from self-sustaining lake trout stocks would be 1.4-1.8 million kg (DesJardine et al. 1995), implying that the other (non-lake trout) salmonines should be able to sustain harvests of 0.6-1.0 million kg. The annual salmonine yield for this five-year reporting period (2000-2004) averaged roughly 1.6 million kg, of which 0.5 million kg was lake trout. These figures are based on reported yields, except that Michigan's reported recreational yield of Chinook salmon was doubled to account for Ontario's Chinook salmon fishery, which was not surveyed (see the Introduction section). Therefore, the estimated yield (reported and non-reported) of other (non-lake trout) salmonines, amounting to 1.1 million kg, exceeded, on average, the upper bound of its objective (1.0 million kg). Lake trout yield, which was largely derived from hatchery fish, was well less than half its objective. However, the yield of Chinook salmon decreased during the reporting period, while the yield of lake trout increased.

Lake Trout

The reported yield of lake trout in 2004 reached approximately 0.7 million kg , which was more than double the 1999 yield but still just half of the yield target specified in the FCO. Unfortunately, the objective applies to wild-born trout, and the entire 2004 yield was essentially of hatchery-origin trout. Commercial harvest amounted to 65% of the 2004 reported overall yield. Increases in yield occurred in both the recreational and commercial fisheries in all basins of Lake Huron, although the greatest increase occurred in the main basin.

Although the lake trout objective is framed in terms of sustainable harvest, the lake trout rehabilitation guide for Lake Huron (Ebener 1998) recommends that success be measured based on population parameters, including abundance, mortality, age structure, growth, and natural reproduction. The guide outlines three milestones for the rehabilitation process, which we paraphrase as:

1. Measurable numbers of wild lake trout are being produced

2. Wild spawning stocks are self-sustaining

3. The ecological community associated with lake trout does not inhibit lake trout survival or reproductive success

The guide also indicates that annual mortality should not be higher than 40% during the process of rehabilitation, and it identifies indicators of progress toward each milestone.

Development of a substantial stock of mature hatchery-origin fish, comprising multiple ages, is a precursor for achievement of the first milestone. To achieve this milestone, an average of 3.4 million age-1 lake trout were stocked annually during 2000-2004 (Fig. 2b), and half of these were stocked in the main basin. This level of stocking has been relatively constant since 1992 but has been below the recommended 4.7-5.9 million per year (Ebener 1998). During 2000-2004, stocking increased in northern and north-central waters (49% of total) partly in response to lower expected lake trout mortality due to improved sea lamprey control and fishery regulation associated with the 2000 Consent Decree (United States vs. Michigan 2000). This change in stocking locations is important because it represents an increase in the proportion of lake trout being stocked into the historically most-important spawning grounds. Several strains of lake trout, including two remnant strains (Parry Sound and Iroquois Bay) continue to be evaluated and utilized in Lake Huron consistent with recommendations in the guide (Ebener 1998).

Based on statistical catch-at-age models (e.g., Woldt et al. 2005b), the abundance of age-5 and older lake trout increased more than 38% (from 0.87 to 1.20 million) in the main basin from 1999 to 2004. The trend of increasing abundance started already in 1992 (Fig. 3) and is attributed to decreases in mortality. Total mortality was below the target of 40% in northern and north-central waters of the main basin. In the southern main basin, total mortality declined through 2002 and fell below 40%, but total mortality increased to more than 50% in 2003 and 2004 due to increased commercial and recreational fishing. As of 2004, estimates of basinwide mortality suggested that approximately half was due to fishing with the remainder resulting from sea lamprey predation and natural sources.

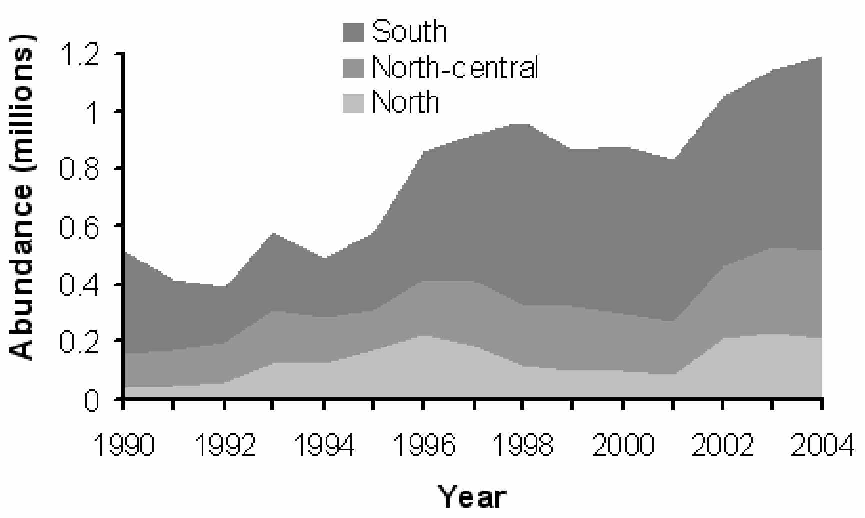


Fig. 3. Estimated abundance of age-5 and older lake trout in three regions of the main basin of Lake Huron based on statistical catch-at-age models. The northern region corresponds to MH-1 and adjacent Ontario waters, the north-central region corresponds to MH-2 and adjacent waters, and the southern region corresponds to MH-3, the adjacent waters, and waters farther south (see Fig. 1 for locations).

In the main basin, estimated female spawning-stock biomass increased nearly 90% (from 0.51 to 0.95 million kg) from 1999 to 2004, which was a much larger increase than the 38% increase in abundance. Substantial decreases in age at maturity caused this increase, and this surprising influence of a life-history response is worth noting. During 2000-2004, the mean age at which 50% of the female lake trout were mature was 6.0, 5.7, and 5.4 years in northern, north-central, and southern waters of the main basin, respectively. This mean age represents about a six-month decrease in mean age at 50% maturity since 1999 and a decrease of 1-2 years (depending on area) since 1990. These changes are important because, all else equal, earlier maturity implies the fish have higher expected lifetime reproductive output and will contribute more to rehabilitation.

Length at age declined in the southern and north-central waters of the main basin, although this decline was only evident for ages 7 and above in the north-central waters. Body condition (mass at length) decreased rapidly lakewide from 2002 to 2004 when it reached its lowest observed level (He et al. 2008). Although lake trout in the northern waters of the main basin also experienced a decrease in age at maturity and a decline in condition, their mean length at age actually increased. Given the similar maturity and condition changes, we suspect the increase in length at age in the north may partly reflect a release from size-selective mortality caused by the sea lamprey (see the subsections on sea lamprey and related discussion for burbot) rather than a growth response. Although body condition remains highest in the southern main basin and lowest in the north-central main basin, the basinwide declines in condition from 2002 to 2004 started in the south, and these waters experienced the largest decline. These declines in condition were associated with a large decline in abundance of alewife and other prey fishes (see the Prey Fish subsection). Beginning in 2002, the contribution of alewife to lake trout diets decreased in the southern main basin, and, by 2004, the species had nearly disappeared from diets (JEJ and JH, unpublished data). A similar decrease began in 2003 in the central waters of the main basin, but alewives remained common in lake trout diets in the northern part of the main basin through 2004. As alewife became scarcer in lake trout diets, total ration decreased, smelt became the most-common prey type, and diet diversity increased.

Increases in recruitment of wild lake trout have been observed in several locations in Lake Huron. Lakewide bottom-trawl surveys conducted by the Great Lakes Science Center (GLSC) in the main basin heretofore have rarely captured age-0 wild-born lake trout, but 22 were captured in the fall of 2004. Similarly, 11 wild age-0 lake trout were caught by the MDNR in 2004 during bottom-trawl surveys of Thunder Bay (Fig. 1), a number nearly matching the total catch from 1996 to 2003. In addition, wild lake trout were making up an increased proportion of older fish. The percentage of unclipped (assumed wild) spawning lake trout observed during fall gillnet surveys at two reefs in Thunder Bay reached or exceeded 35% in 2004. In South Bay (Manitoulin Island, Fig. 1), unclipped lake trout (mostly immature) amounted to 88% of the summer index catch from 2001 to 2004; during spawning assessments, an average of 48% of the catch was unclipped during the same period. In southern Georgian Bay near Owen Sound, the percentage of unclipped adult lake trout in fall spawning-stock assessments increased from 19% in 2000-2002 to 30% in 2004, and more-limited data from other sites suggested that unclipped trout may be widespread. While these are encouraging signs, the Parry Sound lake trout population remains the only spawning stock dominated by wild lake trout and considered rehabilitated (Reid et al. 2001).

In summary, the first milestone for lake trout rehabilitation in Lake Huron, measurable numbers of wild lake trout being produced, appears to be at hand at several locations. This progress may be maintained if, at a minimum, the current levels of yearling stocking, sea lamprey control, and fishery regulation are maintained. With an increasing presence of mature wild adult lake trout in some locations, the second milestone pertaining to self-sustaining wild spawning stocks is within sight.

Other Salmonine Predators

There are neither FCOs nor lakewide management guides for individual salmonine species within the "other salmonines" group, which excludes lake trout. Within this group, quantitative estimates of stock size and consumption of prey have been calculated only for Chinook salmon—the remaining species are considered to have played a lesser role in the overall predator-prey dynamics of the lake (Dobiesz 2003). Although lacking species-specific objectives, the group as a whole is expected to yield 0.6-1.0 million kg annually (see above), and each species contributed to an objective for a diverse salmonine community and fishery.

Chinook Salmon

Chinook salmon have been stocked by the MDNR since 1968 and by nongovernmental agencies in Ontario (Whelan and Johnson 2004; Woldt et al. 2005a). Lakewide stocking rates peaked at 5 million fish in 1989 (Fig. 2b). Stocking was capped at 1990 levels in 1991 due to concerns that predator consumption may have exceeded prey production. From 1991-1998, Chinook salmon stocking averaged nearly 4.2 million fish annually. It was reduced in 1999 to 3.5 million fish annually, in response to concerns of reduced prey abundance (Dobiesz 2003). Large reductions in stocking were considered again in 2004 due to declining prey-fish abundance (see the Prey Fish subsection) and declines in Chinook size-at-age and condition.

Prior to the 1980s, no reproduction of Chinook salmon was detected in Michigan tributaries (Carl 1982) or elsewhere in Lake Huron. However, from 1985-1987, presumed-wild Chinook salmon smolts were found in Ontario tributaries to southern Georgian Bay and to the main basin (OMNR, unpublished data). Shoal spawning by Chinook salmon was also reported in 1987 on lake trout spawning reefs in the North Channel (Powell and Miller 1990).

A study of the 1991-1995 Chinook salmon year-classes suggested that 15% of the age-0 recruits in Michigan waters were wild fish. In a more-recent study of the 2000 to 2004 year-classes as they recruited to the summer recreational fishery in both Michigan and Ontario waters, wild fish made up approximately 80% of the total lakewide catch. In retrospect, the estimate of

15% wild for the 1991-1995 year-classes was likely low, because it was based on sampling only age-0 fish near stocking locations at a time when stocked fish would not have been fully dispersed. On the other hand, because of a coded-wire-tag study reported by Johnson et al. (2007), we are confident that the percentage of wild Chinook salmon recruiting to the fishery was substantially less that 80% during the mid-1990s. Therefore, an overwhelming abundance of wild Chinook salmon did not occur until the late 1990s, at the earliest.

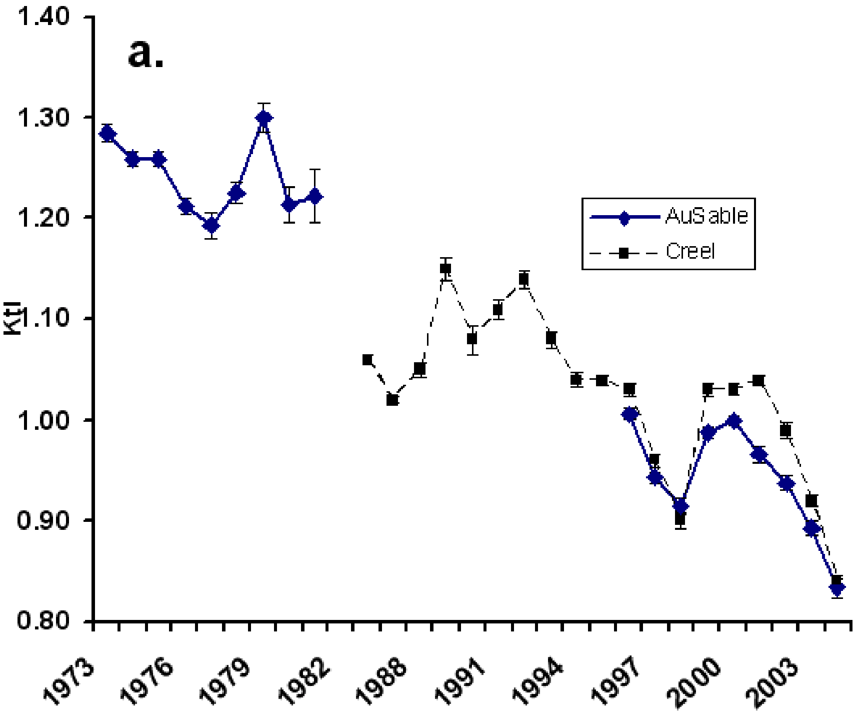
Wild Chinook salmon made up almost all (85-100%) of the spawning fish during 2002-2004 in four northern main basin and North Channel tributaries (Garden, St. Marys, Saugeen, and Carp Rivers) and in three Georgian Bay tributaries (Nottawasaga, Beaver, and Sydenham Rivers) (R. Greil, personal communication, 2005; DG, unpublished data). Therefore, we assume that other relatively unobstructed tributaries in Ontario, of which there are many, also contributed highly to production of naturally reproduced adults. In Michigan waters of Lake Huron, wild fish are thought to contribute measurably to recruitment in only the St. Marys, Carp, and Rifle Rivers, because other large cold-water tributaries are dammed near their mouths (Gebhardt et al. 2005). The contribution of shoal spawning to Chinook salmon recruitment remains to be quantified.

The recreational harvest of Chinook salmon at ten Michigan ports surveyed since 1986 declined in 1998-2001 but remained above 1986-1994 levels (Table 2). Harvest rose again in 2002 and was followed by a steep decline into 2004, when harvest reached its lowest point since 1992. Ontario creel data, available for some ports, indicated similar trends. The cycles of rising and falling rates in both jurisdictions do not appear to be correlated with stocking levels. The commercial yield of Chinook salmon in northern Michigan waters peaked in 1993 and has declined ever since. Total yield, which is reported only for Michigan, reached its second-highest level in 2002 (745,000 kg). However, both commercial and recreational harvests declined subsequently, and by 2004 total yield was less than 50% (322,000 kg) of what it was in 2002.

Table 2. Harvest in numbers of salmonines from ten index ports in the Michigan waters of Lake Huron, 1986 to 2004 (Michigan Department of Natural Resources, unpublished data).

Year	Chinook Salmon	Coho Salmon	Lake Trout	Brown Trout	Pink Salmon	Atlantic Salmon	Rainbow Trout
1986	85,669	6,801	53,530	15,286	104	0	5,090
1987	79,976	3,524	42,430	7,416	9,242	0	6,148
1988	90,134	4,126	39,644	2,730	141	17	2,658
1989	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1990	N/A	N/A	N/A	N/A	N/A	N/A	N/A
1991	43,100	762	18,116	1,685	4,728	0	4,294
1992	40,751	768	13,300	3,312	372	39	5,605
1993	49,115	1,061	6,570	7,765	1,702	158	7,024
1994	55,149	1,360	13,708	12,714	0	0	10,526
1995	96,393	1,897	34,360	14,086	799	301	17,807
1996	84,013	1,970	35,929	9,375	1,286	92	14,472
1997	125,490	2,719	48,142	3,735	751	138	12,146
1998	89,282	1,338	54,539	3,196	742	23	6,267
1999	75,398	5,014	36,810	1,826	1,062	96	8,757
2000	65,351	3,467	27,442	2,697	2,670	143	9,135
2001	58,584	2,003	18,846	1,669	9,332	312	7,546
2002	107,135	12,006	28,209	4,029	3,297	134	7,971
2003	83,376	1,362	43,981	5,743	391	130	4,791
2004	44,350	1,727	60,866	2,200	6,728	110	4,822

Size-at-age and body condition of Chinook salmon have declined since the 1970s (Fig. 4). Lowest values, which occurred in 1997-1998 and 2003-2004, followed times when pelagic prey was at low abundances (see the Prey Fish subsection). Although data are limited, large declines in growth and condition in Ontario waters were similar to those observed in Michigan waters. Chinook salmon now grow slower in Lake Huron than they did in Lake Michigan when a large die-off of salmon was thought to have resulted from diseases induced by food limitation (Holey et al. 1998). The limited data on the diet of Chinook salmon suggest that alewife and rainbow smelt are the dominant food items, and bioenergetics modeling demonstrated that Chinook salmon were the largest consumer of alewives in the late 1990s (Dobiesz 2003). A population decline in both of these prey species (see the Prey Fish subsection) would have serious implications for Chinook salmon condition and survival.



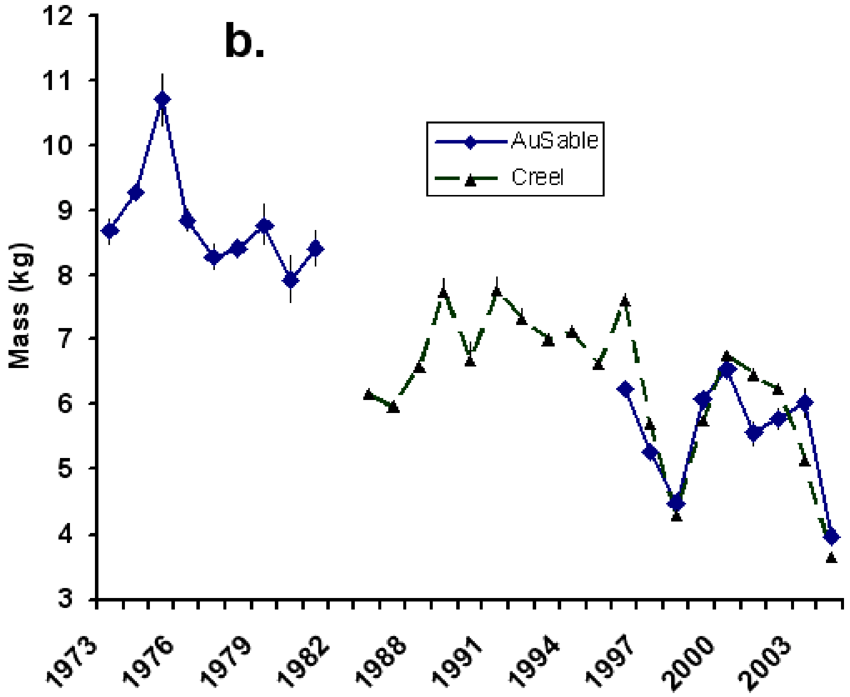


Fig. 4. (a) Body condition (Ktl) and (b) mass at age 3 of Chinook salmon from the recreational catch and fall sampling of the Au Sable River (no data collected 1982-1985).

Rainbow Trout

Stocked and wild rainbow trout (also referred to as steelhead) continued to contribute to a diverse salmonine community and fishery in Lake Huron as they did in 1995-1999 (Woldt et al. 2005a). Stocking of yearling rainbow trout fluctuated during 2000-2004, averaging 107,000 yearlings annually (Fig. 2b). All stockings of rainbow trout in Ontario waters were made by nongovernmental partners, who, in addition to stocking yearlings, planted an average of 313,000 fry annually in tributaries of the main basin and Georgian Bay.

All stocked yearling rainbow trout of the 1995-2004 year-classes were fin clipped to allow for estimation of levels of natural reproduction. During 2000-2004, an average of 42% of the rainbow trout observed in the Michigan creel (resulting from the 1995-2002 year-classes) had fin clips (JEJ, unpublished data). Up to 50% of the rainbow trout sampled at fishways in Ontario's main basin tributaries originated from fish stocked by Michigan, and the remainder were unclipped (Gonder 2005). Natural reproduction is limited in Michigan waters due to the presence of dams on most cold-water streams. Many of the unclipped fish harvested in Michigan waters were suspected of being wild fish produced in Ontario tributaries, although some of these fish could have resulted from fry stockings made in Ontario's waters (fry are not clipped). In Ontario waters, recruitment of wild fish remained substantial during 2000-2004 but was lower than in previous reporting periods.

Recreational harvest at Michigan's ten index ports (commercial harvest is not permitted in either jurisdiction) averaged over 11,000 fish during 1995-1999 (Woldt et al. 2005a) but declined to an average of below 7,000 during 2000-2004 (Table 2). Total yield in Michigan was over 22,000 kg during 2000-2002, which was somewhat above the 20,000 kg average for 1995-1999. Yield then fell to about 12,000 kg for 2003-2004, resulting in an average yield of 18,000 kg during 2000-2004. High exploitation in Ontario waters, despite stricter recreational-fishing regulations initiated in 1999, has contributed to cyclical levels of abundance there. In Georgian Bay, no discernible recovery to former levels of abundance has been observed (Gonder 2005).

In summary, harvest trends and other evidence suggest a possible decline, and certainly no increase, in rainbow trout abundance during the past five years. This species makes up only 1.8% of the total salmonine yield; thus, its current contribution to the desired diverse salmonine fishery is modest.

Brown Trout

Brown trout are stocked in Lake Huron to create diversity in the salmonine community, offer a nearshore fishery less seasonal than that for Chinook salmon, and provide an opportunity for anglers to harvest quality-to-trophy-size fish (Woldt et al. 2005a). Brown trout stocking in all jurisdictions of Lake Huron from 2000 to 2004 averaged 420,000 fish•y^{-1} (Fig. 2b), a figure similar to the average annual stocking rate in the 1990s. During 2000-2004, average reported yield of brown trout in Michigan waters of Lake Huron was 11,000 kg. Very little catch is reported from Ontario waters.

Although the yield for brown trout during 2000-2004 was approximately one-half that of rainbow trout, harvests had been similar for rainbow and brown trout at index ports in Michigan waters in the late 1980s and early 1990s. In the late 1990s, the harvest of brown trout declined more than did that of rainbow trout (Table 2), despite a series of management changes designed to improve the post-stocking survival of brown trout (Johnson and Rakoczy 2004). In years when large spawning aggregations of alewives occurred inshore at the time brown trout were stocked, survival was better, as evidenced by subsequent contributions to the sport fishery (Johnson and Rakoczy 2004). Stocked brown trout apparently do not migrate offshore to areas where predators may be less abundant, so the alewife may buffer them from predation. In the Thunder Bay area, cormorant predation has been implicated in reducing survival of recently stocked brown trout (Johnson and Rakoczy 2004). Recent drastic declines in alewife abundance could lead to even poorer recruitment of brown trout to the sport fishery.

Atlantic Salmon

Beginning in 1985, the Lake Superior State University, Edison Sault Electrical Company, and MDNR cooperatively stocked Atlantic salmon in the St. Marys River (Woldt et al. 2005a). Annual stocking has averaged about 40,000 yearlings. Since the 1990s, gametes for the stocking program have been taken from adults returning to the river, with the exception of 2000 when, because of losses in the university's hatchery, the MDNR provided young Atlantic salmon originally destined for inland lakes. Reported harvests have been low and fluctuated widely, with a peak of more than 300 fish in 2001 and about 100 fish each year during 2002 to 2004 at the ten Michigan index ports (Table 2). Actual harvest is substantially higher because the main Atlantic salmon fishery, located in the St. Marys River and Detour Island area, is not surveyed each year. In 2001, a creel survey estimated that 488 Atlantic salmon were harvested from the St. Marys River (Fielder et al. 2002).

Coho Salmon

Although no coho salmon have been stocked into Lake Huron since 1989, naturalized populations have continued to survive in several locations, including tributaries on the southern shore of Manitoulin Island and the Alcona, Black and Carp Rivers in Michigan. The harvest of coho salmon at the ten Michigan index ports on Lake Huron peaked in 2002 at more than 12,000 fish, almost double that of any other year. In most years, harvest was less than 2,000 fish (Table 2). Average annual yield during 2000-2004 was

10,000 kg. Without the exceptional yield of 32,000 kg in 2002, the average would be closer to 5,000 kg.

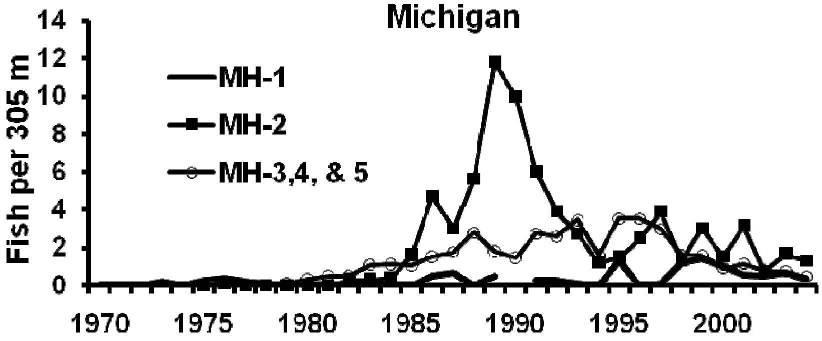
Pink Salmon

Pink salmon naturalized in Lake Huron following an accidental introduction into Lake Superior in the 1950s (Nunan 1967). Pink salmon normally mature and spawn at age 2 before dying (Kwain 1982), but, in recent years, substantial numbers of pink salmon returning to spawn in the St. Marys River have been of ages 3 and 4, a life-history pattern that has not been reported elsewhere (Kennedy et al. 2005). Since 1986, the average Michigan index-port sport-harvest estimate amounted to 2,500 fish (Table 2). A peak harvest of more than 9,000 fish was recorded at the same ports in 2001, but lower harvests followed in 2002 and 2003. In 2004, almost 7,000 fish were harvested, which was the first time a high harvest had occurred in an even-numbered year (Table 2). Average reported yield in Michigan during 2000-2004 was 3,000 kg. Spawning runs in the St. Marys River at one time were dominant in odd-numbered years, then changed to roughly equal numbers each year, and then became dominant in even years (Kennedy et al. 2005).

Burbot

The FCOs for Lake Huron recognize that burbot is important because of its ecological significance; intrinsic value; and social, cultural, and economic benefits (DesJardine et al. 1995). Burbot accounted for roughly 15% of the estimated predator consumption in the main basin of Lake Huron in the late 1990s (Dobiesz et al. 2005). Burbot are caught incidentally in bottom-set graded-mesh gillnet surveys and in the commercial fishery. The commercial fishery harvested nearly 15,000 kg of burbot annually during 1990-1999 (Lake Huron Technical Committee, unpublished data), but only 1,064 kg were reported harvested in 2004.

Burbot inhabit all depths of Lake Huron but are most abundant in waters 20-45-m deep. Large burbot appear to inhabit shallower water than small burbot, as evidenced by a decline in average total length of 628 mm at 0-9 m depths to near 500 mm in depths of 30 m or greater, based on graded-mesh gillnet samples from northwestern waters of the main basin (MH-1) during 1991-2004. Abundance of burbot has declined since 1999 (Schaeffer and Woldt 2005; Stapanian et al. 2008), but the declines occurred primarily in Michigan waters, most markedly in the southern part of the main basin (MH-3, 4, and 5) (Fig. 5).



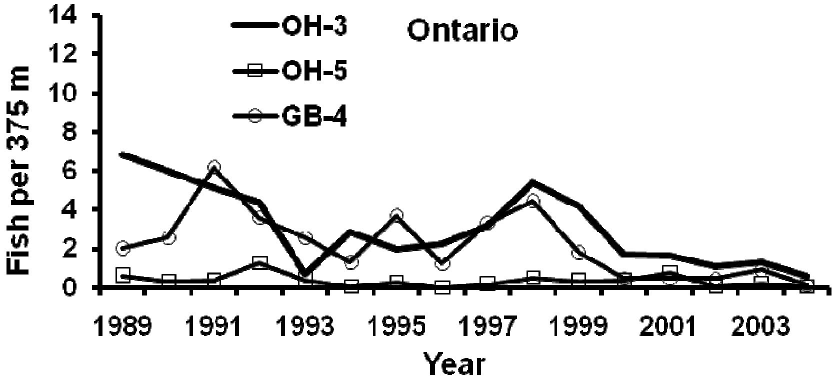


Fig. 5. Catch per effort of burbot in graded-mesh gillnets in Michigan and Ontario statistical districts of Lake Huron (see Fig. 1 for locations).

Burbot from Michigan waters of Lake Huron exhibited a broad age structure indicative of low mortality. From 1997 to 2004, burbot sampled in Michigan waters ranged in age from 3 to 28 y and had a median age of 12 y. Burbot captured in the Northern Refuge (Fig. 1) during the same period had the same age range and a median age of 13 y. The total instantaneous mortality rate of burbot in the Northern Refuge during 1997-2004 was estimated by catch-curve analysis to be $0.21•y^{-1}$ at ages 13-18 and $0.64•y^{-1}$ at ages 18-22.

The presence of older-aged burbot in northern parts of the lake may reflect slow growth and the consequent long delay in reaching larger sizes. A sizable amount of size-selective mortality may have been occurring on burbot in MH-1. Only 3% of burbot caught during spring graded-mesh gillnet surveys exceeded 650-mm total length during 1997-2004, as compared to 23% and 58% in MH-2 and MH-3, 4, and 5 (combined), respectively. In MH-1, mean length-at-age of burbot reached an asymptote of roughly 540 mm at age 10. In comparison, length-at-age continued to increase after age 10 in MH-2 and even more so in MH-3. Either growth has been very limited for larger fish in MH-1, or size-selective mortality has removed the largest burbot. Consistent with this latter hypothesis, sea lamprey marking of burbot has been substantially higher in MH-1 than in other statistical districts. Marking on burbot in MH-1 declined from an average of 8.5 marks/100 fish during 1991-1995 to 2.3 marks/100 fish during 1996-2000. Marking then increased to 4.5 marks/100 fish during 2001-2004. The reason for the change in marks per fish remains unclear as this pattern was not like that observed for lake trout.

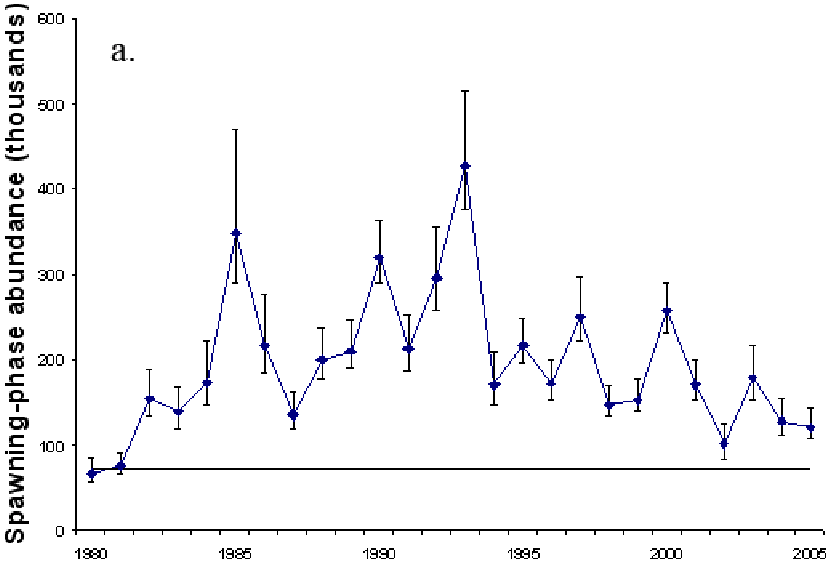
Double-Crested Cormorant

The consumption of prey fish by double-crested cormorants has become large enough that it needs to be considered in estimates of lakewide prey-fish consumption. The population of this piscivorous waterbird declined to low levels by the 1970s due to eggshell thinning and other reproductive anomalies associated with DDT contamination (Ludwig and Summer 1997). Following the ban on DDT, the lakewide population increased, occupying about 45,000 nests by 2000 (DGF, personal communication, 2006; Weseloh et al. 2002), with 38% of nests dispersed around the main basin and the remaining nests divided about equally between the North Channel (including the St. Marys River) and Georgian Bay (Dobiesz et al. 2005). Dobiesz et al. (2005) estimated that resident cormorants in 2000 consumed approximately 13.9 million kg of fish, 5.3 million kg of which was consumed in the main basin. This main basin consumption equaled 18% of the consumption these authors had estimated for the major piscivores (lake trout, Chinook salmon, burbot, and walleye) in the main basin, exclusive of Saginaw Bay in 1996-1998. By 2000-2001, cormorant populations may have been approaching carrying capacity. By 2004-2005, the number of nests declined by about 38% (DGF, personal communication, 2006; Ridgway et al. 2006), possibly in response to declines in alewife abundance (Ridgeway et al. 2006). These declines were most marked in the North Channel (including the St. Marys River area) and in Georgian Bay. In the main basin, declines in bird numbers in Ontario waters and in the Les Cheneaux Islands were offset by increases in Thunder Bay and Saginaw Bay. Control efforts, such as those that began in the Les Cheneaux Islands and used experimentally in the North Channel and Georgian Bay, may cause future declines in cormorant numbers.

Sea Lamprey

Reduce sea lamprey abundance to allow the achievement of other fish-community objectives. Obtain a 75% reduction in parasitic sea lampreys by the year 2000 and a 90% reduction by the year 2010.

The above objectives (DesJardine et al., 1995) were augmented by the LHC in 2004 to include a population reduction of adults to less than 73,000 and a reduction in marking rates on lake trout to five per 100 fish or less. These objectives are indeed ambitious in view of an estimate that, in 1999, the sea lamprey population of Lake Huron exceeded the populations in all the other Great Lakes combined (Morse et al. 2003). Although both adult (spawning-phase) sea lamprey abundance and lake trout marking rates have subsequently declined, they remain above target levels. Average abundance of spawning sea lamprey was 11% lower during 2000-2004 than it was during 1995-1999 (Fig. 6a). A1-A3 marks on lake trout (King 1980; Ebener et al. 2006) declined approximately 40% between these periods (Fig. 6b).



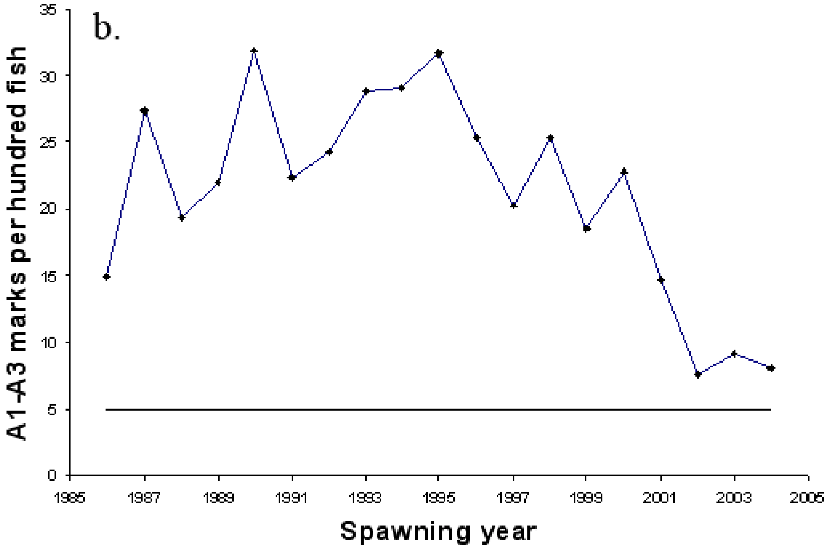


Fig. 6. Population estimates and 95% confidence intervals of spawning sea lampreys in Lake Huron (a), and spring A1-A3 sea lamprey marking rates on lake trout >533 mm total length, 1986-2004 (b). The horizontal lines represent the Lake Huron Committee's targets.

Trends in abundance of recently metamorphosed and parasitic-phase sea lampreys available for 1994-1995 and for 1999-2004 (Bergstedt et al. 2003; Klar and Young 2005) are inconsistent. Taken together, the trends for each life stage do not clearly indicate a decline since the mid-1990s (Young 2005). The contradictory patterns could reflect either large measurement errors in the mark and recapture studies or substantial temporal changes in the survival of transformers. The latter possibility would imply that, in the short term, damage caused by sea lamprey will only weakly correlate with control effort.

During 2000-2004, the GLFC increased its lampricide treatments on nursery streams and maintained its integrated control efforts on the St. Marys River. The TFM lampricide is the primary sea lamprey control tool used in Lake Huron tributaries, exclusive of the St. Marys River (Brege et al. 2003; Morse et al. 2003; Schleen et al. 2003). These TFM-treated tributaries contain approximately 66% of the larval habitat in the basin (GC, unpublished data). The average annual number of streams treated with TFM increased by approximately 10% from 2000-2004 (16.6 treatments annually) to 1990-1999 (15.0 treatments annually) (Morse et al. 2003; Morse and Young 2005).

Prior to 1995, the production of recently transformed sea lampreys from the St. Marys River, which contains the remaining third of larval habitat in the basin, was virtually unchecked. TFM treatment would have been too costly, and its effectiveness on the St. Marys River was questioned. An integrated control strategy was initiated in 1997 and consisted of targeted Bayluscide applications, enhanced trapping of spawning-phase lampreys, and release of sterilized male lampreys (Schleen et al. 2003; Twohey et al. 2003). Prior to 2000, integrated lamprey control reduced the larval population from 5.2 million to 2.1 million (Morse and Young 2005; J. Adams, personal communication, 2005). An additional 221 hectares of larval habitat have been treated or re-treated with granular Bayluscide since 1999. Also, an average of 10,800 spawning-phase lampreys have been trapped and 30,400 sterile males have been released annually, resulting in an 88% reduction in spawning potential. We believe these control efforts are a major reason why spawning-phase lamprey abundance and sea lamprey marking rates on lake trout have declined in the main basin.

Parasitic-phase sea lampreys move between Lakes Huron and Michigan (Bergstedt et al. 2003), and sea lampreys increased in abundance in Lake Michigan during 2000-2004 (Klar and Young 2005). A newly established population above a disintegrating dam on the Manistique River, a north-shore tributary of Lake Michigan, was identified as a major potential supplier to Lake Huron, but other suppliers remain to be identified. Reducing further the sea lamprey population of Lake Huron, especially in the northern main basin, may depend upon identification and treatment of sources in Lake Michigan.

Barriers have been constructed on some Lake Huron tributaries to deny adult sea lampreys access to spawning habitat, thus reducing the need for TFM treatments. As of 2004, a total of 19 barriers had been built or modified on Lake Huron tributaries (Lavis et al. 2003; Klar and Young 2005). Although no new barriers were constructed during this reporting period, in 2000, the GLFC expanded its partnership with the U.S. Corps of Engineers to build barriers in U.S. tributaries of Lake Huron under authority of the Water Resources Development Act. By 2004, at least four additional barriers were being planned for Lake Huron tributaries.

Prey Fish

Maintain a diversity of prey species at population levels
matched to primary production and to predator demands.

By the late 1950s, the exotic alewife and rainbow smelt came to dominate the offshore prey-fish community, supplanting a more-diverse assemblage of indigenous species (O'Gorman and Stewart 1999). However, a return to a more-diverse prey community is implied in the above objective (DesJardine et al. 1995). Native (lake trout and walleye) and non-native (Pacific salmon) predator species have been stocked in Lake Huron in an attempt to control the alewife population, which had reached nuisance levels by the 1960s. With high numbers of predators stocked annually in the Great Lakes, concern has been expressed that predator biomass would remain high regardless of prey abundance (Stewart et al. 1981; Jones et al. 1993). Consequently, predator stocking rates occasionally have been adjusted in Lake Huron, an attempt to both maintain predator pressure on alewife and avoid outright prey shortages.

Based on bottom trawling (Argyle 2005), alewife numbers and biomass declined more than 99% between 1999 and 2004, which led to major consequences for the fish community. Adult alewives increased in abundance during 1998-2002 due primarily to strong year-classes produced in 1998 and 1999 (Fig. 7) (Argyle 2005). However, the 2001 year-class suffered an estimated 94% annual mortality (based on a relative abundance of ages-1 and -2 trawl samples), and no fish of this year-class over age 3 were ever collected. The 2002 and 2003 year-classes suffered almost complete mortality during their first year of life, even though the 2003 year-class was exceptionally abundant to begin with. Thus, by 2004, the adult spawning stock was at an all-time low for the series. The 2004 year-class at age 0 was the smallest ever observed in the history of the survey. The failure of three consecutive year-classes, combined with high adult mortality, led to a rapid reduction in both alewife abundance and biomass by 2004.

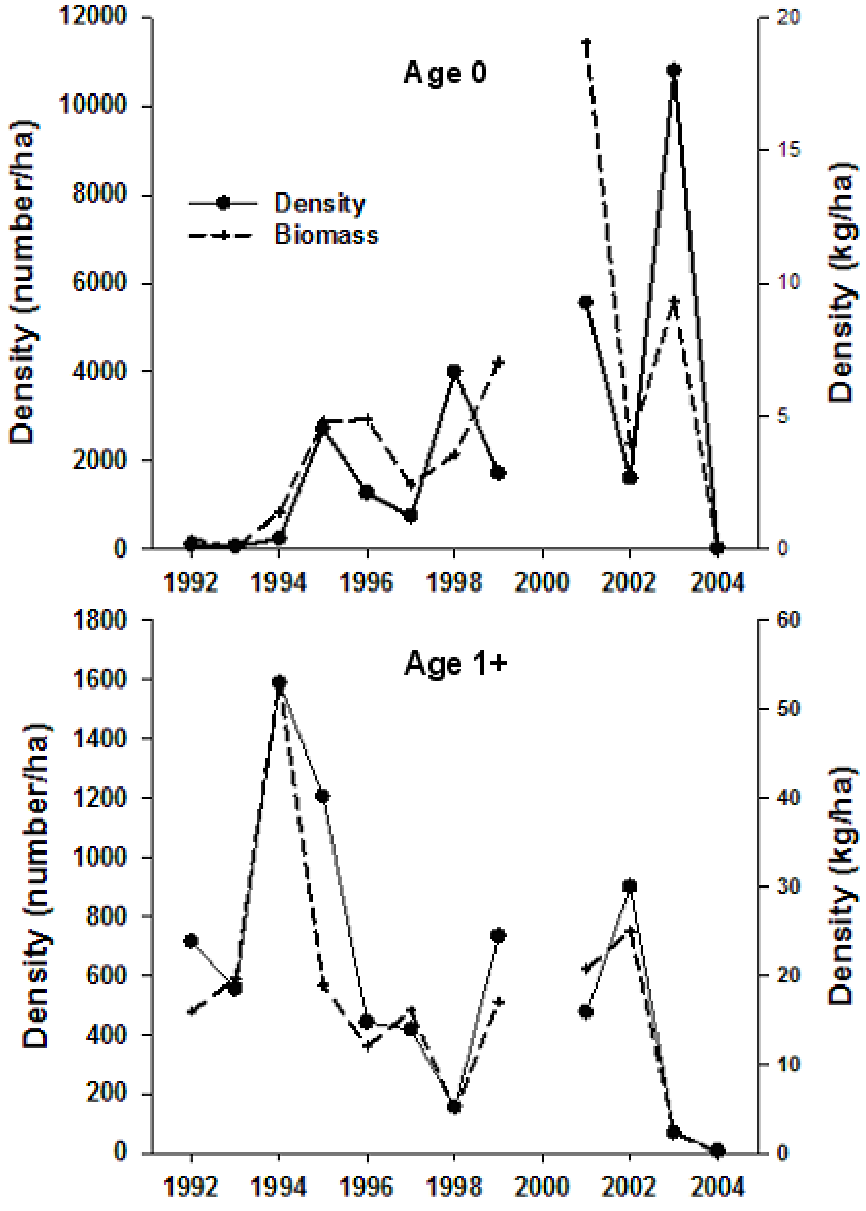


Fig. 7. Density (number/ha) and biomass (kg/ha) of age-0 and age-1 and older (1+) alewife, Lake Huron main basin, 1992-2004. No survey occurred in 2000.

The most-likely reason age-1 and older alewives declined was heavy predation by predators, with Chinook salmon and cormorants having the greatest impact (Dobiesz 2003, Dobiesz et al. 2005), although the winters of 2003-2004 and 2004-2005 were colder than normal and may have resulted in unusually high juvenile mortality (JSS, unpublished data). As predatory demand and mortality on juvenile and adult alewives increased during the 1990s, older and larger alewives began to disappear from the population. By 2001, adults were scarce, and alewife abundance was highly dependent on the number of age-0 fish surviving into their second year. Thus, when the 2003 and 2004 year-classes failed, the age-1 and older population declined rapidly.

Overall prey biomass declined 65% from 1999 to 2004, because no species fully replaced the alewife (Fig. 8). Rainbow smelt, bloater, and deepwater sculpin all exhibited higher recruitment after the alewife population declined. However, these species remained scarce numerically compared to earlier alewife abundances. Rainbow smelt density and biomass, although higher, remained low, and most individuals were less than 100-mm total length in 2004. Rainbow smelt are a preferred prey of salmonines (Diana 1990), but their low numbers and small size probably are inadequate to support robust growth of large salmonines, especially adult lake trout (Martin 1966; Madenjian et al. 1998). Round goby abundance increased through 2003 and then decreased in 2004. Other potential prey species, such as ninespine stickleback and trout-perch, declined in abundance during this reporting period.

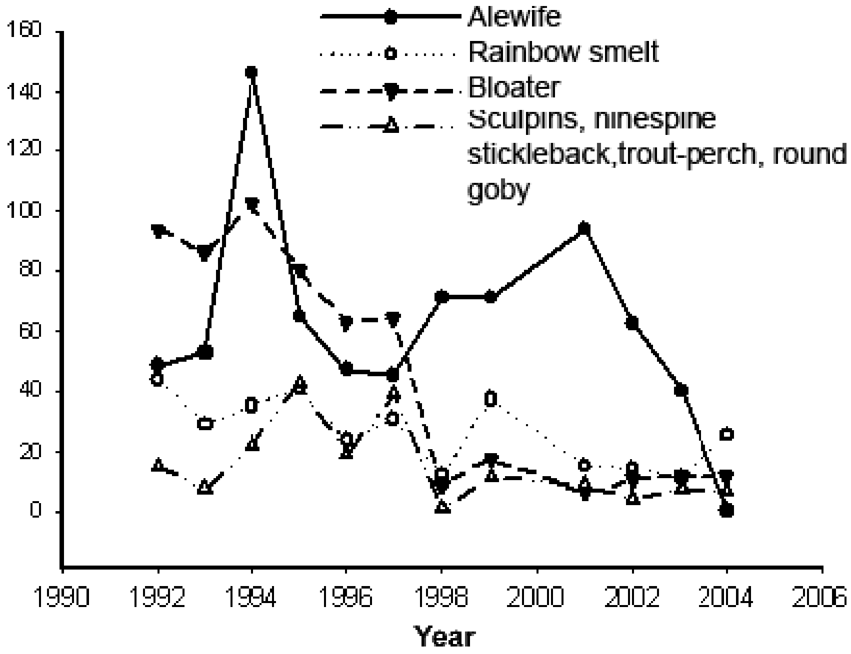


Fig. 8. Biomass of major prey species in U.S. waters of Lake Huron, 1992-2004. No survey occurred in 2000.

Although the alewife population was substantially reduced in abundance by 2004, alewives had not been extirpated from Lake Huron, and they remained abundant in Lake Michigan (Madenjian et al. 2005). Low numbers of adults can produce large year-classes (O'Gorman and Schneider 1986). Thus, alewives have the potential to regain their former abundance, although we suspect that this is unlikely if predator abundance remains similar to that seen during 2000-2004.

The resurgence in recruitment of native prey species, when adult alewives were scarce during 2003-2004, was a major finding. Bloaters produced strong year-classes in both years, and recruitment of wild lake trout and of deepwater sculpin were up in 2004. In Saginaw Bay, walleye and yellow perch produced strong year-classes in both years (see the Nearshore Fish Community section). The native species showing strong responses in recruitment represented four distinct fish families: Salmonidae, Coregonidae, Cottidae, and Percidae. Each species differed ecologically, but all had a common trait of having pelagic larvae, which are thought to be vulnerable to predation and competition by co-occurring alewife (Smith 1970; Crowder 1980; Eck and Wells 1987), although not all these responses may have been due to the alewife decline (see Madenjian et al. (2008) for additional discussion). These changes are consistent with the FCOs for Lake Huron, but the changes also raise important issues regarding prey availability, ecosystem stability, and the future diversity of the salmonine community.

Ecological Change

The most-striking change in the offshore fish community was the more than 99% decline in alewife abundance and biomass from 1999 to 2004. While the alewife population declined lakewide, recruitment increases were observed in other prey fishes and in wild-born lake trout and, in Saginaw Bay, in walleye and yellow perch (see the Nearshore Fish Community section). Increased recruitment of other prey fishes, however, was not sufficient to replace alewife, and total prey biomass declined. Whether other prey fishes can replace the alewife is not clear. In the short term, the scarcity of prey fish is likely responsible for the decline in Chinook salmon mass-at-age and body condition and for the very low harvest and catch rate in 2004 in the sport fishery. These observations suggest that natural mortality of Chinook salmon increased substantially or large numbers migrated to Lake Michigan, or both. The low abundance of alewife may also have contributed to high post-stocking mortality of brown trout and other salmonines. Larger-sized lake trout have also experienced declines in growth that appear to be related to decreases in the availability of larger prey, although the effect of prey scarcity on recruitment remains to be seen. Primary productivity during 2003-2004 may have been lower than in the past, and prey-fish production may have declined because the production at lower trophic levels is following different pathways (see the Issues Relevant across Fish Communities section). A substantial decline in productivity of prey fish could potentially impede the reaching of lakewide yield goals.

High levels of predatory demand were likely the major factor that contributed to the alewife population decline in Lake Huron and resulted from both continued hatchery releases of salmon, trout, and walleye and increased recruitment of wild Chinook salmon and walleye. The proportion of wild Chinook salmon in the population reached almost 80%, an unexpected level. When wild salmon began to dominate and the extent to which this domination represents a substantial change in total recruitment are unknowns. Regardless, if wild Chinook salmon continue to dominate, managers will have less ability to reduce predation pressure by reducing stocking. Increased overwinter mortality and changing lower-trophic-level impacts cannot be ruled out as factors that contributed to the decline of the alewife population.

The spread of round gobies, an invasive species (see the Issues Relevant across Fish Communities section), is also of concern. The species established in 1991 (Jude et al. 1992) and became widespread during 1998-2004, extending its range into both deepwater and shallow-water habitats (Schaeffer et al. 2005b). Round gobies have the potential to impact lake trout both as an egg and fry predator and as a source of food. Round goby abundance declined in trawl samples during 2004, perhaps because of predation by walleye, yellow perch, and lake trout.

Recommendations

We recommend an emphasis on determining the causes and consequences of the recent, dramatic decline in prey-fish abundance. Addressing these issues requires continued updating of existing models and assessing of predators, analyzing existing data on prey-fish stock sizes and productivity, and augmenting data collection. We recommend that all stocked fish in Lake Huron be marked so that hatchery-reared and wild-born fish can be distinguished. We also recommend that agencies consider approaches for fishery-independent assessments of predator populations and that prey-fish assessment designs allow for estimating absolute stock sizes and productivity. Such efforts should focus on understanding future responses of the prey-fish community to low alewife abundance.

We recommend aggressive planning for and implementation of actions that might diversify the prey base and the fish community as a whole, including, for example, selected reintroductions of cisco. Reintroductions should take into account many factors, such as genetics, feasibility, spread of disease, and potentially high rates of predation that the introduced fish may face given low prey-fish abundance. We further recommend a review of the current management of Chinook salmon and development of an interagency management plan for this species. Such a review should consider new kinds of data or information that will be required to manage a largely self-sustaining Chinook salmon population.

We recommend a thorough reevaluation of the lakewide status of all salmonines to include stocking rates, prey requirements, wild production, habitat needs, and harvest regimes. For species less impacted by declining prey fish (e.g., rainbow trout), we recommend remediating spawning habitat and keeping adult mortality rates at sustainable levels. Efforts to diversify the predator community should consider the ability of predators to feed on a diversity of prey, including invertebrates, and to survive periods of low food availability.

We also recommend aggressive action to promote lake trout rehabilitation (Johnson et al. 2004). Of particular importance is increasing the number of yearlings stocked while keeping mortality rates on adults sufficiently low. Sea lamprey control needs to be enhanced to meet the targets for marking rates and sea lamprey abundance. Harvest may need to be reduced in some parts of the lake.

Research and monitoring needs include refinement of fishery-independent lake trout indices of abundance, particularly for age-0 lake trout; continued monitoring of sea lamprey parasitic- and spawning-phase abundance, temporal variation in parasitic-phase survival, and interlake movements; standardization of surveys of spawning lake trout on reefs; improved understanding of factors influencing recruitment of hatchery-reared and wild lake trout; and additional evaluation and refinement of harvest management, including consideration of how life-history changes influence the selection of mortality targets and the effectiveness of lake trout refuges.