Feasibility of Rehabilitating and Supplementing Fisheries by Stocking Lake Whitefish in the Upper Great Lakes

White paper prepared for the Great Lakes Fishery Trust

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Authors:

James R. Bence (bence@msu.edu)

Travis O. Brenden (brenden@msu.edu)

Emily M. Liljestrand (liljest3@msu.edu)

Quantitative Fisheries Center

Michigan State University

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Summary

Lake Whitefish (*Coregonus clupeaformis*) have been highly valued by commercial fishers in the Great Lakes for more than a century, and have until recently been a crucially important part of commercial fisheries in Lakes Huron and Michigan. Lake Whitefish stocks have declined substantially in Lakes Huron, Michigan, and Erie over the past 15 years. Fishery yields have declined due to reductions in stock abundance, fishing effort, and changes in fishing conditions. Weight at age declines have also occurred, but these declines had largely already taken place when the fishery was producing peak yields. Herein, we consider the feasibility of augmenting fishery yields in Lakes Huron and Michigan through stocking of hatchery-reared Lake Whitefish. We consider the potential to increase yield through stocking fish at the summer fingerling (~2g), fall fingerling (>15g), and yearling stages. We used estimates of costs associated with various stocking scenarios based on construction costs for developing a coregonine rearing facility at the Jordan River National Fish Hatchery, and estimates of production to various stages based on the Ontario Ministry of Natural Resources and Forestry's protocol for Lake Whitefish stocking for Lake Simcoe. Through a review of primary and secondary scientific literature, we estimated survival of hatchery fish stocked at various life stages and calculated eventual recruitment to the fishery. We then expanded these estimates to yield enhancement based on yield per recruit calculations using 1836 treaty-ceded waters stock assessment results. Our results, based on the literature, suggest that stocking Lake Whitefish as summer fingerlings would not be cost effective because the enhanced production of this earlier stage is not sufficient to compensate for what is anticipated to be very low survival. Given published survival data, stocking at fall fingerling or yearling life stages would seem to be more viable alternatives. Running counter to this is experiences in Little Traverse Bay for Lake Herring, where stocking of summer age-0 fish appears to have been more successful than stocking older fish. This points out the need for direct investigations in Lakes Michigan and Huron as to the survival and success of stocking different life stages of Lake Whitefish. Based on published survival information, the return that might be expected from a Great Lakes Lake Whitefish stocking program, given best estimates of survival would be difficult to justify on purely economic grounds. Lake-wide declines from peak fishery yields for Lakes Huron and Michigan are approximately 2,200 and 1,250 metric tons, respectively. Within 1836 treaty-ceded waters, declines in yield have been about 700 and 900 metric tons for Lakes Huron and Michigan. We estimated the magnitude of hatchery operations and associated costs with enhancing yields by amounts equal to half the 1836 treaty-ceded water declines to the full lake-wide declines. Costs to produce the lowest levels of yield enhancement were substantial. For example, we estimated that to produce the lowest level of yield enhancement considered for Lake Michigan, it would be necessary to stock 21.2 million summer fingerlings and 24.4 million fall fingerlings, or 13.3 million spring yearlings under the most plausible levels of survival. Such operations would have annual long-term costs of $12 milllion to $14 million USD, and would require facilities on the order of 10 times those that will be in place for coregonine rearing at the Jordan River National Fish Hatchery. Survival of stocked fish is highly uncertain and alternative but not totally implausible survival values can lead to substantially different results from stocking. Alternative approaches to stocking are being explored, and potentially could improve return on investment over those calculated here.

Introduction

Lake Whitefish (*Coregonus clupeaformis*) have been highly valued by commercial fisheries in the Great Lakes for more than a century (Ebener et al. 2008). Lake Whitefish populations suffered adverse effects from habitat loss, overfishing, and introduction of exotic invasive species during the 1930s and 1940s. Following the establishment of large piscivore (Chinook Salmon [*Oncorhynchus tshawytscha*]) populations and resulting declines in exotic pelagic prey (Alewife [*Alosa pseudoharengus*] and Rainbow Smelt [*Osmerus mordax*]) densities, Lake Whitefish populations recovered considerably. By the early 1970s, Lake Whitefish were the mainstay for commercial fisheries in the three upper Great Lakes, and strong consistent recruitment (Casselman et al. 1996, Cook et al. 2005, Ebener 1997, Schneeberger et al. 2005) led to Great Lakes commercial yields that by the late 1990s were higher than what had been seen in nearly a century (Brenden et al. 2012, Ebener et al. 2008). Since the early 2000s, Lake Whitefish populations have experienced steady and substantial declines in stock size in four of the five Great Lakes (excluding Lake Superior). Declines in stock biomass have resulted from a combination of slower growth and reduced recruitment, with the decline in growth starting prior to recruitment declines (Hoyle 1999, Hoyle et al. 2005, Lenart and Caroffino 2016 & 2017, Mohr and Ebener 2005, Nalepa et al. 2005, Pothoven et al. 2001). Quantitative estimates of changes in recruitment are available for Lakes Superior, Huron, Michigan, and Erie based on stock assessments conducted in these lakes to set allowable harvest levels. On average, recruitment has remained relatively stable in Lake Superior, whereas recruitment to the fishery (estimated at age-4) has declined by approximately two-thirds in Lakes Huron and Michigan (with substantially larger declines in some areas), between the 1995-2004 and 2010-2016 periods. Recruitment in Lake Erie has declined to near zero (M. Ebener, Michigan State University, personal communication). Because recruitment is estimated at age-3 or age-4 in most assessment models, and the most recent estimates are the most uncertain in stock assessment models, there remains considerable uncertainty about recruitment in recent years. Available information suggests that Lake Whitefish recruitment has remained low in Lakes Huron and Michigan.

In February 2018, the Great Lakes Fishery Trust (GLFT) and Great Lakes Fishery Commission (GLFC) hosted a workshop to understand recent trends in Lake Whitefish populations across the three upper lakes, engage fishery managers in discussions about ongoing risks and threats to Lake Whitefish stocks, identify what is needed to address those risks and threats, and from identified information gaps develop priorities for research and management. During this workshop, stocking Lake Whitefish to augment wild populations and supplement Lake Whitefish fisheries was identified by stakeholders as a management action to possibly be considered. Prompted by this response, the GLFT elected to evaluate the feasibility of stocking Lake Whitefish to offset some of the yield losses that have occurred in the lakes.

At this point, it is unknown whether the substantial decline in natural recruitment of Lake Whitefish in the Great Lakes will be reversed. An evaluation of whether it is feasible to make up for natural recruitment decreases through planting of hatchery reared fish will address whether this potential management option could help make up for the losses the fishery has experienced, and at what cost.

On its face, supplementation or rehabilitation of Great Lakes Lake Whitefish stocks through stocking cannot be ruled out, and the potential viability of this option has led management agencies to previously explore this option. Todd (1986) concluded that large-scale fry stocking was not a practical option for augmenting natural reproduction of Great Lakes Lake Whitefish. Todd (1986) pointed out that although 32 billion fry were stocked in the Great Lakes between 1870 and 1960, these efforts did not prevent the collapse of Lake Whitefish stocks. Likewise, Christie (1963) did not find evidence of increases in yield stemming from historical fry stocking in Lake Ontario, including from an alternate year stocking experiment. Van Oosten (1942) also was not able to find evidence of increases in Lake Whitefish harvest from fry stocking in Lake Erie. Todd (1986) concluded that historical stocking efforts were not sufficient to have affected Great Lakes Lake Whitefish populations or fisheries; Todd (1986) estimated that stocking on the order of 41% of the natural hatch would be needed for stocking to augment natural reproduction. Todd (1986) estimated that fry stocking densities in the Great Lakes would need to be between 575 and 1,944 fry/ha for stocking to be successful. This equated to needing to stock 1.1 to 3.7 billion fry in Lake Ontario, 1.5 to 5.1 billion fry in Lake Erie, and 1.0 to 3.3 billion fry in U.S. waters of Lake Huron on an annual basis for stocking to have a reasonable chance of success (Todd 1986). A stocking program of this scale was not considered to be practical.

There are instances of *Coregnous* spp. stocking having beneficial effects on recipient populations and/or the fisheries that exploit the populations. For example, the Ontario Ministry of Natural Resources and Forestry has stocked Lake Simcoe with fingerling Lake Whitefish since 1982, with some demonstrated contributions to the recruited populations (Amstaetter and Willox 2004). Fry stocking of *Coregonus* spp. in Europe is a widespread practice and there is evidence from some systems that stocking results in substantial yields (e.g., Eckman et al. 2007, Gerdeaux 2004; Jokikokko and Huhmarniemi 2014, Leskelä et al. 2002, Salojärvi, K. and Huusko, A. 2008). Fry stocking programs that have been successful in Europe have typically involved stocking densities that far exceeded historical fry stocking densities of Lake Whitefish in the Great Lakes. Oldenburg et al. (2007) recommended stocking of Lake Whitefish be carried out in Lake Erie to help recover Lake Whitefish stocks, although they recommended that stocking involve egg seeding on areas that might be suitable spawning habitat for the species and with fingerling or yearling-stage Lake Whitefish.

Todd (1986) acknowledged that a stocking program involving fingerling or yearling Lake Whitefish could be successful in the Great Lakes region as required stocking densities would be lower, but noted that at that time the culturing of *Coregonus* spp. to those later life stages was not frequently practiced and much needed to be learned before fish could be raised successfully to these older ages. As noted previously, Lake Whitefish are now being successfully cultured to fingerling and yearling stages (Amstaetter and Willox 2004). Consequently, the timing seems appropriate for a thorough evaluation of the possibility of stocking Lake Whitefish as a means to supplement/rehabilitate populations and/or fisheries in the Great Lakes.

Our focus in this report is stocking Lake Whitefish at the fingerling or later life stages. Given the substantial declines in recruitment that has occurred in the Great Lakes, it is possible that the survival of fry has substantially decreased, whereas older stages may not have experienced as severe declines in survival. There have been some studies on the relative success in stocking later stages of Lake Whitefish and other *Coregonus* species, which could provide some guidance on survival of these stages (e.g., Amtstaetter and Willox 2004). There are also a number of studies that have evaluated appropriate rearing conditions for Lake Whitefish (e.g., Brooke 1975, Drouin et al. 1986), and this and other information has been used to develop rearing protocols for Lake Whitefish in Ontario, and to inform hatchery practices for coregonines in the Great Lakes.

Herein we seek to evaluate the biological and economic feasibility of rehabilitation and supplementation of Great Lakes Lake Whitefish fisheries through planting of hatchery-reared fish. A review of stock sizes in the upper Great Lakes indicates that although recruitment has been low in these areas, spawning biomass is not critically low, and is in fact higher than in the 1980s. The 1980s spawning stocks produced some of the strongest year classes seen in the upper Great Lakes, which led to peak performance of the fishery. Thus, our emphasis has been on how yield would be enhanced by stocking, rather than on how stocking would cause increases in spawning stocks. This said, sustained low recruitment could eventually put spawning stocks in jeopardy, and our estimates of recruits produced at age 4 could easily be used to calculate potential contributions to the spawning stock by multiplying recruits produced by stocking and spawning stock per recruit estimates.

This evaluation was conducted based on existing data and information (i.e., no new data were collected, rather we reviewed and synthesized information available from the literature or that could be provided by a working group of hatchery experts). We specifically evaluated how many Lake Whitefish would need to be stocked at different life stages to substantially enhance Lake Whitefish fisheries. We evaluated the costs associated with producing these required stocking numbers, and more generally considered the economic costs of production versus the beneficial return to commercial fisheries. In addition to providing best estimates, we discuss uncertainties associated with our calculations and evaluation.

The extent of declines in Lake Whitefish in the Upper Great Lakes

In the upper Great Lakes, substantial declines in Lake Whitefish populations and yields have been reported for Lakes Huron and Michigan, with biomass estimated to have declined between 50 and 90% from peak levels in the mid to late 1990s. On Lake Superior, there is little evidence of widespread declines in Lake Whitefish. The declines seen in Lakes Michigan and Huron have been attributed to declines in both growth and recruitment (Broadway et al. 2016).

On Lake Michigan, reported Lake Whitefish yields peaked at approximately 3.6 million kg (round weight) in 1996, equating to 7.9 million pounds. Yield declined somewhat and appeared to fluctuate without strong trend during 2002-2012 within the established Fish Community Objective range of 1.8 to 2.7 million kg (4-6 million pounds). Starting in 2013, reported yield declined again and appeared to be approaching around 1 million kg (2.2. million pounds) (Broadway et al. 2016). These lake-wide patterns reflect a mixture of different dynamics in different areas. Notably, although yield declines in many areas of the lake have been severe, lake-wide declines have been ameliorated by yield increases in Green Bay associated with the emergence of river-run spawning populations, although the increases in those stocks have little effect on fisheries in eastern Lake Michigan including 1836 treaty-ceded waters. Quantitative estimates of Lake Whitefish abundance at age are available in 1836 treaty-ceded waters of Lakes Michigan (as well as for treaty waters of Lakes Huron and Superior) based on relatively consistent applications of statistical catch at age analyses (SCAA). The assessed treaty-ceded waters represent areas where the bulk of the lake-wide yield was taken in Lake Michigan during the peak of the fishery (e.g., approximately 83% in the peak year). In the assessed treaty areas, yield values are adjusted for non-reporting so tend to be somewhat higher than yields for the same areas based directly on catch reports and reported in other sources, but are likely more accurate reflections of actual yields. These yields in treaty waters began declining before 1995 even though population biomass continued to increase until 2005. The reasons for the initial declines in yield are complex and involve management actions, declines in desirable large fish, and deteriorating fishing conditions (water clarity and net fouling by filamentous algae). After 2005, declines in stock abundance in treaty-ceded waters clearly played a role in yield declines.

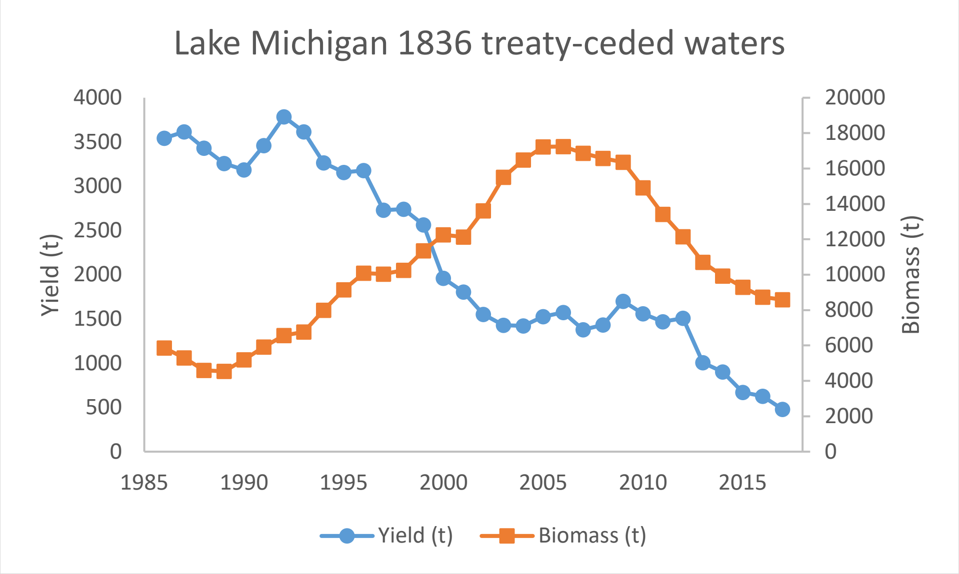

Figure 1. Yield and biomass trends in assessed areas of 1836 treaty-ceded waters of Lake Michigan. Values are in metric tons (t, 1 metric ton = 2205 pounds).

The population biomass reflects the combined influence of recruitment, growth, and mortality. Extensive analyses in treaty-ceded waters indicate that increased mortality rates are not a primary cause of population declines, as these stocks have generally been managed at or below fishing target levels, with no overall pattern of increasing mortality over time. While size-at-age has declined over time in Lake Michigan, the timing of this decline is such that it does not explain the decline in biomass in the latter part of the time series in the treaty waters. Averaged over units, there has been little change in size at age since 2005 in treaty waters, with perhaps some evidence of increased growth more recently (Figure 2). In contrast, recruitment has declined substantially in Lake Michigan within the assessed treaty-ceded waters (Figure 3).

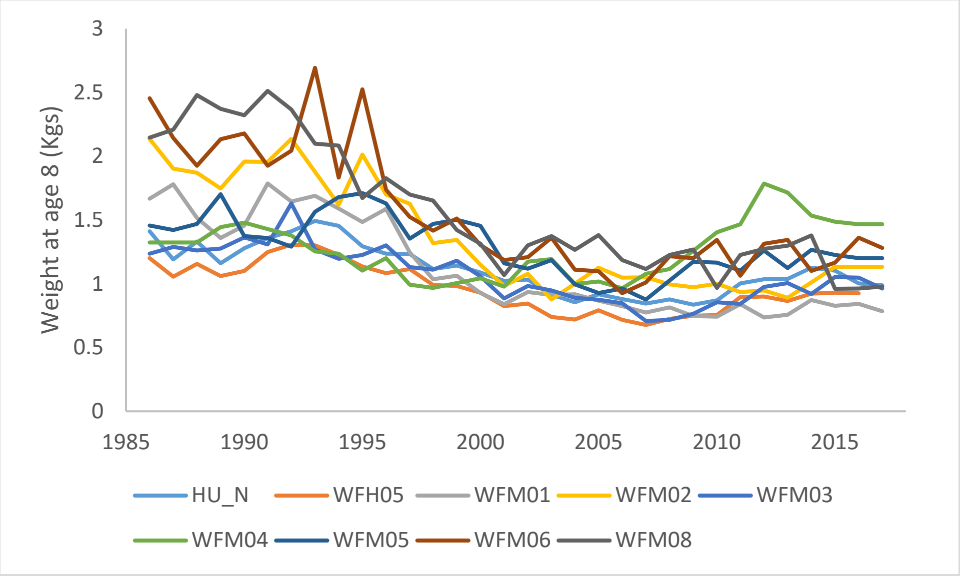

Figure 2. Weight at age-8 by assessment unit. HU_N is a unit in northern main basin Lake Huron that combines 4 statistical reporting units. Other units correspond to statistical reporting units. For example WFM04 is Lake Whitefish Lake Michigan reporting unit 4, and WFH05 is Lake Whitefish Lake Huron reporting unit 5.

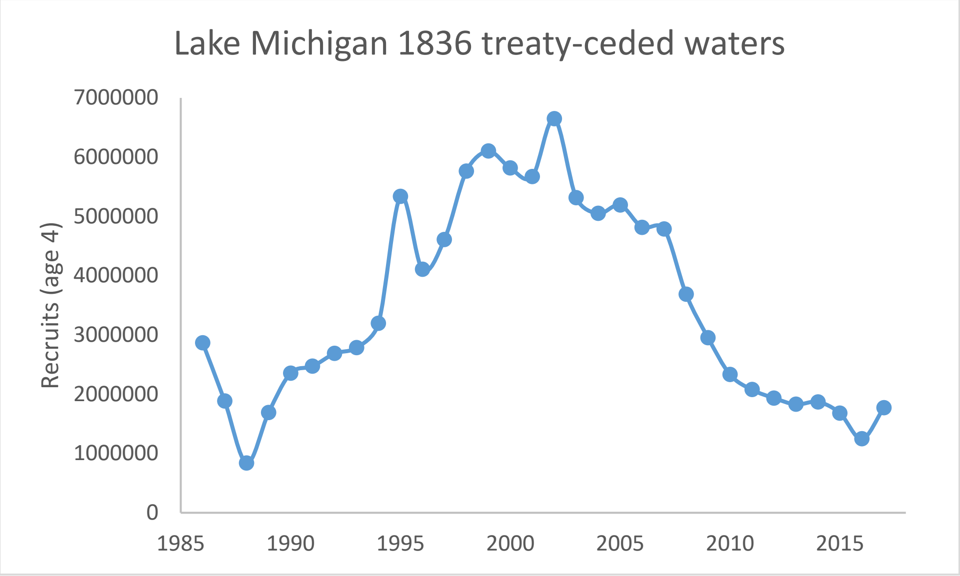

Figure 3. Estimated total recruitment (summed over spatial units) within the assessed 1836 treaty-ceded waters of Lake Michigan.

It is challenging to ascertain how much of the decline in yield was caused by the decline in recruitment, and more importantly in the current context, how much might be recovered by adding recruits through stocking. In the treaty-ceded waters, yield declined from ≈1.5 million kg (3.3 million pounds) per year (averaged over 2003-2012) to 0.59 million kg per year (1.3 million pounds) during 2015-2017 (39% of the earlier period) with a low in 2017 of 0.48 million kg (32% of the earlier period). Thus the decline was 900,000 kg (2 million pounds) in treaty waters. Biomass values in treaty waters for the same periods were 15.5 million kg, 8.9 million kg (57%), and 8.5 million kg (55%). Given that the biomass declines were not as large as the yield declines, it is likely that not all the declines in yield can be ascribed to declines in fish availability. On the other hand, recruitment in treaty waters during 2013-2017 averaged 30% of that seen during 1997-2004, a period supplying the bulk of the population during the early period (2003-2012). Based on these numbers, it is reasonable to conclude that the observed decline in recruitment will ultimately be responsible for a loss in yield in treaty waters at least equal to the decline in yield between 2003-2012 and 2015-2017. In treaty waters this would be 900,000 kgs (2 million pounds) and accounting for expected losses in yields outside treaty waters a total of 1.25 million kg (2.8 million pounds) in yield lakewide.

In the assessed treaty-ceded waters of Lake Huron, biomass increased until 1995, was relatively stable through 2005, and then began declining (Figure 4). Yields in treaty waters fluctuated substantially but without trend from 1986 until 1998, and then began declining. Size at age within the treaty-ceded waters of Lake Huron declined but has been, averaged over areas, relatively stable or slightly increasing since 2005 (Figure 2). While there is spatial variation, this same general pattern appears consistent lake-wide (Cottrill et al. in review). Recruitment in treaty-ceded waters of Lake Huron has been declining since 1999 (Figure 5). Based on these temporal patterns, we considered an early period for recruitment from 1995-2000, and for yield and biomass from 2001-2006, compared to 2015-2017. Biomass in treaty waters fell from 11.4 million kg to 5.8 million kg between periods (to 50% of the early period), with yield in treaty waters falling from 0.80 to 0.12 million kg (to 15.6%), and recruitment falling in treaty waters to 41% of the early period levels during 2015-2017. Fish in treaty-ceded waters represent a smaller proportion of the overall Lake Whitefish fishery in Lake Huron than in Lake Michigan. Lake-wide yield declined from 3.7 to 1.5 million kg between the early period and 2015-2017, representing a decline to 41% of the early period. If the early period is redefined as 1997-2001, to bracket the peak of lake-wide yield, yield in 2015-2017 is 35% of that in this period.

Yield has declined for reasons other than Lake Whitefish availability. Cottrill et al. (in review) reported a one-third reduction in gillnet effort between 2002 and 2017, which likely contributed to yield reductions. The lake-wide decline in yield is, on a percentage basis, substantially less than what was seen in treaty-ceded waters. We suspect more of the decline in treaty-ceded waters reflects management limitations due to attempts to limit lake trout mortality. Given that we know gillnet effort has been reduced by a third, and that in treaty-ceded waters the yield reduction is likely much larger than the population biomass reduction, we believe it is reasonable to attribute 50% of the lake-wide reduction to declines in recruitment.

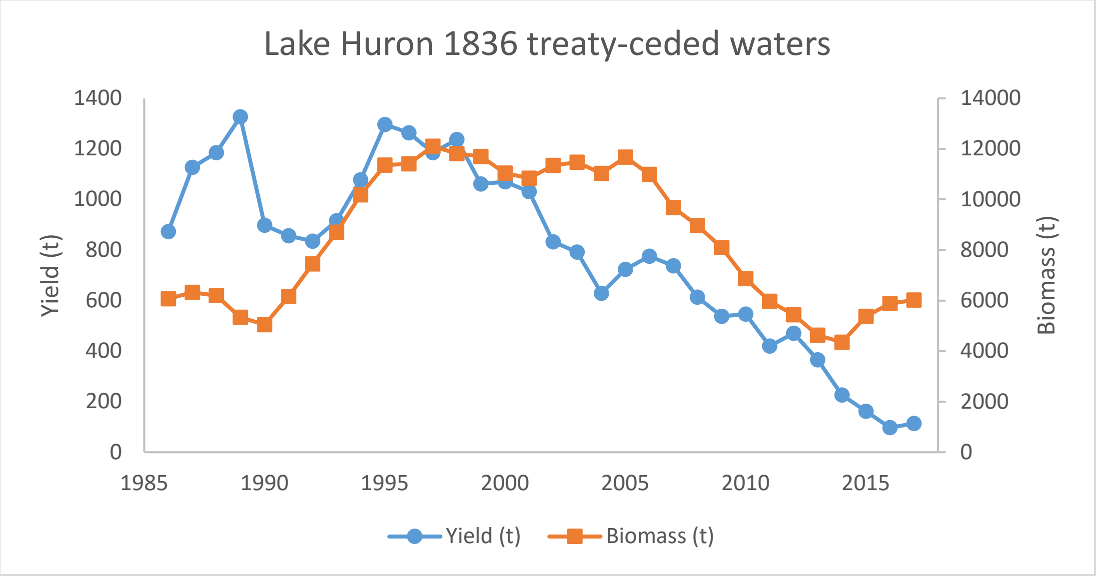

Figure 4. Yield and biomass in assessed areas of 1836 treaty-ceded waters of Lake Huron. Values are in metric tons (1 metric ton = 1000 kg or 2205 lbs).

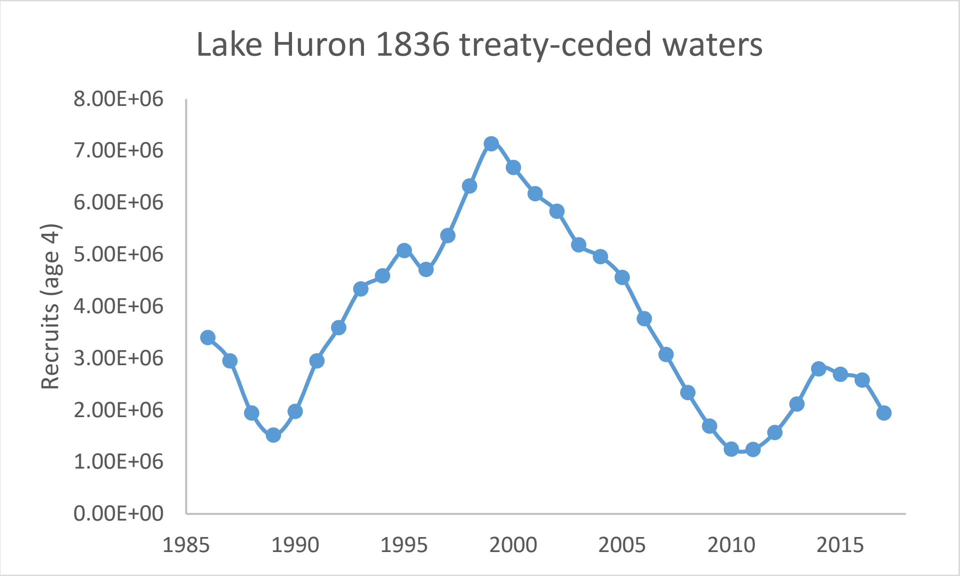

Figure 5. Estimated total recruitment (summed over units) within the assessed 1836 treaty-ceded waters of Lake Huron.

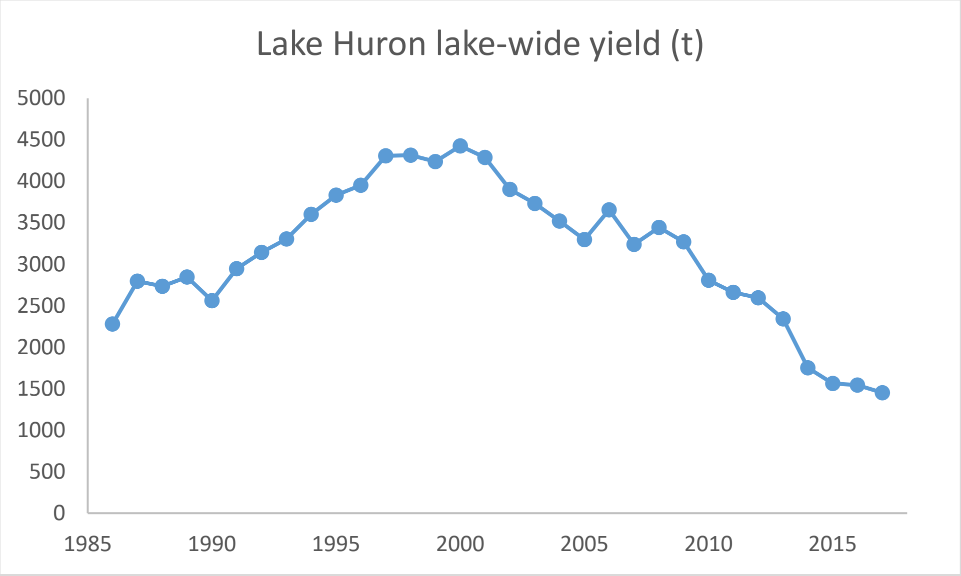

Figure 6. Lake-wide Lake Huron total Lake Whitefish yield based on data summarized in Cottrill et al. in review. Units are metric tons (1000 kg or 2205 lbs).

Estimates of survival from various stages to recruitment to the fishery

We reviewed primary and secondary scientific literature to identify survival rates of stocked or wild *Coregonus* spp. in natural systems. The literature review was conducted primarily using Google and Google Scholar; we also attempted to locate references to survival rates in published works identified from the literature review. Terms that were used in the searches included combinations of 'Lake Whitefish', 'whitefish', 'Coregonus', 'survival', 'mortality', 'recruitment', 'hatchery', 'fingerling', 'larvae', 'juvenile', and 'stocking'. We additionally searched primary and secondary scientific literature for studies that compared survival between stocked fish and wild fish at the same age to determine the degree to which survival of stocked fish was expected to decline relative to that of wild fish.

The preponderance of survival values that we found in the scientific literature were for egg-stage and adult *Coregonus* spp., which were not relevant for this study as stocking egg-stage Lake Whitefish is not presently being considered and adult survival values came from Lake Whitefish stock assessments being performed in 1836 treaty-ceded areas of Lakes Michigan and Huron. For larval-stage Lake Whitefish, the majority of published survival rates were from laboratory and hatchery settings, which also were not relevant to this study as survival in these settings is believed to be much higher than survival in natural systems.

Multiple studies reported survival rates for wild age-0 Lake Whitefish or other *Coregonus* spp. Taylor et al. (1987) and Freeberg et al. (1990) reported larval survival rates for weeks 1 to 7 after hatching of 72.4% in 1983, and for weeks 1 to 6 after hatching of 40.6% in 1984 in Grand Traverse Bay, Lake Michigan. This would equate to a daily instantaneous mortality ranging from 0.0077 to 0.0258. Extrapolating those mortality levels to the entire year and assuming Lake Whitefish hatch around March 15 results in age-0 survival rates from the larval stage ranging from 0.06% to 10.7%, although this assumes that survival of larval Lake Whitefish is the same as that of older age-0 fish. Henderson et al.

(1983) reported egg to end of age-0 survival rates for Lake Whitefish in Lake Huron ranging from 0.008% to 6.518%, with an average survival of 1.224%. In Lesser Slave Lake, Alberta, Canada, Bell et al. (1977) reported egg to end of age-0 survival rates of approximately 0.02% for Lake Whitefish. For vendace (*Coregonus fera*) in Sweden, Hamrin (1986) reported first year of life survival values as high as 5%, but noted that in most years survival was generally much closer to 0%. Karjalainen et al. (2000) estimated survival rates for newly hatched vendace for the first 6 months as high as 15.4% but as low as 0.5%. Eckmann (2012) reported survival rates from egg to commercial size in natural recruited European whitefish (*Coregonus lavaretus*) of around 0.019%; survival rates increased to 0.046% when eggs laid by age-2 females were excluded from the analysis because eggs of this age class were believed to be of lower quality than older females. Nümann (1967) cited in Todd (1986) for European whitefish in Lake Constance on the border of Austria, Germany, and Switzerland reported egg to commercial size survival rates ranging from 0.024 to 0.192%, with an average survival of 0.076%.

Survival rates for wild Lake Whitefish as juveniles (i.e., fish age-1 and older but that have not yet recruited to commercial or recreational fisheries) have been reported in several studies. Bell et al. (1977) estimated an average juvenile survival rate for Lake Whitefish in Lesser Slave Lake of 62.7%. Mills (1985) estimated juvenile survival rates ranging from 55 to 88% in a lake in the Experimental Lakes Area in northwestern Ontario, with an average survival rate of 73%. Taylor et al. (1987) estimated a juvenile annual survival of 60% for Lake Whitefish in East Traverse Bay, Lake Michigan. In a modeling study examining population regulation in Lake Whitefish, Jensen (1981) assumed a juvenile survival rate of 58%.

The scientific literature is largely devoid of stage-specific survival rates of stocked *Coregonus* spp. during their first year. Herein we refer to fingerling and fall fingerling, which we take as functionally equivalent to the summer and fall age-0 fish we consider in stocking scenarios, although there is some variability in nomenclature for these stages in the primary literature. As an example of the dearth of information on stage-specific survivals, we were unable to find any mention in the literature of expected survival of Lake Whitefish between fry and the fingerling stage or between fish stocked at that stage and fall fingerling. For European whitefish, Gerdeaux (2004) indicated that a general rule of thumb was that 1 stocked fall fingerling equated to 10 stocked fingerlings or 100 stocked larvae. This suggests a 10% survival rate between the larvae and summer age-0 stage and between that stage and fall age-0, irrespective of the survival rate of fall age-0 fish to the end of age-0. Most survival values for stocked *Coregonus* spp. found in the literature were for all of age-0 or extended out to even older ages. For European whitefish, Vostradovsky (1986) reported that survival of larvae stocked in systems with numerous predators ranged from 0.06 to 0.15%, although they did not specify the time span that these survival rates covered.

We found few published studies that compared survival rates between stocked and wild conspecifics. The few studies that we did find on this subject did not address differences in survival of *Coregonus* spp. It is generally believed that stocked fish suffer elevated mortality rates immediately after stocking due to high predation rates, but that shortly after stocking survival rates of stocked fish are comparable to that of wild fish (Brown and Day 2002). Differences in survival between hatchery and wild conspecifics are largely believed to stem from hatchery fish having poor antipredator responses (Brown and Day 2002), although some studies have also indicated there is a genetic or heritable component of poor survival in hatchery individuals (Reisenbichler and McIntrye 1977; Garcia de Leániz et al. 1989). For Atlantic salmon, Garcia de Leániz et al. (1989) estimated that recruitment to the fishery was 5 times greater in wild eggs versus stocked eggs. Svasand et al. (1989) estimated that for Atlantic cod (*Gadus morhua*) survival of hatchery fish is less than half that of wild fish.

Based on our literature review, we identified baseline, low, and high stage-specific survival rates for evaluating expected returns to the fishery based on stocking of different life stages (Table 1). The baseline rates represent our best estimates of survival that wild and hatchery-reared Lake Whitefish would experience in the Great Lakes, whereas the low and high rates represent plausible worst and best possible conditions for survival. Using these stage-specific survival rates, we calculated predicted overall survival rates that were reported in some of the studies identified from the literature review. These expected overall survival rates along with the actual values from the individual studies are shown in Table 2. In most cases, the baseline survival rates predict survivals within the range of values identified in individual studies. The low and high survival rates predict survivals that are generally outside the range of values identified in individual studies, but are still plausible estimates for these rates.

The Little Traverse Bay Bands of Odawa Indians has been culturing coregonines since 2013, starting primarily with Lake Herring but in the last year stocking 40,000 spring age-0 Lake Whitefish >60 mm in length as well 85,000 Lake Herring. Lake Herring stocking as fall age-0 and spring yearling has not been successful whereas stocking of spring fish has produced detectable returns in surveys out to over age-2. The spring age-0 Lake Whitefish have been seen in netting throughout the summer as age-0 suggesting reasonable survival. Taken in total these results suggest that survival of spring Lake Whitefish in Little Traverse Bay, at least, might be higher than what we have calculated based on literature reports.

Table 1. Assumed survival rates of wild Lake Whitefish at different age-0 life stages and as juveniles (from age-1 to the age of recruitment to the fishery) for the purpose of evaluating the feasibility of rehabilitating/supplementing Great Lakes Lake Whitefish fisheries through planting of hatchery-reared fish. Also shown is the assumed reduction in survival for hatchery-reared Lake Whitefish (post-stocking survival). Survival rates in the Baseline column represent baseline values for evaluations, whereas the rates in the Low and High columns represent the worst and best possible conditions for survival.

Life stage	Baseline	Low	High
Fry to (summer) Fingerling	10%	2.5%	15%
Fingerling to Fall Fingerling	10%	5.0%	20%
Fall Fingerling to End of First Year	50%	30%	70%
Juvenile (age-1 and older)	65%	45%	85%
Post-stocking survival	25%	5%	50%

Table 2. Survival rates identified from the scientific literature review and expected survivals for similar age and time spans calculated using the assumed survivals presented in Table 1.

Survival Rate/Metric	Citation	Published Values	Expected Values		
			Baseline	Low	High
Larvae:fingerling:fall fingerling equivalents	Gerdeaux (2004)	100:10:1	100:10:1	800:40:1	33.3:6.7:1
Age-0 survival of wild Lake Whitefish (from larval stage)	Taylor et al. (1987)	0.06 to 10.7%	0.5%	0.04%	2.1%
Age-0 survival of wild Lake Whitefish (from egg stage)	Henderson et al. (1983)	0.01% to 6.52%	0.1%[a]	0.008%[a]	0.42%[a]
Age-0 survival of wild Lake Whitefish (from egg stage)	Bell et al. (1977)	0.02%	0.1%[a]	0.008%[a]	0.42%[a]
Survival from egg to exploitable age	Nümann (1967)	0.024 to 0.192%	0.042%[a,b]	0.002%[a,b]	0.303%[a,b]
Survival from egg to exploitable age	Eckmann (2012)	0.019 to 0.042%	0.042%[a,b]	0.002%[a,b]	0.303%[a,b]
Age-0 survival of stocked fish (from larval stage)	Vostradovsky (1986)	0.06 to 0.15%	0.125%	0.002%	1.05%
Juvenile survival	Bell et al. (1977)	62.7%	65%	45%	85%
Juvenile survival	Mills (1985)	55 to 87%	65%	45%	85%
Juvenile survival	Taylor et al. (1987)	60%	65%	45%	85%
Juvenile survival	Jensen (1981)	58%	65%	45%	85%

[a] – Calculated assuming a 20% wild egg survival rate (Todd 1986)

[b] – Calculated assuming age 3 is exploitable age

Calculation of recruitment given numbers stocked at a stage

Our basic approach to calculating recruitment was to apply stage-specific survival of fish from the time of stocking until fish reached age/size of recruitment to the fishery. We also calculated yearling equivalents for a given amount of numbers stocked. This was done by calculating survival to the yearling stage for fish stocked at earlier stages, including application of post-stocking survival, and for fish stocked as yearlings post-stocking survival of hatchery fish was also applied, so the yearling we equate to is a wild fish. We did not account for possible density dependent reduction in survival or growth after stocking because there is little information on such processes and because we assumed we were attempting to augment very low levels of recruitment past the fry stage. We acknowledge that the extent to which density dependence limits survival and/or growth of stocked fish could cause us to overestimate the return that could be expected when stocking large numbers of hatchery fish. We address the possibility of density-dependence affecting survival and growth of stocked and wild Lake Whitefish in the discussion.

In our calculations, we assumed lower survival of hatchery fish during their first year post stocking than wild fish of the same age/stage. We refer to this factor as post-stocking survival. Thus, with a post-stocking survival of 25%, and stocking at the fall age-0 stage we are assuming that the survival of hatchery fish to the next stage (spring yearling) is a quarter the survival of a wild age-0 fish in the fall. The allocation of the enhanced mortality to the first stage after a fish is stocked reflects our thinking that poor survival of hatchery products is likely to be temporary and by the time fish have survived to the next stage they will survive like fish of that stage born in the lake. There is nothing in the mathematics that requires all the increased mortality to have occurred in the first stage. What is required is that by the time of recruitment to the fishery, a hatchery fish is indistinguishable from a wild fish, and that the cumulative survival to the fishery of fish being stocked would be 25% that of a wild fish present at that same stage that is being stocked, for a post-stocking survival of 25%. We emphasize that the reduction in post-stocking survival is applied only to the life stage at which a fish is stocked; the reduction in survival is not applied to all subsequent life stages.

A summary of the overall survival rate of a hatchery product to recruitment to the fishery is in Table 3.

Table 3. Survival by hatchery stage (summer age-0, fall age-0, (spring) yearling) to recruitment to the fishery at age 4 for the low, baseline, and high mortality rates of Table 1.

Hatchery Stage	Baseline	Low	High
Summer	0.0034	0.000068	0.043
Fall	0.0340	0.0014	0.210
Yearling	0.0690	0.0046	0.310

Calculation of yield per recruit

To calculate the number of hatchery fish to stock to produce a desired enhancement in yield (Y) requires knowing the yield per recruit (YPR). With YPR in hand, the necessary number of recruits, R, can be calculated by rearranging Y = YPR * R, to obtain R=Y/YPR. Once we know the necessary number of recruits we can calculate the required stocking level by rearranging R=RPS*S, where RPS is the recruits produced per fish stocked, to obtain S=R/RPS. Of course the calculations of the numbers needed to be stocked are somewhat more complicated in cases where a mix of different stages are to be stocked in different ratios (see section: “Estimates of numbers of fish to plant and costs to produce specified augmentation of yield to fisheries”).

We calculated YPR, following the Bell-Thompson method (Ricker 1975), as

$$YPR = \sum_{a=a_R}^{\infty} N_a W_a \frac{F_a}{Z_a} (1 - \exp(-Z_a))$$

where N_a is abundance at the start of the year at age a, W_a is the average weight of a harvested fish at age a, F_a is the instantaneous fishing mortality rate at age a, Z_a is the total instantaneous mortality rate at age a, and a_R is the age of recruitment to the fishery. In practice the summation was through age-25 as few fish survived past that age.

Weight at age was obtained by using weight at age of harvested fish from 1836 treaty-ceded water models in the most recent harvest recommendation calculations. Unit-specific values were averaged for a lake to obtain generic lake-specific weight at age schedules for Lakes Huron and Michigan. Fishing mortality at age was calculated as the product of age-specific selectivity and fishing intensity, which was adjusted so that the peak total mortality rate matched a target level. A generic lake-wide selectivity pattern was calculated by first compiling all of the 1836 treaty-ceded water assessment fishing mortality rates used in the projections (recent rates). When multiple fishery components existed (i.e., both a trap and gill net fishery) for a unit these separate fishing mortality rates were summed. These unit-specific fishing mortality rates were then averaged over units, and then normalized to produce a maximum value of 1, the result being the age-specific fishery selectivity.

Historically, Lake Whitefish have been managed in treaty-ceded waters with a peak (over ages) target total annual mortality rate A=1-exp(-Z) of 65% although there are growing concerns that this rate might be too high, especially given apparent reductions in the amount of recruitment that a given amount of spawning stock can produce. For this report, we used a 50% peak total annual mortality rate as a target in our calculations, which is at the upper end of what recent simulations suggest is a reasonable rate for sustaining natural populations. We use this target rate because with supplemental stocking there would still be wild-born fish and a desire to sustain these populations.

Total age-specific values of Z are calculated by adding the age-specific fishing mortality rates (adjustable as described above) to the assumed fixed potentially age-specific natural mortality rates. These natural mortality rates were calculated by summing the background natural mortality rates and sea lamprey natural mortality rates (non-zero only on Lake Huron). Because the background natural mortality rate was assumed to be constant for recruited fish in the assessments the total natural mortality rate was constant for Lake Michigan but varied with age for Lake Huron.

The resulting YPR values are 0.495 kg and 0.125 kg for Lakes Michigan and Huron, respectively. The difference is the result of slower growth (lower weights at age), slower increase in selectivity, and higher levels of natural mortality for Lake Huron than for Lake Michigan (Figure 7).

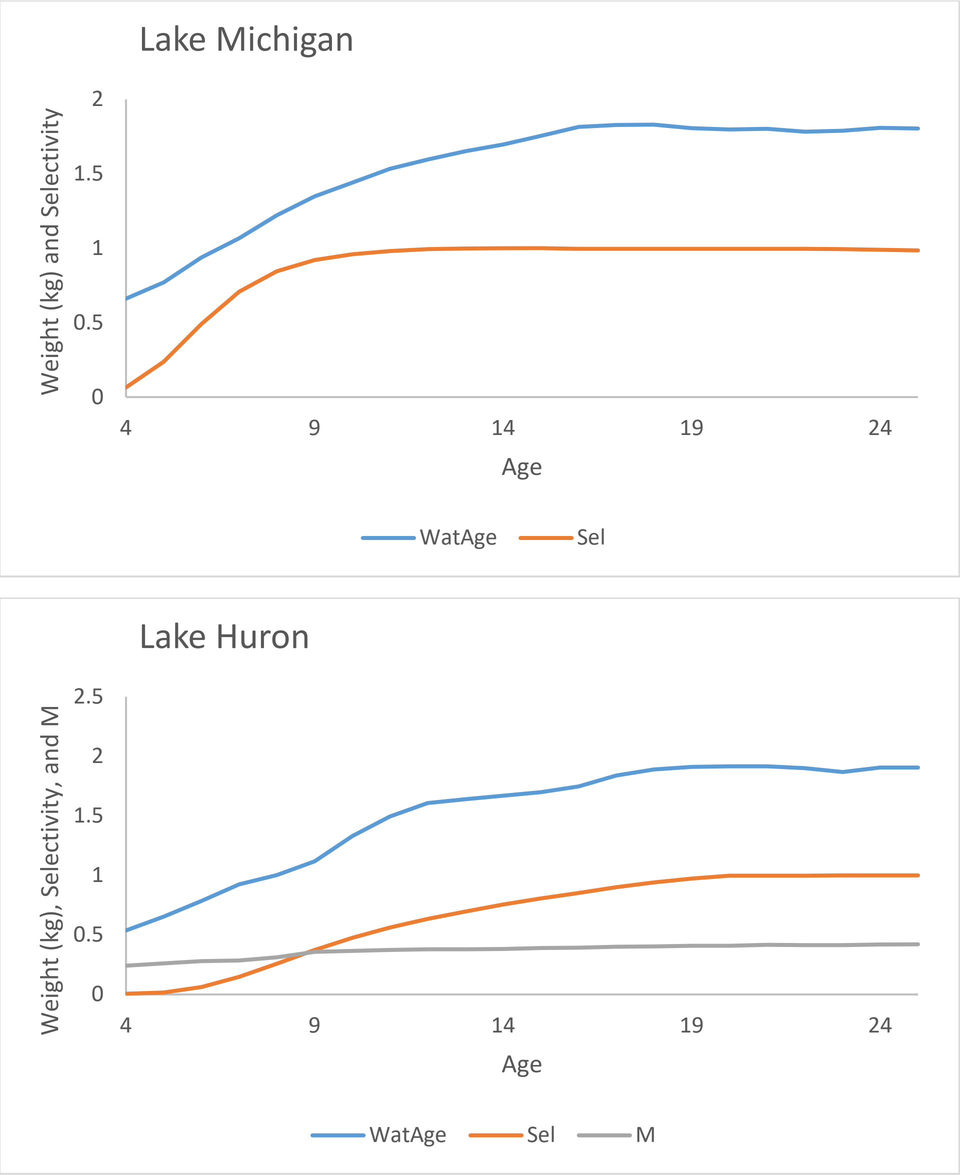

Figure 7. Inputs used to calculate yield per recruit. For both Lake Michigan and Lake Huron weight at age in kg, and selectivity (*F* at age normalized to 1.0 at a maximum) are shown. For Lake Huron, the instantaneous natural mortality rate (*M*) is also shown, while *M* was constant over ages (0.198) in Lake Michigan.

It is likely that the *M* is lower in other areas of Lake Huron than in treaty-ceded waters because of lower sea lamprey densities, but it is highly unlikely that YPR exceeds the value for Lake Michigan in much of Lake Huron. These YPR values are influenced by the target mortality rate, with YPR increasing as fishing mortality rate does until growth overfishing occurs. This said, relatively little is gained in terms of YPR by increasing the target mortality rate to 65% on Lake Michigan, with YPR being 0.538 kg at this higher target. On Lake Huron there is a substantial proportional change to 0.200 kg at the higher target, but the value is still low relative to that of Lake Michigan.

Hatchery logistics and costs associated with stocking Lake Whitefish

Hatchery costs and logistics depend upon a wide range of design and siting characteristics such as land costs, water supply, and whether a recirculating system is required. It was not feasible for this report to develop detailed cost estimates for such a wide range of conditions. Instead, we based our cost estimates on the actual costs of reconfiguring and expanding the Jordan River National Fish Hatchery (hereafter JRNFH) for the production of coregonines, and estimates by the hatchery manager of that facility of production cost following a protocol developed by OMNRF for hatchery production of Lake Whitefish.

The Sault Ste. Marie Tribe of Chippewa Indians has had some success in culturing Lake Whitefish and has explored both flow through and recirculating systems. They are also investigating the feasibility of pond culture of Lake Whitefish, which has proved successful, albeit with some challenges, for culturing whitefish in Finland (Russell Aikens, personal communication). The Little Traverse Bay Bands of Odawa Indians have experimented with rearing Lake Whitefish at different temperatures, and found that if temperature is increased to 17 degrees, conversion efficiency increases, disease issues are reduced, and maximum culture density can be increased three fold (Kris Dey, personal communication). Refinement of culture techniques, and particularly a successful pond rearing approach, could bring down costs compared to the estimates made herein based on an established protocol. Any benefit of rearing at a higher temperature needs to weigh the increased performance against higher utility costs.

Our initial discussions with those knowledgeable of the hatchery systems indicated there is currently no unallocated hatchery capacity in the Great Lakes. In addition, as detailed below, the necessary infrastructure to convert a legacy trout or salmon hatchery to production of coregonines provides only a modest cost benefit. Thus, we provide baseline estimates of costs based on the JRNFH, and then discuss how these costs might relate to costs at other locations.

When the conversion to coregonine production is complete at the JRNFH, the hatchery will include space and equipment for egg hatching and early fry rearing, and other tanks and raceways capable of rearing fish from about 0.5 grams or larger to fall fingerling or yearling stages. In some cases we consider scenarios for stocking yearlings that assume additional raceway capacity could be converted or constructed to hold additional Lake Whitefish past the fall fingerling stage, and include rough estimates of the associated costs in our calculations.

The maximum capacity for rearing Lake Whitefish to a fall age-0 stage >15 g at the JRNFH is 2.3 million fish, which is a limit imposed both by the capacity of large circular tanks and raceways to hold fish at the fall fingerling stage, and the capacity to hold fish at the initial stages post-hatch in more expensive RAS culture systems. The tanks and raceways at the JRNFH that can hold fish through the fall fingerling stage have a total volume of 988 m^3, which can handle up to 2,333 fish/m^3 until they reach 15 g. When producing the maximum number of fall fingerlings, it could be possible to produce an additional 2 million summer fish of approximately 2 g. This is possible by using temperature to adjust growth rates so that the summer fish grow out and are stocked before the space they would require would be needed for the fall fingerling fish. This additional production does not require additional infrastructure, although there would be moderate additional utility, labor, and feed costs.

Because production is also limited by the availability of RAS culture system, if the facility was completely dedicated to the production of summer age-0 fish at ≈2 g, a single crop production of summer fish is limited to 2.3 million fish and a two crop production of summer fish is limited to 4.4 million fish. The first crop would be hatched in a temperature controlled fry rearing array (40 tanks of 1 m^3) and 10 of the larger 12' 10 m^3 tanks. This limits the first crop to 2.3 million fish. The second crop is constrained to 2 million fish because some of overlapping space requirements with the first crop. Again, the higher double crop stocking would not require substantial additional costs in infrastructure but would add to production costs (utilities, personnel, feed, stocking costs).

Another option would be to hold fish over the winter and then stock them as spring yearlings. However, a production roadblock is that these fish would not be stocked until late March or April, thus temporally overlapping with the subsequent cohort and creating conflicts in space allocation. Assuming a maximal crop of 2.3 million fall fish were reared, 540K yearlings could be reared through March/April, with the others (approximately 1.76 million fish) stocked as age-0 the previous fall. This would require use of some raceways currently not part of the Coregonine project, and would require some modest increases in infrastructure costs that have not been accounted for.

The above yearling option could be paired with the double cropping scenario so that an additional 2 million summer age-0 fish could be produced.

If the current facility was adapted to rear all individuals reared to the fall age-0 stage to the yearling stage, additional raceway space for 1.76 million fish would be necessary, totaling ≈1500 m^3. While there is some additional raceway space at the JRNFH that is not part of the current coregonine rearing project, no feasibility study has been done on whether sufficient raceway space could be made available there for this level of yearling production. Of course construction of other hatcheries specifically to raise Lake Whitefish to the yearling stage could plan for adequate raceway space. There would also be additional costs associated with rearing additional fish to the yearling stage.

The total cost to completely reconfigure the JRNFH for the production of coregonines is estimated at approximately $6.12 million USD. In addition, the estimated replacement value of incorporated infrastructure is $2.14 million USD. We take the sum of these as the cost of constructing a facility with similar characteristics as the JRNFH for the production of Lake Whitefish ($8.26 million USD). To estimate the cost of incorporating or building an additional 1500 m^3 of raceways to expand yearling production to 2.3 million, we used the incorporated raceway volume of 688 m^3 and replacement value to estimate per m^3 at $3110 USD. Multiplying this by the needed volume leads to an estimated cost to expand yearling production of $4.7 million USD.

The above estimates of expenses do not include any property value costs. In addition, the tanks and raceways at JRNFH are a mix of RAS and once through systems. RAS systems have substantially higher production costs and likely would be required at many sites. Thus, the JRNFH can be viewed as a reasonable but perhaps lower end estimate of costs associated with developing similar capacity elsewhere. We did not attempt to do calculations with different facility costs, but we recognize there is uncertainty in these values, albeit likely much less uncertainty than in information on the survival rates of fish that are stocked, unless substantially less costly culture methods are proven.

The estimated production costs of the base scenario that produces 2.305 million fall and 2 million summer fish is $1.05 million US annually (Table 4). Hatchery labor is the majority of this cost (62%), but costs associated with collecting wild fish for egg take, planting of fish, feed, and utilities are also substantial. As shown in Table 4, the most substantial of these other costs is feed. The labor costs are those associated with US federal employees. There is potential to reduce costs if facilities are managed by state, tribal, or private sector entities, with lower pay scales. While we do not run scenarios with lower pay scales, we believe a reasonable lower bound for Personnel costs for a facility like the modified JRNFH envisioned would be $320,000 (basically half federal costs).

Table 4. Estimated production costs (US dollars) by expense category for producing 2.305 million fall and 2 million summer age-0 Lake Whitefish at the JRNFH , following the protocol used for such production of Lake Whitefish by OMNRF. Personnel costs based on pay rates and benefits for U.S. federal employees.

Category	**Cost**
Personnel	$644,000
Utilities	$75,000
Eggs	$35,000
Feed	$180,000
Distribution	$32,000
Equip.	$30,000
Misc.	$50,000
TOTAL	**$1,046,000**

Producing only summer fish would reduce costs of personnel, utilities, and feed. We assume an overall reduction in production costs of 25%, though we recognize that this may be optimistic. While fish would not be in production for a period of 3-4 months when they otherwise would be when rearing fish to the fall, it is not clear that the reduction in operations would fully translate to reduced personnel costs.

Another option is to produce only fall fish, and no summer fish. We estimate a reduction in production costs of 10% below the baseline for this scenario.

Within the existing coregonine project footprint, the yearling option allows for the production of 540K yearlings, which could be combined with the production of fall or fall and summer fish. This yearling option could be combined with the double-cropping production option so that 2 million summer fish could also be stocked (at an additional 10% of baseline costs). This production of yearlings is estimated to increase production costs by 25%, given it would require rearing these fish for an additional six months. As a very rough estimate of the additional costs associated with rearing 2.3 million additional yearlings, we assume some economy of scale (mainly associated with personnel costs) and estimate an additional 50% of baseline production costs.

The total annual cost associated with each scenario described above includes the annual operational costs plus one thirtieth of the construction costs- basically using a 30 year straight-line depreciation schedule to account for the fact that various larger items will need to be repaired or replaced over a 30 year time-horizon, essentially reproducing an entire facility in that timeframe. These construction costs are larger for the expanded yearling scenario.

Summing the production costs with the facility depreciation costs leads to the total annual costs associated with a hatchery operation scenario for Lake Whitefish given in Table 5.

Table 5. Estimated annual costs associated with various Lake Whitefish stocking options if implemented in a facility similar to the JRNFH .

Scenario	**Annual Production Cost**	**Total Annual Cost**
2S/2.3F/0Y (baseline)	$1,046,000	$1,321,333
4.4S/0F/0Y	$784,500	$1,059,833
0S/1.76F/0.54Y	$1,359,800	$1,635,133
2S/1.76F/0.54Y	$1,464,400	$1,739,733
0S/0F/2.3Y	$1,882,800	$2,039,466

In the next section the costs for these scenarios are converted into costs of stocking enough fish to produce a specified amount of yield, by proportionally adjusting the number stocked and costs for each scenario so as to meet the target. Note that if labor costs could be cut in half, the baseline scenario total annual cost would be reduced to approximately $1 million.

Estimates of numbers of fish to plant and costs to produce specified augmentation of fishery yield

We calculated the numbers of fish that would recruit to the fishery at age-4 based on the assumed numbers stocked at each stage. Shown in Table 6 are these numbers as well as the yearling equivalents and cost information for production at one facility like the JRNFH, using our baseline or most plausible estimates of survival.

Table 6. Numbers that could be reared to stages for stocking, and the associated yearling equivalents, fishery recruits (at age-4) produced, annual costs including facility depreciation, and cost per yearling equivalent for the different hatchery scenarios based on one hatchery characteristic of the JRNFH coregonine facility (with possible additional raceways for rearing to yearling stage). Yearling equivalents and recruits based on baseline in-lake survival from Table 1. Scenario names indicate the numbers in millions that could be reared to each stage (S = summer age-0, F = fall age-0, and Y = spring yearling).

	Numbers stocked						
Scenario Name	Summer	Fall	Yearling	YE	Recruits	Annual Cost	Cost/YE
2S/2.3F/0Y	2,000,000	2,305,000	0	313,125	85,992	$1,321,333	$4.22
4S/0F/0Y	4,400,000	0	0	55,000	15,104	$1,059,833	$19.27
0S/1.76F/0.54Y	0	1,760,000	540,000	355,000	97,492	$1,635,133	$4.61
2S/1.76F/0.54Y	2,000,000	1,760,000	540,000	380,000	104,358	$1,739,733	$4.58
0S/0F/2.3Y	0	0	2,300,000	575,000	157,909	$2,039,466	$3.55

Given our assumptions about some economies of scale for yearling production in an expanded facility, the lowest cost per yearling equivalent was for the yearling only strategy, although scenarios that attempted to produce some yearlings within the current JRNFH coregonine facility footprint had a higher cost per yearling equivalent than the 2S/2.3F/0Y baseline strategy. The highest estimated cost per yearling equivalent was for for the 4S/0F/OY scenario, which directly reflects the assumption that only 10% of summer fingerlings would survive to a fall fingerling stage.

Given that a number of the hatchery scenarios involve raising a mix of different stages, and we are interested in projections when the total number of fish is substantially more than the amount that could be generated under the specific assumptions we made based on the JRNFH, we used the following approach. We took the numbers stocked at each stage and the associated total annual costs in Table 5 for a given scenario to be proportional to one another. We scaled up the numbers stocked and the costs based on the capacity of the JRNFH to produce different amounts of specified yield. Thus, we scaled stocking up until the product of recruitment at age-4 and yield per recruit met a target yield. The specified levels of yield we present correspond roughly to: low - half the estimated decline in yield in treaty waters from the early period to the 2015-2017 period on Lake Huron or Lake Michigan; medium - all of this decline; and high - the entire estimated lake-wide decline from the early period until recently (Table 7). Note that not all the declines in yields that these benchmarks are based on may be due to actual declines in Lake Whitefish abundance (see section: "The extent of declines in Lake Whitefish in the Upper Great Lakes").

Table 7. Specified low, medium, and high yield levels in metric tons (t, equals 1000 kg or 2205 lbs) that stocking scenarios were adjusted to match, for Lakes Huron and Michigan.

Yield cases	Huron	Michigan
Low: 50% of yield loss in 1836 treaty-ceded water	335 mt (739,000 lbs)	450 mt (992,000 lbs)
Medium: 100% of yield loss in 1836 treaty-ceded water	700 mt (1.5 million lbs)	900 mt (2.0 million lbs)
High: Estimate lake-wide yield lost	2200 mt (4.8 million lbs)	1250 mt (2.8 million lbs)

Not considering the summer fish only stocking strategy, annual costs associated with providing yield equal to half the decline in treaty-ceded waters of Lake Michigan ranged from $12 million to $15 million USD, and required on the order of 10 times the capacity of a hatchery like that of the JRNFH Coregonine project (Table 8). Matching higher yield targets were proportionally more expensive and required proportionally more stocking (Table 8). To recover 100% of the yield declines in treaty-ceded waters of Lake Michigan, annual cost estimates ranged from $23.5 to $30 million. Although the low-end target of replacing half the decline in treaty-ceded waters of Lake Huron was less than the corresponding target in Lake Michigan, the costs and levels of stocking necessary to meet this target were roughly three times higher on Lake Huron (Table 9) than they were on Lake Michigan (Table 8). This is a result of the lower yield per recruit on Lake Huron, which in turn stems from higher natural mortality (due to sea lamprey), slower growth, and later entry to the fishery.

These results are sensitive to the mortality assumptions (Tables 10-13). At the low end survival values and when using the baseline hatchery strategy, one would need to stock 553 million summer and 638 million fall age 0 fish at a calculated annual cost of $366 million USD to meet the lower yield target on Lake Michigan (Table 10). In the face of these low survivals, other stocking strategies produce similarly huge requirements, and resources needed to meet yield targets are again higher on Lake Huron (Table 11).

At the high end of survival estimates using the baseline scenario, the lower target yield enhancement on Lake Michigan could be achieved at about 50% above the capacity of a hatchery like the JRNFH, for an estimated $2.1 million USD per year (Table 12, 2S/2.3F/0Y scenario). Again, yield enhancement requires more fish and funds on Lake Huron (Table 13), and the higher yield enhancements require proportionally more money and stocked fish (Tables 12&13).

Table 8. Calculated numbers of Lake Whitefish that would need to be stocked to reach specified target yields (in metric tons, t) and the associated estimated annual cost of such an operation for **Lake Michigan** based on different scenarios for hatchery operations. Values are based on **baseline** survival estimates. Scenario names reference scenarios in Table 6 and refer to millions by stage (S = summer age-0, F = fall age-0, and Y = spring yearling) that could be produced at a modified JRNFH facility. The actual estimated numbers needed to be stocked reported here are multiples of the numbers from Table 6, with the multiplier set so as to match the specified yield target.

Lake Michigan (baseline survival)			Stocking Amounts			
Scenario	Target Yield (t)	Recruits	Summer	Fall	Yearlings	Cost
2S/2.3F/0Y	450	909,713	21,158,085	24,384,693	0	$13,978,438
	900	1,819,425	42,316,169	48,769,385	0	$27,956,876
	1250	2,526,979	58,772,457	67,735,257	0	$38,828,994
4S/0F/0 Y	450	909,713	265,005,011	0	0	$63,832,058
	900	1,819,425	530,010,021	0	0	$127,664,116
	1250	2,526,979	736,125,030	0	0	$177,311,272
0S/1.76F/0.54Y	450	909,713	0	16,422,846	5,038,828	$15,257,691
	900	1,819,425	0	32,845,691	10,077,655	$30,515,383
	1250	2,526,979	0	45,619,016	13,996,744	$42,382,476
2S/1.76F/0.54Y	450	909,713	17,434,540	15,342,395	4,707,326	$15,165,722
	900	1,819,425	34,869,080	30,684,791	9,414,652	$30,331,445
	1250	2,526,979	48,429,278	42,617,765	13,075,905	$42,127,007
0S/0F/2.3Y	450	909,713	0	0	13,250,251	$11,749,320
	900	1,819,425	0	0	26,500,501	$23,498,640
	1250	2,526,979	0	0	36,806,251	$32,636,999

Table 9. Calculated numbers that would need to be stocked to reach different specified target yields (in metric tons, t) and the associated estimated annual cost of such an operation for **Lake Huron**, based on different scenarios for hatchery operations. Values are based on **baseline** survival estimates. Scenario names reference scenarios in Table 6 and refer to millions by stage (S = summer age-0, F = fall age-0, and Y = spring yearling) that could be produced at a modified JRNFH facility. The actual estimated numbers needed to be stocked reported here are multiples of the numbers from Table 6, with the multiplier set so as to match the specified yield target.

Lake Huron (baseline survival)			Stocking Amounts			
Scenario	Target Yield (t)	Recruits	Summer	Fall	Yearlings	Cost
2S/2.3F/0Y	335	2,684,513	62,436,383	71,957,931	0	$41,249,626
	700	5,609,431	130,464,083	150,359,856	0	$86,193,249
	2200	17,629,639	410,029,976	472,559,547	0	$270,893,069
4S/0F/0 Y	335	2,684,513	782,015,693	0	0	$188,365,009
	700	5,609,431	1,634,062,643	0	0	$393,598,526
	2200	17,629,639	5,135,625,449	0	0	$1,237,023,938
0S/1.76F/0.54Y	335	2,684,513	0	48,462,944	14,869,312	$45,024,636
	700	5,609,431	0	101,265,854	31,070,205	$94,081,329
	2200	17,629,639	0	318,264,112	97,649,216	$295,684,178
2S/1.76F/0.54Y	335	2,684,513	51,448,401	45,274,593	13,891,068	$44,753,240
	700	5,609,431	107,504,121	94,603,627	29,026,113	$93,514,234
	2200	17,629,639	337,870,095	297,325,684	91,224,926	$293,901,877
0S/0F/2.3Y	335	2,684,513	0	0	39,100,785	$34,671,618
	700	5,609,431	0	0	81,703,132	$72,448,157
	2200	17,629,639	0	0	256,781,272	$227,694,206

Table 10. Calculated numbers that would need to be stocked to reach different specified target yields (in metric tons, t) and the associated estimated annual cost of such an operation for **Lake Michigan**, based on different scenarios for hatchery operations. Values are based on **low** survival estimates. Scenario names reference scenarios in Table 6 and refer to millions by stage (S = summer age-0, F = fall age-0, and Y = spring yearling) that could be produced at a modified JRNFH facility. The actual estimated numbers needed to be stocked reported here are multiples of the numbers from Table 6, with the multiplier set so as to match the specified yield target.

Lake Michigan (low survival)			Stocking Amounts			
Scenario	Target Yield (t)	Recruits	Summer	Fall	Yearlings	Cost
2S/2.3F/0Y	450	909,713	553,465,154	637,868,590	0	$365,655,886
	900	1,819,425	1,106,930,308	1,275,737,180	0	$731,311,772
	1250	2,526,979	1,537,403,206	1,771,857,194	0	$1,015,710,795
4S/0F/0 Y	450	909,713	13,310,836,954	0	0	$3,206,196,423
	900	1,819,425	26,621,673,909	0	0	$6,412,392,846
	1250	2,526,979	36,974,547,095	0	0	$8,906,101,175
0S/1.76F/0.54Y	450	909,713	0	329,031,925	100,952,977	$305,688,044
	900	1,819,425	0	658,063,849	201,905,954	$611,376,089
	1250	2,526,979	0	913,977,569	280,424,936	$849,133,457
2S/1.76F/0.54Y	450	909,713	363,684,070	320,041,981	98,194,699	$316,356,589
	900	1,819,425	727,368,140	640,083,963	196,389,398	$632,713,178
	1250	2,526,979	1,010,233,527	889,005,504	272,763,052	$878,768,302
0S/0F/2.3Y	450	909,713	0	0	199,662,554	$177,045,648
	900	1,819,425	0	0	399,325,109	$354,091,297
	1250	2,526,979	0	0	554,618,206	$491,793,467

Table 11. Calculated numbers that would need to be stocked to reach different specified target yields (in metric tons, t) and the associated estimated annual cost of such an operation for **Lake Huron**, based on different scenarios for hatchery operations. These values based on **low** survival estimates. Scenario names reference scenarios in Table 6 and refer to millions by stage (S = summer age-0, F = fall age-0, and Y = spring yearling) that could be produced at a modified JRNFH facility. The actual estimated numbers needed to be stocked reported here are multiples of the numbers from Table 6, with the multiplier set so as to match the specified yield target.

Lake Huron (low survival)			Stocking Amounts			
Scenario	Target Yield (t)	Recruits	Summer	Fall	Yearlings	Cost
2S/2.3F/0Y	335	2,684,513	1,633,246,236	1,882,316,287	0	$1,079,031,074
	700	5,609,431	3,412,753,329	3,933,198,212	0	$2,254,691,797
	2200	17,629,639	10,725,796,177	12,361,480,094	0	$7,086,174,220
4S/0F/0 Y	335	2,684,513	39,279,571,977	0	0	$9,461,315,138
	700	5,609,431	82,076,717,563	0	0	$19,769,912,228
	2200	17,629,639	257,955,398,056	0	0	$62,134,009,861
0S/1.76F/0.54Y	335	2,684,513	0	970,955,712	297,906,866	$902,069,162
	700	5,609,431	0	2,028,862,681	622,491,959	$1,884,920,638
	2200	17,629,639	0	6,376,425,570	1,956,403,300	$5,924,036,291
2S/1.76F/0.54Y	335	2,684,513	1,073,212,349	944,426,867	289,767,334	$933,551,470
	700	5,609,431	2,242,533,267	1,973,429,275	605,483,982	$1,950,704,564
	2200	17,629,639	7,047,961,696	6,202,206,292	1,902,949,658	$6,130,785,772
0S/0F/2.3Y	335	2,684,513	0	0	589,193,580	$522,452,293
	700	5,609,431	0	0	1,231,150,763	$1,091,691,358
	2200	17,629,639	0	0	3,869,330,971	$3,431,029,982

Table 12. Calculated numbers that would need to be stocked to reach different specified target yields (in metric tons, t) and the associated estimated annual cost of such an operation for **Lake Michigan**, based on different scenarios for hatchery operations. These values based on **high** survival estimates. Scenario names reference scenarios in Table 6 and refer to millions by stage (S = summer age-0, F = fall age-0, and Y = spring yearling) that could be produced at a modified JRNFH facility. The actual estimated numbers needed to be stocked reported here are multiples of the numbers from Table 6, with the multiplier set so as to match the specified yield target.

Lake Michigan (high survival)			Stocking Amounts			
Scenario	Target Yield (t)	Recruits	Summer	Fall	Yearlings	Cost
2S/2.3F/0Y	450	909,713	3,129,263	3,606,476	0	$2,067,399
	900	1,819,425	6,258,526	7,212,951	0	$4,134,799
	1250	2,526,979	8,692,397	10,017,988	0	$5,742,776
4S/0F/0 Y	450	909,713	21,161,641	0	0	$5,097,229
	900	1,819,425	42,323,283	0	0	$10,194,457
	1250	2,526,979	58,782,337	0	0	$14,158,968
0S/1.76F/0.54Y	450	909,713	0	2,942,567	902,833	$2,733,800
	900	1,819,425	0	5,885,134	1,805,666	$5,467,600
	1250	2,526,979	0	8,173,797	2,507,869	$7,593,889
2S/1.76F/0.54Y	450	909,713	2,887,553	2,541,047	779,639	$2,511,786
	900	1,819,425	5,775,107	5,082,094	1,559,279	$5,023,572
	1250	2,526,979	8,020,982	7,058,464	2,165,665	$6,977,183
0S/0F/2.3Y	450	909,713	0	0	2,962,630	$2,627,036
	900	1,819,425	0	0	5,925,260	$5,254,072
	1250	2,526,979	0	0	8,229,527	$7,297,322

Table 13. Calculated numbers that would need to be stocked to reach different specified target yields (in metric tons, t) and the associated estimated annual cost of such an operation for **Lake Huron**, based on different scenarios for hatchery operations. These values based on **high** survival estimates. Scenario names reference scenarios in Table 6 and refer to millions by stage (S = summer age-0, F = fall age-0, and Y = spring yearling) that could be produced at a modified facility. The actual estimated numbers needed to be stocked reported here are multiples of the numbers from Table 6, with the multiplier set so as to match the specified yield target.

Lake Huron (high survival)			Stocking Amounts			
Scenario	Target Yield (t)	Recruits	Summer	Fall	Yearlings	Cost
2S/2.3F/0Y	335	2,684,513	9,234,289	10,642,518	0	$6,100,785
	700	5,609,431	19,295,529	22,238,097	0	$12,747,910
	2200	17,629,639	60,643,091	69,891,162	0	$40,064,859
4S/0F/0 Y	335	2,684,513	62,446,878	0	0	$15,041,651
	700	5,609,431	130,486,015	0	0	$31,430,315
	2200	17,629,639	410,098,903	0	0	$98,780,989
0S/1.76F/0.54Y	335	2,684,513	0	8,683,358	2,664,212	$8,067,299
	700	5,609,431	0	18,144,331	5,567,011	$16,857,042
	2200	17,629,639	0	57,025,039	17,496,319	$52,979,275
2S/1.76F/0.54Y	335	2,684,513	8,521,017	7,498,495	2,300,674	$7,412,147
	700	5,609,431	17,805,109	15,668,496	4,807,379	$15,488,068
	2200	17,629,639	55,958,915	49,243,845	15,108,907	$48,676,785
0S/0F/2.3Y	335	2,684,513	0	0	8,742,563	$7,752,243
	700	5,609,431	0	0	18,268,042	$16,198,718
	2200	17,629,639	0	0	57,413,846	$50,910,256

Discussion

Under pessimistic assumptions regarding survival, a major enhancement of Lake Whitefish fishery yields through hatchery operations is probably not feasible. We believe this basic conclusion would remain true even if lower cost labor were used than we assumed here. Even if sufficient financial resources could be brought to the table, it seems unlikely that enough appropriate hatchery sites could be identified to execute a program of the magnitude that would be necessary to elicit the desired change. , Likewise, if effective pond culture methods were developed it would be challenging to identify enough pond sites. Under more optimistic levels of survival, stocking might be a feasible solution, particularly at the lower end of the target levels of enhancement we considered (i.e., 50% of yield loss in 1836 treaty-ceded water).

Stocking to enhance commercial fishery yields would need to be justified on more than just economic grounds, even if mortality rates are such that it is feasible. Given our best estimates of survival, the hatchery costs associated with producing one pound of Lake Whitefish in Lake Michigan is about $8. Costs to produce a pound of fish in Lake Huron would be higher.

One can reasonably ask why it is so expensive to enhance yield given there are major operations with this objective for European Lake Whitefish, and OMNRF is enhancing yield of Lake Whitefish in other systems, and stocking was used to successfully build up spawning stocks of lake trout in the Great Lakes. At least part of the explanation has to do with the poor growth conditions for Lake Whitefish in Lakes Michigan and Huron. Fish take a long time to recruit to the fishery (e.g, 50% recruitment is not until about age-8) and they recruit at small sizes. In Europe, stocked *Coregonus* spp. recruit to the fishery at much younger ages. Under the better growth conditions of 30 years ago, yield per recruit would, have been about 2 to 3 times what it is under current conditions, and such growth would have reduced costs of achieving target yields by a similar factor. Survival of stocked Lake Whitefish also might have been substantially higher in Lakes Michigan and Huron when predator fish were less abundant and their prey more abundant. Evidence supporting this supposition is that the best success in lake trout stocking occurred before predator abundances increased and prey abundance declined. The general survival values used in our calculations likely reflect a mix of conditions with respect to predation.

Some complexities of calculation and presentation were required as hatchery logistics suggest it might make sense to stock mixtures of different stages and yield per recruit calculations can be quite complex. Understanding the results may be facilitating by thinking about the probability an individual stocked fish will make it to recruit to the fishery and what yield this would produce. Under our best estimate assumptions for Lake Michigan, a fish stocked as a fall age-0 fingerling has about a 1% chance of reaching age-7, the first age that is more than 50% recruited, and a fish harvested at this age will weigh about 1kg. That is for each fall fingerling stocked we can expect to get about 0.01 kg of yield, and the costs associated with producing a fall fingerling are about $0.5 of the fall fingerlings make it to this age.

As should be evident from the sensitivity of results to assumptions about mortality rates, uncertainty about mortality matters. We are quite uncertain about mortality because estimates that are available are largely from other species in other systems, and these rates can be quite variable. At least for the best mortality assumptions and our assumptions about economies of scale if gearing up for yearling production, the most efficient approach would be to rear fish to the yearling stage. We caution reading too much into this. First, it depends on very uncertain mortality assumptions. There are reports where yearling stocking was no more effective than stocking of fall fingerlings (Amtstaetter and Willox 2004), and for Lake Herring summer age-0 fish appear to have done as well as fall fish age-0 fish in Little Traverse Bay (Kris Dey, personal communication). Second, the cost estimates are also uncertain, so before committing to a large yearling facility it would make sense to carefully price this and rerun calculations regarding optimal stocking strategy. Third, the costs associated with yearling production is in part from a larger front-end investment in facilities, which could be a roadblock to moving forward. This would be unfortunate, particularly if later testing showed that this stage did not have the assumed survival advantage, and ultimately such raceways were not used.

We did not evaluate a fry stocking option because the decline in recruitment of Lake Whitefish appears likely to have resulted from very high mortality rates at early life stages. The best options for succeeding with hatchery enhancement are to produce fish at stages past such a mortality barrier. This said, we are not certain that mortality rates at other stages prior to recruitment are also not quite high, at least in some areas of the Great Lakes. Given the increases in mortality of other stocked fishes such as Lake Trout (*Salvelinus namaycush*) and Chinook Salmon, and recent observations of what seems to be very high mortality of stocked Bloater (*Coregonus hoyi*) in This said, the observation of non-negligible survival of Lake Herring and Lake Whitefish in Little Traverse Bay is encouraging.

An implicit assumption that we made in our evaluations was that the stocking of hatchery-raised Lake Whitefish would not affect survival or growth of wild fish. We believe it is important to acknowledge that whether this assumption would be met in the real-word is not known. Eckmann (2012) reported that survival of wild European whitefish declined by 90 to 99% once stocking of hatchery-raised fish was initiated. Possible reasons for this reduction in survival included competition between wild and stock conspecifics, elevated mortality rates of eggs and larvae stemming from increased adult biomass that disproportionately affected wild fish because of longer periods of risk than hatchery fish, and overall decreases in fitness of the population as a result of introgression of hatchery fish (Eckmann 2012). In Lakes Huron and Michigan, the causal factors leading to decline in recruitment have not been conclusively established, nor has the critical time period been determined as to when recruitment levels are set. If density-dependent mechanisms are causing declines in recruitment of Lake Whitefish at ages older then when fish would be stocked, the stocking of fingerling and/or yearling Lake Whitefish likely would lead to even poorer conditions for recruitment and growth. In turn, this would mean the realized yields that might stem from a particular stocking strategy could be much smaller than what we predicted in this report.

If a large-scale Lake Whitefish stocking program is to be considered further for the Great Lakes, we would encourage that further research be first undertaken, beyond just a desktop study, to estimate anticipated survival rates for both stocked and wild Lake Whitefish at early life stages. Of particular importance is studies within the Great Lakes on the relative and absolute survival of fish stocked at age-0 summer and fall and yearling stages. Research to identify the critical period when recruitment levels in Lake Whitefish are set would also be beneficial as this could help determine the target age for when stocking should occur. If the critical period for Lake Whitefish occurs during the first year of life, then a strategy of stocking yearlings could help avoid reducing recruitment levels even further. If the critical period occurs at age-1 or older, then anticipated benefits of stocking may be strongly curtailed. There have been attempts to culture *Coregonus* spp. to older ages (i.e., age 2 and age 3) in cages deployed in natural systems, although, survival rates of these older fish have been found to be poor (Mamcarz and Szczerbowski 1984). There is ongoing research on ways to improve post-stocking survival of hatchery fish through so-called enriched rearing practices (Brown and Day 2002). These enriched rearing practices are intended to impart behaviors that will lead to improved survival, such as improved predator avoidance, acquiring and processing food, and the ability to find or construct nests (Brown and Day 2002). Instituting enriched rearing practices in Lake Whitefish hatcheries may lead to improved survival rates of hatchery individuals, although they may also elevate hatchery costs. Some exploration of alternative culture approaches has begun for the Great Lakes (Russel Aikman and Kris Dey, personal communications).

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