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Canadian Science Advisory Secretariat (CSAS)

Research Document 2022/044

Ontario and Prairie Region

Information in support of a Recovery Potential Assessment of Lake Whitefish (*Coregonus clupeaformis*), Lake Opeongo large-bodied and small-bodied Designatable Units

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June 2022

Canada

Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-43837-5 Cat. No. Fs70-5/2022-044E-PDF

Correct citation for this publication:

Colm, J.E., and Drake, D.A.R. 2022. Information in support of a Recovery Potential Assessment of Lake Whitefish (*Coregonus clupeaformis*), Lake Opeongo large-bodied and small-bodied Designatable Units. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/044. iv + 40 p.

Aussi disponible en français :

*Colm, J.E., et Drake, D.A.R. 2022. Données utiles pour l'évaluation du potentiel de rétablissement des unités désignables de grand corégone (*Coregonus clupeaformis*) de petite taille et de grande taille du lac Opeongo. Secr. can. des avis sci. du MPO. 2022044. iv + 45.*

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ABSTRACT

The Lake Whitefish (*Coregonus clupeaformis*) is a coldwater benthivore with a broad distribution and highly variable ecological and morphological traits across Canada. A species pair of Lake Whitefish in Lake Opeongo, consisting of a large-bodied and small-bodied form, was first discovered in 1940. Both forms (now considered separate Designatable Units, DUs) were assessed as Threatened by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in April 2018. The reason for this designation was that both DUs are known only from Lake Opeongo, Algonquin Provincial Park, Ontario, and the introduction of aquatic invasive species could disrupt the unique ecological processes that drove divergence and maintains the species pair (COSEWIC 2018). The Recovery Potential Assessment provides background information and scientific advice needed to fulfill various requirements of the federal *Species at Risk Act*. This research document provides the current state of knowledge of the species pair including its biology, distribution, population trends, habitat requirements, and threats, which will be used to inform recovery plans. Limited information exists to adequately assess the status of either DU, particularly the small-bodied form. A threat assessment identified the greatest threats to the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo as aquatic invasive species, climate change, and human disturbances; however, the impacts of these threats are not well understood. Mitigation measures and alternative activities related to the identified threats are presented, as appropriate. Important knowledge gaps remain regarding population trends, as well as differences in niche occupancy and impacts of current and anticipated threats on the two DUs.

INTRODUCTION

The Lake Whitefish (*Coregonus clupeaformis* Mitchill 1818) is a coldwater benthivore in the family Salmonidae. It has a broad distribution across North America, found in lakes and rivers from Alaska to Labrador (west to east), and Victoria Island to the northeastern United States (north to south). In Canada, it is found in all provinces and territories except Prince Edward Island (PEI). The Lake Whitefish is one of the most important commercial freshwater species in Canada and is of significance to recreational fisheries and as a food fish (Scott and Crossman 1998, DFO 2018). In addition to its socio-economic importance in Canada, Lake Whitefish has garnered much attention in the scientific community because of the substantial variation observed across its range, both within and between populations. Some populations contain two distinct forms, a smaller (usually limnetic), “dwarf” form, and a larger (usually benthic), “normal” form that have resulted from local adaptations. This degree of differentiation has made the species difficult to classify, and ultimately to assess and manage.

Some populations of whitefish were prioritized early on for conservation efforts. In 1987, the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) assessed the first distinct group of whitefish (formerly the Squanga Whitefish) as Special Concern (Bodaly et al. 1987); though this group has recently been re-classified and re-assessed (COSEWIC 2018). In November 2000, the Mira River population of Lake Whitefish was assessed as data deficient (Goodchild 2001), and in April 2005, the Lake Simcoe population was also assessed as data deficient (COSEWIC 2005). No Lake Whitefish populations have been listed under the *Species at Risk Act* (SARA). Continued confusion and difficulty in prioritizing populations led to a special report (Rogers 2009) and further efforts (Mee et al. 2015) to classify the species into Designatable Units (DUs) that warranted independent consideration based on new COSEWIC guidelines for classification below the species level (COSEWIC 2012).

A total of 36 DUs were identified based on nested criteria of “1) reproductive isolation, 2) phylogeographic history, 3) local adaptation, and 4) biogeographic separation” (Rogers 2009, Mee et al. 2015). Some of these DUs represent a single form with a broad geographic distribution, and others represent members of species pairs found in isolation. Species pairs may be the result of two distinct species (e.g., Yukon lakes *C. lavaretus* and *C. clupeaformis*) coming together in sympatry, of two formerly-allopatric populations (i.e., from different glacial refugia; e.g., Como Lake pair) coming together, and/or from local adaptations (i.e., shifting to an unexploited niche in the lake to reduce intraspecific competition; e.g., Lake Opeongo pair) in sympatry. The species pairs have diverged to differing degrees through different mechanisms and, as such, are unique to their lakes and represent discrete and significant units of whitefish diversity (Bodaly 1979, Vuorinen et al. 1993, Landry et al. 2007, Rogers 2009, Landry and Bernatchez 2010, Mee et al. 2015).

From these classification efforts, 10 DUs representing species pairs from five Canadian lakes were identified for conservation prioritization based on evidence of reproductive isolation between forms and sufficient evidence of local adaptations that resulted in differentiation of the species pairs (Mee et al. 2015). These 10 DUs were assessed by COSEWIC in April 2018 (COSEWIC 2018). Two of the DUs found in Como Lake, Ontario, were assessed as Extinct as neither the original dwarf or normal forms were found in the lake following the invasion of a zooplankton (Reid et al. 2017); these DUs will not be considered further at this time. For six of the DUs found in Yukon lakes, a Recovery Potential Assessment (RPA) was conducted in April 2020 (DFO 2021). Two of the other Lake Whitefish DUs assessed in 2018 are found in Lake Opeongo, Ontario and consist of a large-bodied DU and a small-bodied DU. Both DUs were assessed as Threatened, based on D2 Criteria of a restricted Index Area of Occupancy in a single location, and due to the risk of establishment of aquatic invasive species that could disrupt the ecological processes that drove divergence and maintain the species pair.

The RPA process was developed by Fisheries and Oceans Canada (DFO) to provide information and science-based advice needed to fulfill requirements of SARA. The process is based on DFO (2007) and updated guidelines (DFO unpublished) that assess 22 recovery potential elements. This document summarizes information about the biology, distribution, life history, population parameters, and threats and applicable mitigation measures to support the RPA process for these two Lake Opeongo DUs. This research document accompanies a recovery potential modeling research document (Fung et al. 2022) and together these address the 22 elements outlined in the RPA process (DFO 2007, DFO unpublished).

Where available, information about the Lake Opeongo large- and small-bodied DUs of Lake Whitefish will be presented first, supplemented by information on species pairs from elsewhere, and finally by Lake Whitefish in general when specific information is lacking.

BIOLOGY, ABUNDANCE, DISTRIBUTION AND LIFE HISTORY PARAMETERS

Element 1: *Summarize the biology of Lake Whitefish*

SPECIES DESCRIPTION

The Lake Whitefish is a coldwater, benthic species in the Salmonidae family (coregonine subfamily). This species, along with others in the genus *Coregonus*, show great variation in morphology and ecology across their range, and are often referred to as a “species complex”. The Lake Whitefish is generally silvery in colour with little colouration on the fins; however, body and fin colour vary regionally (Scott and Crossman 1998). It has an elongate body shape that is somewhat laterally compressed. The dorsal fin has 11–13 soft rays; there is an adipose fin; the caudal fin is deeply forked; the anal fin has 10–14 rays; and a pelvic axillary process is present. It has a relatively short head, a small eye, two nostril flaps (characteristic of *Coregonus*) and a snout that overhangs a small, subterminal mouth. It has large, cycloid scales that are variable in number along the lateral line. The species has a thick mucous layer. Older individuals may develop a hump behind the head and prominent nuptial tubercles develop on breeding males and, to a lesser extent, on breeding females (Scott and Crossman 1998). In Lake Opeongo, Lake Whitefish occurs with other coregonines. It is distinguished from Round Whitefish (*Prosopium cylindraceum*) that has a single nostril flap and a notch in the base of the eyelid, and from the Cisco (*Coregonus artedi*) that has a snout that does not overhang the mouth (Scott and Crossman 1998, Holm et al. 2009).

Lake Whitefish populations have adapted to such a degree that some lakes contain two distinct forms, usually a larger “normal” form and a smaller “dwarf” form. The larger form grows faster, reaches a larger size and older age at maturity, lives longer and typically occupies a benthic niche. The smaller form grows slower, matures earlier and at a smaller size, has a shorter lifespan and typically occupies a limnetic niche. Two distinct Lake Whitefish forms in Lake Opeongo were first documented by Kennedy (1943), distinguished by a bi-modal size distribution of mature adults. The large-bodied form had a mean standard length (SL) of 251 mm, matured later (ages 4–7), grew faster and for a longer period during the growing season, and lived longer (up to age 14). Recent sampling by the Ontario Ministry of Natural Resources and Forestry (OMNRF) detected mature large-bodied individuals with a mean fork length (FL) of 301 mm, aged 4–24 (OMNRF unpublished data). The small-bodied form had a mean SL of 126 mm, reached a maximum observed SL of 160 mm, matured earlier (age 2), grew slower and for a shorter period of the growing season, and was shorter-lived (up to age 5) (Kennedy 1943). In 2018, OMNRF detected mature small-bodied individuals with a mean FL of

145 mm, aged 2–8 (OMNRF unpublished data). Kennedy (1943) also noted differences in gill raker and lateral line scale counts between the forms. The large-bodied form had a mean (± SD) of 27.7 (± 1.1) gill rakers and 83.3 lateral line scales, and the small-bodied form had a mean (± SD) of 25.4 (± 0.14) gill rakers and 77.3 lateral line scales (Kennedy 1943). Modern morphometric/meristic data and diet information are not available for either form. Slight differences in other body measurements (e.g., eye diameter, head length and caudal peduncle length) were noted by Kennedy (1943) between the two forms but differences were not significant. The only significant differences in body morphology between sexes were the pectoral fin length and weight of large-bodied adults. There is some evidence to suggest that, in contrast to species pairs elsewhere, the large-bodied form in Lake Opeongo occupies shallower waters than the small-bodied form (Kennedy 1943, Mark Ridgway, OMNRF, pers. comm.).

LIFE CYCLE

The large-bodied DU of Lake Whitefish in Lake Opeongo reaches sexual maturity at ages 4–7 (few specimens matured as early as age 3); the small-bodied DU matures at age 2 (Kennedy 1943). Little is known about life cycle differences between the large- and small-bodied DUs so information is presented for both combined.

In Lake Opeongo, spawning occurs in late October to end of November, with the peak occurring when temperatures are between 4–7°C (Ihssen et al. 1981, Cucin and Faber 1985). Spawning lasts for seven to ten days in other populations (Hart 1930). Broadcast spawning occurs nearshore (depths < 8 m) over rock ledges and cobble shoals where eggs remain until hatch in late April through May (Ihssen et al. 1981, Cucin and Faber 1985, Scott and Crossman 1998). Eggs incubate at 0.1–6.0°C for approximately 175 days; the optimal incubation temperature range for Lake Whitefish, in general, was found to be 0.5–8.1°C in laboratory settings (Price 1940, Brooke 1975). Ihssen et al. (1981) found that Lake Opeongo Lake Whitefish eggs incubated for up to two weeks longer than other Lake Whitefish populations nearby in Ontario. Eggs have a colourless membrane, an amber-coloured yolk and are slightly adhesive.

Larval Lake Whitefish hatch in Lake Opeongo when surface temperatures reach 5–8°C (peak hatching 6.5–10°C); larvae are approximately 11.5 mm in length (mean length at peak hatching was 13 (± 1.07) mm) (Cucin and Faber 1985). Larvae remain close to the surface over the spawning grounds for 4–6 weeks, then generally move to deeper water by early summer (Scott and Crossman 1998, McKenna and Johnson 2009). All life stages of Lake Whitefish remain below the thermocline in summer, and adults return to shallower waters to spawn in the fall. It is expected that spawning by both large- and small-bodied DUs occurs every year in Lake Opeongo once maturity is reached (Scott and Crossman 1998).

Reproductive isolation between the Lake Opeongo large- and small-bodied Lake Whitefish DUs is inferred based on the differences in body morphology and life history noted by Kennedy (1943). Genetic evidence has confirmed reproductive isolation in other lakes with two sympatric forms (Mee et al. 2015). The mechanism(s) of isolation is unclear, but evidence from other Canadian sympatric pairs suggest post-zygotic barriers are most likely, where developmental abnormalities are observed in crosses (Rogers and Bernatchez 2007 and references therein). The large-bodied and small-bodied DUs in Como Lake, Ontario, spawned over the same grounds at the same time (Vuorinen et al. 1993). Some evidence of pre-zygotic barriers has been noted outside of Canada. In a lake in Maine with a sympatric species pair, large-bodied Lake Whitefish started spawning up to several weeks before the small-bodied individuals (Fenderson 1964), suggesting that temporal isolation could be occurring. In sympatric pairs of European Whitefish (*Clupeaformis lavaretus*) in Scandinavia, large-bodied forms appeared to spawn in shallow habitats in the lake, and small-bodied forms in deeper lake areas and riverine habitats (Ohlund et al. 2020).

DIET

Sandercock (1964) analyzed the stomachs of 280 Lake Whitefish in Lake Opeongo ranging in (standard) length from 160–450 mm (i.e., most were likely large-bodied, but not formally differentiated) and found the diet was composed mostly of benthic organisms with some pelagic plankton and other items. Throughout the summer, Cladocera made up a mean of 32.4% of stomach volume (most commonly: *Sida crystallina*, *Eurycercus lamellatus*, *Latona setifera*, and *Ophroxyous gracillis*), followed by Ephemeroptera (mean of 18.2%), Diptera (12.2%; mostly Chironomidae), Bivalvia (11.3%; *Pisidium* sp.), with the rest composed of Gastropoda, Copepoda, Hydracarina, and rarely fish (Yellow Perch (*Perca flavescens*)) and Amphipoda. Stomach contents varied seasonally. In May, Lake Whitefish consumed Ephemeroptera nymphs almost exclusively. In June, gastropod *Amnicola limosa* and cladoceran *Leptodora kindtii* were the dominant prey items. In July, bivalve *Pisidium* sp. and cladoceran *Eurycercus lamellatus* dominated. In august, Yellow Perch and cladoceran *Sida crystallina* were the most abundant items by stomach volume. Ihssen et al. (1981) found that Lake Whitefish in Lake Opeongo generally consumed smaller food items compared to Lake Whitefish in nearby lakes that contained a single form. The Lake Whitefish, in general, is known to have a variable diet depending on food availability, as well as the intensity of competition with other species (Ihssen et al. 1981, Carl 2007, MacPherson et al. 2010).

In other lakes where both forms exist, the large-bodied form typically consumes a benthic diet and the small-bodied form consumes a limnetic diet (Mee et al. 2015). Large-bodied forms often have shorter and fewer gill rakers, more effective for feeding on benthic invertebrates, whereas the small-bodied forms often have longer and more gill rakers best for retaining zooplankton (Lindsey 1981, Trudel et al. 2001). However, in Lake Opeongo, the large-bodied DU has a significantly higher gill raker count (Kennedy 1943). Doyon et al. (1998) found that both forms in a Quebec lake consumed plankton (predominantly chironomid pupae and cladocerans) until age 2–3, after which point the large-bodied form shifted to feeding on benthic invertebrates while the small-bodied form continued consuming zooplankton.

In general, young of year (YOY) Lake Whitefish consume copepods shortly after hatch, later feeding on cladocerans in early summer and moving to larger benthic invertebrates (often chironimids), a diet similar to adults, by late summer (Hart 1930, Scott and Crossman 1998, Claramunt et al. 2010, Pothoven et al. 2014, Pothoven 2020). Chouinard and Bernatchez (1998) found no difference in diet of larval large- and small-bodied forms of Lake Whitefish in Cliff Lake, Maine during the 4 weeks after hatch, despite strong differences in adult diet between these two forms.

SPECIAL SIGNIFICANCE

A commercial fishery was established for Lake Whitefish in Lake Opeongo during the First World War to supplement food supplies but closed shortly after (Kennedy 1943; Kerr 2010). The Lake Whitefish elsewhere in Canada has, historically, been the most commercially valuable freshwater fish species. Although stocks have declined across much of its traditionally-fished range, it still remains a commercially important species (third most valuable freshwater species as of 2018; DFO 2018).

Lake Opeongo is one of only 18 lakes in Canada (Mee et al. 2015; plus others in Maine and Europe) known to contain a sympatric species pair of whitefish. Each of these species pairs appears to be the result of local adaptations to independent ecological processes unique to each lake, maintained by geographic isolation. Regardless of the mechanisms of differentiation, each species pair contributes to whitefish diversity in Canada (Vuorinen et al. 1993, Bernatchez et al. 1996, Pigeon et al. 1997, Landry and Bernatchez 2007, Mee et al. 2015, COSEWIC 2018).

In many other lakes with a species pair, the large-bodied (or "normal") form occupies a benthic niche, inhabiting deeper waters, and having fewer gill rakers typical of consuming a benthic diet; the small-bodied (or "dwarf") form normally occupies a limnetic niche, inhabiting shallower waters, and having more gill rakers typical of consuming a pelagic diet of zooplankton (Bodaly 1979, Lindsey 1981, Bodaly et al. 1991, Lu and Bernatchez 1999). The species pair in Lake Opeongo does not necessarily align with these observations. Both gill raker counts and depth observations recorded by Kennedy (1943) suggest the opposite may be true in the Lake Opeongo Lake Whitefish pair; however, other life history traits (e.g., growth, age and size at maturity) align with those observed for species pairs elsewhere (Mee et al. 2015). Additionally, no other species pair exists in the presence of Cisco, yet the Lake Opeongo pair has persisted despite the introduction of Cisco into the lake in 1948.

Element 2: *Evaluate the recent species trajectory for abundance, distribution and number of populations*

ABUNDANCE

Two estimates of abundance were made for the large-bodied DU in Lake Opeongo (OMNRF unpublished data). An initial estimate was made from modeling site-scale counts of Lake Whitefish from 2010 from 64 m profundal gill net sets (two hour soak time) as a function of depth, and then pooling the resulting abundance estimate from each site (64 m^2 grid). This yielded a lakewide abundance estimate of 11,378 (95% CI 6,509, 18,712). A second estimate was made from modeling detection-corrected site-scale counts of Lake Whitefish from 2019 from 50 m gill net sets (one hour soak time, four passes), and then pooling the resulting abundance estimate from each site (50 m^2 grid). This yielded an estimate of 22,792 (95% CI 10,437, 54,414). The difference in abundance estimates from these two data sets are attributed to the difference in site size and use of a detection correction factor, and are not thought to be representative of a change in population size over the time period (OMNRF unpublished data). Most individuals captured were mature and greater than 190 mm FL and considered large-bodied individuals; few immature individuals were captured during these efforts, but were assumed to be large-bodied individuals based on size and age.

There are currently no estimates of population size available for the small-bodied DU of Lake Whitefish in Lake Opeongo. From OMNRF sampling in 2018 using small-mesh gill nets, there were 23 small-bodied individuals (i.e., mature and < 180 mm FL) captured out of a total of 73 Lake Whitefish captured in this gear in 16 depth-stratified nets (OMNRF unpublished data). Ratios of large-bodied to small-bodied forms in other lakes have not been widely reported, likely due to differences in size selectivity between gears.

DISTRIBUTION

The Lake Opeongo large- and small-bodied DUs of Lake Whitefish are found in Lake Opeongo in Algonquin Provincial Park, Ontario (Figure 1). The lake has an area of 58.6 km^2 and consists of three arms (East, North and South) connected by channels. Although most studies on Lake Whitefish have focused on the East and South arms, it is presumed that the species pair exists throughout the lake. There are no longer any passable hydrologic connections to other lakes (Martin and Fry 1973), although movement out of Lake Opeongo could occur through the Annie Bay Dam during high water events (Mark Ridgway, OMNRF, pers. comm.). As the two DUs are known only from this lake and are assumed to exist throughout the lake, in this case, the Index Area of Occupancy (IAO) and Extent of Occurrence (EOO) were both calculated as the lake area of 58.6 km^2 (COSEWIC 2018[1]). This is the first assessment for these two DUs, so no comparisons to historic IAO or EOO can be made.

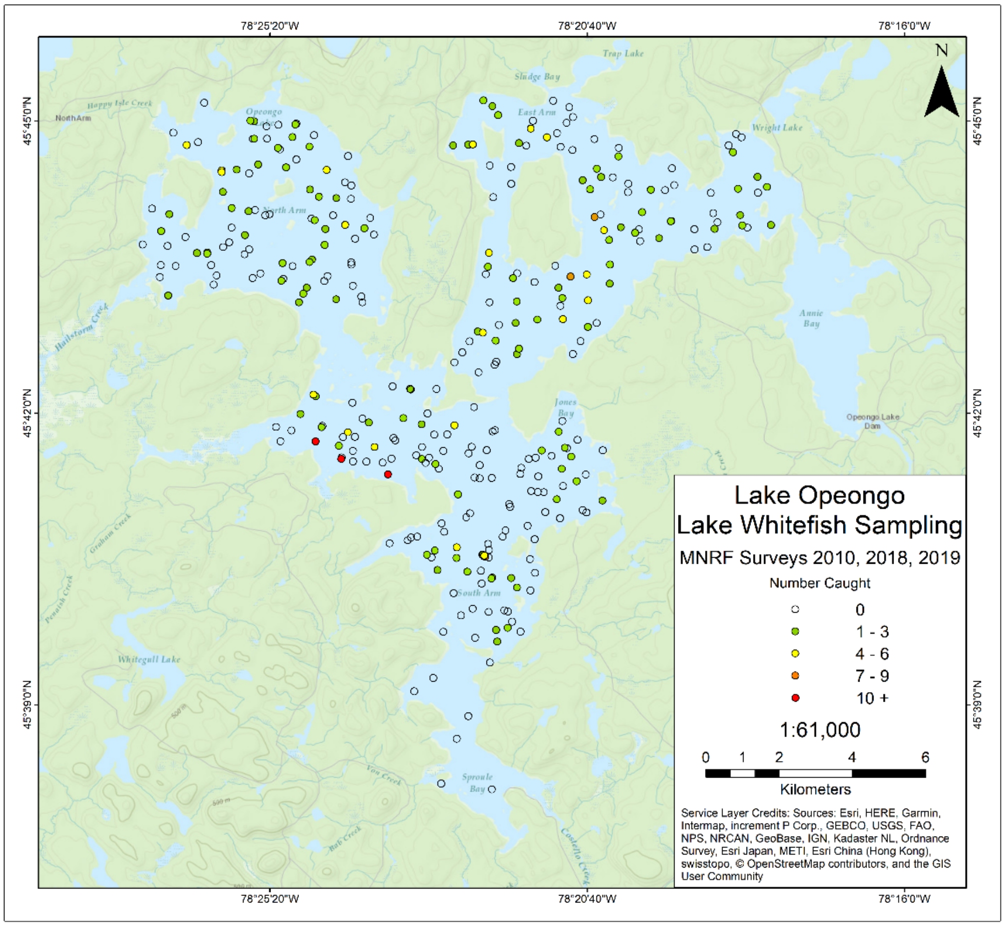

Figure 1. Map of Lake Opeongo, Algonquin Provincial Park, Ontario. Index Area of Occupancy and Extent of Occurrence are assumed to be the full lake area (58.6 km^2) for the large- and small-bodied DUs of Lake Whitefish. Lake Whitefish catches (not differentiated by DU) from Ontario Ministry of Natural Resources and Forestry (OMNRF) summer surveys from 2010 (summer profundal index netting), 2018 (small-mesh gill nets) and 2019 (large-mesh gill nets) are displayed (OMNRF unpublished data, Table 1).

Kennedy (1943) caught adult Lake Whitefish of both forms together during much of the spring and fall when the lake temperature was homogenous, but did note some differences in depth (and temperature) distribution between the two forms occasionally during the summer. In June, large-bodied individuals were captured in slightly shallower (approximately 3 m of water) and warmer (7–16°C) waters, and small-bodied individuals were captured in deeper (6.0–12.2 m) and cooler (7–14°C) waters. Similarly, in August, the large-bodied form was again concentrated in shallower (approximately 9 m depth) and warmer (15°C) waters, and the small-bodied form was concentrated in deeper (15.2 m) and cooler (9°C) waters; however, Kennedy (1943) noted this difference in August was largely driven by two net sets each containing a large number of

[1] The EOO and IAO in COSEWIC (2018) were reported as 150.5 km^2 in error, and should be the lake area (N. Mandrak, University of Toronto Scarborough, pers. comm.).

large-bodied individuals or small-bodied individuals, respectively. The small-bodied DU was also found deeper than the large-bodied DU in the East Arm during a recent survey (Mark Ridgway, OMNRF, pers. comm.). The observed depth distribution in Lake Opeongo is contrary to observations of species pairs in other lakes, and could be related to competition from Cisco in the limnetic zone, where the large-bodied DU is better able to compete.

A recent survey revealed differences in depth distribution between the East and South arms in the summer (Figure 2; note catches assumed to be the large-bodied DU). In the East Arm, Lake Whitefish was distributed across a wide range of depths (mean ~ 27 m). In the South Arm, Lake Whitefish was not found as deep (mean ~ 16 m), and was concentrated where the metalimnion is in contact with the substrate (OMNRF unpublished data, Challice et al. 2019). Challice et al. (2019) described catching significantly more Lake Whitefish in the morning compared to afternoon, likely related to foraging on vertically migrating insect larvae. Both DUs move back to nearshore areas for spawning in October and November (Ihssen et al. 1981). Distribution of Lake Whitefish in Lake Opeongo during winter months is not known.

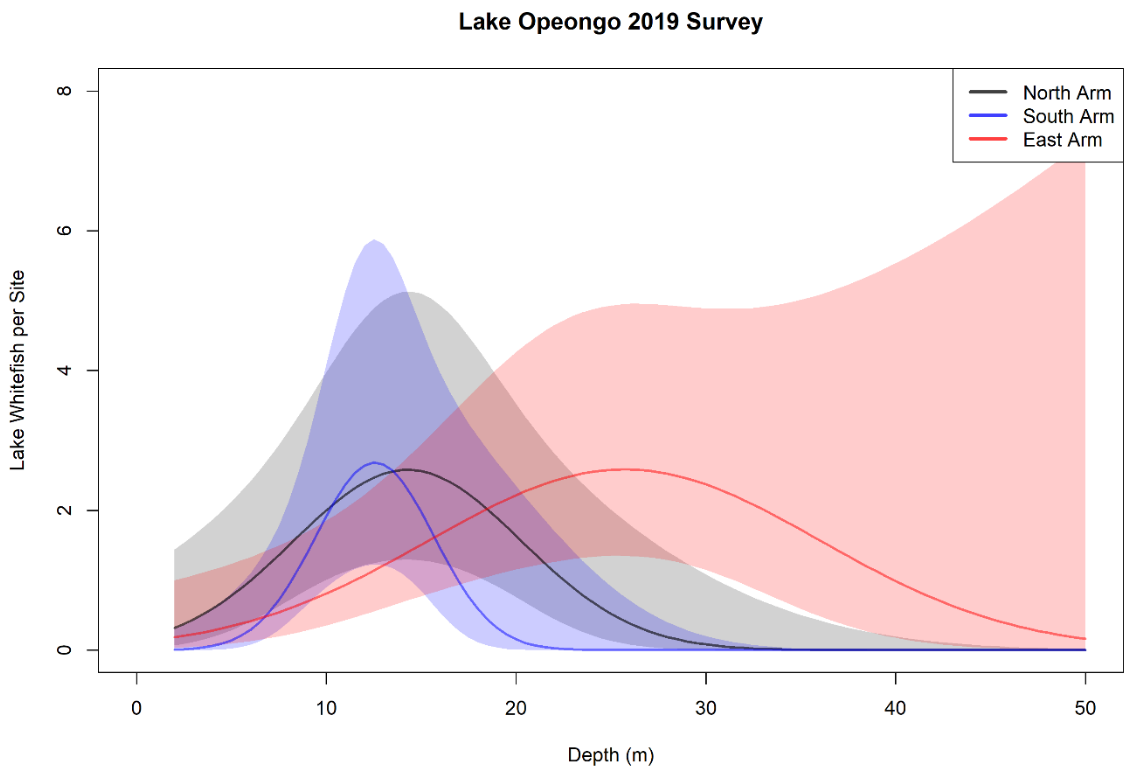

Figure 2. Number of large-bodied Lake Whitefish captured as a function of depth in the three arms of Lake Opeongo during Ontario Ministry of Natural Resources and Forestry 2019 large-mesh gill net surveys. 95% Confidence intervals presented (OMNRF unpublished data; figure provided by OMNRF).

CURRENT STATUS

The current distribution of Lake Whitefish in Lake Opeongo is shown in Figure 1 (DUs not differentiated). Time series data with the two DUs distinguished are not available. The large and small-bodied forms of Lake Whitefish were first reported in Lake Opeongo by Kennedy (1943). Sampling was extensive in the East and South arms in 1939 and the South Arm in 1940; sampling occurred May through November each year. Kennedy (1943) deployed three gangs of multi-panel gill nets as well as a veiling net that was used to target smaller fish. He found that the 2.54 cm (1”) mesh gill nets captured two to nine times as many small-bodied individuals as did the 3.18 cm (1 ¼”) mesh nets. Recent sampling by OMNRF from various protocols has confirmed the persistence of both DUs (OMNRF unpublished data). Targeted sampling for the small-bodied DU was conducted in 2018 to confirm its presence in the lake (Figure 3). Sampling efforts where the DUs were distinguished are summarized in Table 1.

Table 1. Summary of fishing effort in Lake Opeongo where large-bodied and small-bodied Lake Whitefish forms were identified. Immature Lake Whitefish are assumed to be large-bodied. Additional details of OMNRF sampling can be found in Sandstrom and Lester (2009). Mean temperature and mean dissolved oxygen (DO) were calculated from sites where Lake Whitefish was captured.

Year	Study	Gear	Effort	Depths Sampled	Imma-ture Lake White-fish	Large-bodied Lake White-fish	Small-bodied Lake White-fish
1939–1940 (May–Nov)	Kennedy (1943)	Multi-panel gill nets (274 m length; 45.7 m per panel; mesh 2.5–12.7 cm (1–5”)) Veiling nets (1.27 cm (½”) mesh milliner net between two 3.81 cm (1 ½”) mesh gill net panels)	166 overnight sets	3–43 m	524	524	167
1984, 1986	Evans and Ihssen (1993)	Unknown	Unknown	Unknown	-	65	42
2010 (July–Aug)	OMNRF Summer Profundal Index Netting	Multi-panel gill nets (64 m length; 8 panels; mesh 5.72–12.7 cm stretched); stratified random sampling design	150 two-hour sets	(mean depth of capture = 19.1 m; mean temperature = 8.7°C; mean DO = 9.19 mg/L)	(25)	186 * (89)	0
2018 (Aug)	OMNRF Small-mesh Gill Net	Multi-panel gill nets (25 m length; 5 panels; mesh 1.3–3.8 cm stretched)	16 two-hour sets	10.9–24 m (mean depth of capture = 12.6 m)	41	9	23
2019 (July)	OMNRF Multi-pass Large-mesh Gill Net	Multi-panel gill nets (50 me length; 8 panels; mesh 3.8–12.7 cm stretched); depth-stratified systematic sampling design	173 one-hour sites, 4 passes each	(mean depth of capture = 16.4 m, mean temperature = 9.0°C; mean DO = 9.45 mg/L)	(1)	109 † (20)	0

* 186 Lake Whitefish (all assumed to be large-bodied) were captured, but biological information was available for 114 (89 mature and 25 immature). A mean of 2.4 (range 1–7) individuals were caught per net set.

† 109 Lake Whitefish (all assumed to be large-bodied) were captured, but biological information was available for 21 (20 mature, one immature)

Other sampling has occurred in Lake Opeongo in the 1980's through early 2000's that targeted Lake Whitefish (Table 2; COSEWIC 2018, OMNRF unpublished data), but the two DUs were not formally distinguished (i.e., maturity information is not available); all captures were likely large-bodied individuals. This is not a complete list of all sampling that has occurred in Lake Opeongo, but represents effort where Lake Whitefish was captured. Additional sampling completed over this time as part of other research projects is not summarized (Ihssen et al. 1981, Cucin and Faber 1985, Evans and Ihssen 1993, Carl and McGuiness 2006, Morbey et al. 2007, Challice et al. 2019)

Table 2. Summary of fishing effort in Lake Opeongo where Lake Whitefish were captured, but large-bodied and small-bodied DUs were not distinguished (OMNRF unpublished data).

Year	Study	Gear	Lake Whitefish (n)
1981, 1982, 1986, 1988, 1995, 1996, 1997, 1998, 1999, 2000	OMNRF Summer Index Netting	Multi-panel gill nets	2512 (38, 44, 13, 56, 735, 347, 344, 117, 426, 392)
1990, 1991	OMNRF Lake-access Creel	-	3 (2, 1)
1990	OMNRF Summer Littoral Zone Netting	Multi-panel gill nets	1
1990	OMNRF Short-set gill nets	Multi-panel gill nets	319
1994, 1998	OMNRF Nearshore Community Index Netting	Multi-panel gill nets	47 (20, 27)
1999, 2002	OMNRF Nordic Netting	Multi-panel gill nets	147 (80, 67)

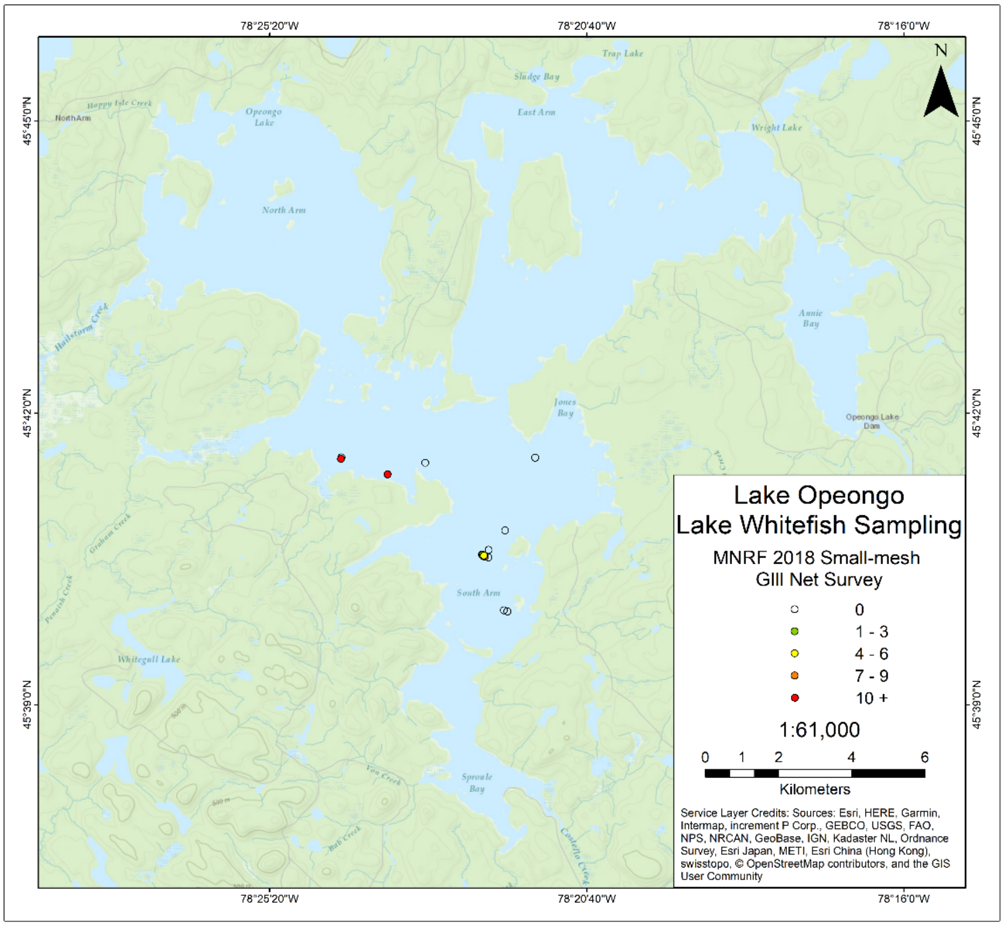

Figure 3. Lake Whitefish catches (not differentiated by DU at time of capture) from Ontario Ministry of Natural Resources and Forestry (OMNRF) summer survey from 2018 using small-mesh gill nets; 16 nets were set for approximately two hours each. A total of 73 Lake Whitefish were captured, 23 of which are from the small-bodied DU (mature and < 180 mm FL; OMNRF unpublished data).

POPULATION ASSESSMENT

To assess the DU status (traditionally, Population Status) of the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo, both DUs were ranked in terms of abundance (Relative Abundance Index) and Trajectory (Table 3).

The Relative Abundance Index was assigned as Extirpated, Low, Medium, High or Unknown. The number of individual Lake Whitefish caught during each sampling period was considered when assigning the relative abundance index. The Relative Abundance Index is a relative parameter in that the values assigned to each DU are relative to the most abundant DU. In the case of Lake Whitefish in Lake Opeongo, most studies that caught Lake Whitefish used gears with mesh sizes most suitable for detecting the large-bodied DU.

The Trajectory was assessed as Increasing (an increase in abundance over time), Decreasing (a decrease in abundance over time), or Stable (no change in abundance over time). The number of individuals caught over time for each DU was considered. If insufficient information was available to inform the Trajectory, the DU was listed as Unknown.

Definitive estimates of the abundance of large- and small-bodied DUs of Lake Whitefish do not exist. Two estimates of presumed large-bodied individuals were 11,378 and 22,792 (OMNRF unpublished data). The large-bodied DU has been consistently detected since its discovery by Kennedy (1943); most Lake Whitefish captured in Lake Opeongo have been > 200 mm FL, presumed to be of the large-bodied DU (Tables 1, 2). Catches of the large-bodied DU in Lake Opeongo are comparable to Lake Whitefish catches in other lakes in Algonquin Provincial Park that have similar size structure, and fish and invertebrate communities (including native and introduced species), and have been sampled using the same protocols (OMNRF unpublished data, Carl and McGuiness 2006). The small-bodied DU has not been consistently detected since its discovery and was thought to have possibly disappeared from the lake (COSEWIC 2018). Its continued presence was confirmed in 2018 by the capture of mature individuals < 180 mm FL (OMNRF unpublished data); however, very few were captured (n = 23). Most of the sampling effort in Lake Opeongo has used mesh sizes unlikely to detect the small-bodied DU, making inferences about population trends difficult.

Table 3. Relative Abundance Index and Trajectory of Lake Whitefish DUs in Lake Opeongo. Certainty has been associated with the Relative Abundance Index and Trajectory rankings and is listed as: 1=quantitative analysis; 2=CPUE or standardized sampling; 3=expert opinion.

DU	Relative Abundance Index	Certainty	Trajectory	Certainty
Large-bodied	Medium	2	Stable	2
Small-bodied	Unknown	3	Unknown	3

The Relative Abundance Index and Trajectory values were then combined in the DU (i.e., Population) Status matrix (Table 4) to determine the status for each DU. DU Status was subsequently ranked as Poor, Fair, Good, Unknown or Not applicable (Table 5).

Table 4. The Designatable Unit (DU; i.e., Population) Status Matrix combines the Relative Abundance Index and Trajectory rankings to establish the DU Status for each Lake Whitefish DU in Lake Opeongo, Ontario. The resulting DU Status has been categorized as Extirpated, Poor, Fair, Good, or Unknown.

<table>
<tr><th colspan="2"></th><th colspan="4">Trajectory</th></tr>
<tr><th colspan="2"></th><th>Increasing</th><th>Stable</th><th>Decreasing</th><th>Unknown</th></tr>
<tr><th rowspan="5">Relative Abundance Index</th><th>Low</th><td>Poor</td><td>Poor</td><td>Poor</td><td>Poor</td></tr>
<tr><th>Medium</th><td>Fair</td><td>Fair</td><td>Poor</td><td>Poor</td></tr>
<tr><th>High</th><td>Good</td><td>Good</td><td>Fair</td><td>Fair</td></tr>
<tr><th>Unknown</th><td>Unknown</td><td>Unknown</td><td>Unknown</td><td>Unknown</td></tr>
<tr><th>Extirpated</th><td>Extirpated</td><td>Extirpated</td><td>Extirpated</td><td>Extirpated</td></tr>
</table>

Table 5. DU Status of Lake Whitefish in Lake Opeongo, resulting from an analysis of both the Relative Abundance Index and Trajectory. Certainty assigned to each DU Status is reflective of the lowest level of certainty associated with either initial parameter (Relative Abundance Index, or Trajectory).

DU	DU Status	Certainty
Large-bodied	Fair	2
Small-bodied	Unknown	3

Element 3: *Estimate the current or recent life-history parameters for Lake Whitefish*

LIFE HISTORY PARAMETERS

Information on growth rates for both the large-bodied and small-bodied DUs of Lake Whitefish in Lake Opeongo comes primarily from Kennedy's (1943) assessment of scales. Overall, the large-bodied form grows larger and faster, and matures later (ages 4–7) than the small-bodied form. It had a mean SL of 251 mm and most individuals lived to age 9, but could exceed 400 mm and reach age 14 (Figure 4). Recent sampling by OMNRF found mature large-bodied individuals ranging from 198–519 mm FL, and up to age 24 (assessed from otoliths; Figure 5) (OMNRF unpublished data). Challice et al. (2019) found a Lake Whitefish of 658 mm FL in Lake Opeongo. Scales are generally considered valid for coregonines up to ages 7–10 (Barnes and Power 1984, Yule et al. 2008, Herbst and Marsden 2011). Scale ages of older individuals caught by Kennedy (1943) may have been underestimated compared to ages assessed on otoliths (OMNRF unpublished data).

The large-bodied form grew at a similar rate to the small-bodied form during the first year, then growth was faster after year one (Figure 6; Kennedy 1943). Growth appears to slow between ages 2 through 6, and then accelerates again towards the end of life. This trend is unexpected, and Kennedy postulated it could be because the small number of individuals that reached ages greater than 9 years may have had a particularly fast growth rate; however, a similar trend was also observed by Ihssen et al. (1981) in Lake Opeongo, and in large-bodied Lake Whitefish in Como Lake, Ontario (Bodaly et al. 1991) and Cliff Lake, Maine (Fenderson 1964).

The small-bodied form in Lake Opeongo grows slower and to a smaller size, and matures earlier (age 2) than the large-bodied form. The small-bodied form had a mean SL of 126 mm, and a maximum observed age of 5 (assessed from scales; Figure 4). Growth is similar to the large-bodied form in the first year, but nearly stops after age 2 (Kennedy 1943). Recent sampling by OMNRF found mature small-bodied individuals up to 176 mm FL, and up to age 8 (assessed from otoliths; Figure 5) (OMNRF unpublished data). Growth also ceases earlier in the growing season for the small-bodied DU compared to the large-bodied (Kennedy 1943). The growth curves from other populations of small-bodied Lake Whitefish are comparable to the Lake Opeongo small-bodied DU, but others may achieve a slightly larger size or older age (Figure 6; Fenderson 1964, Bodaly et al. 1991).

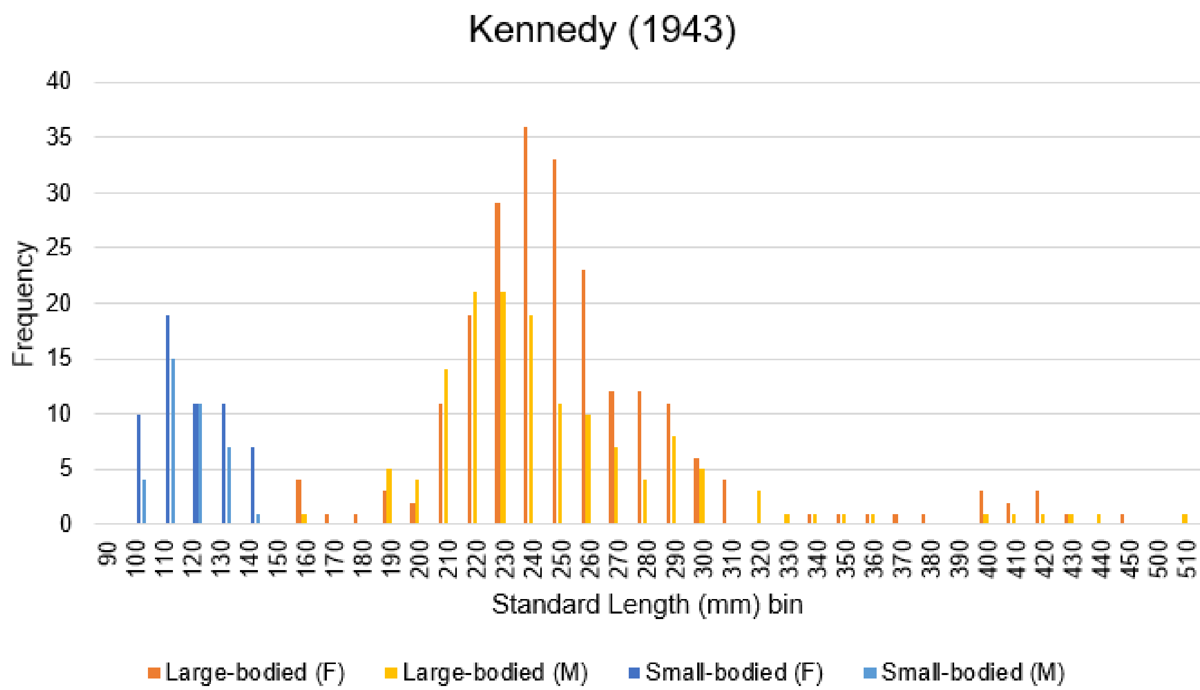

Figure 4. Bimodal size distribution of mature Lake Whitefish in Lake Opeongo, distinguished by sex and form. There was a gap in mature individuals from 150–160 mm and modes occurred at 120 and 240 mm. Data from Kennedy (1943) collected in 1939 and 1940. Lengths are reported as standard length.

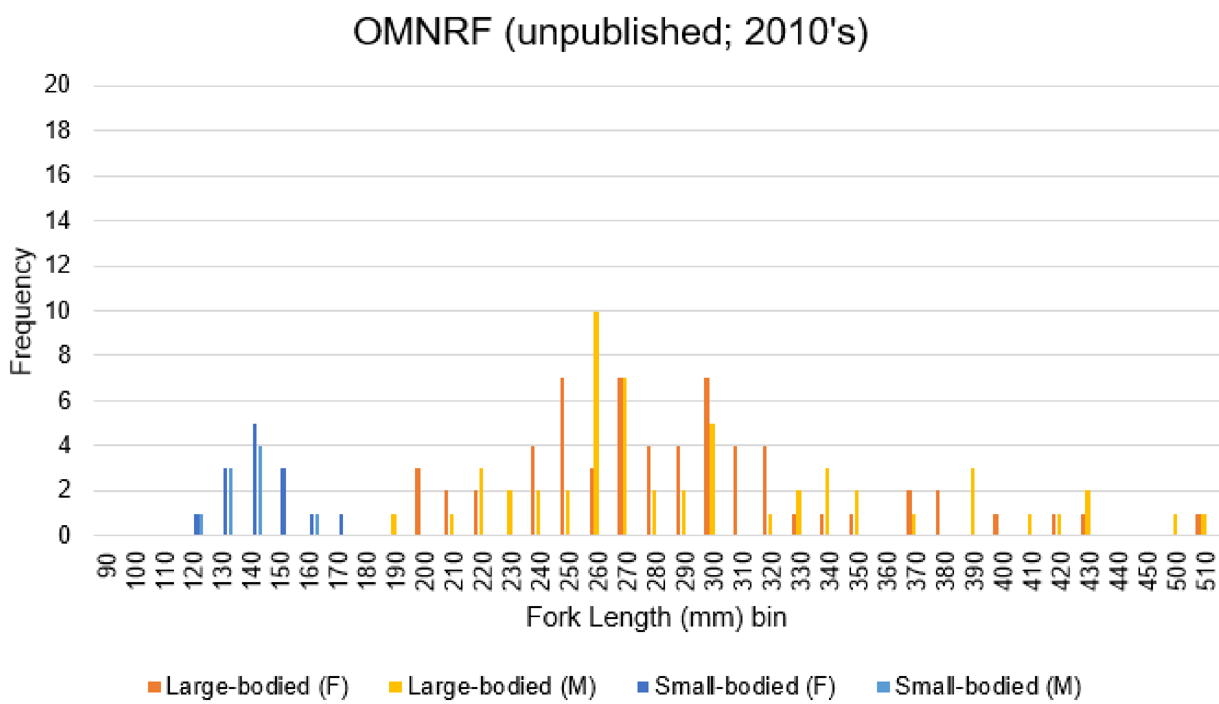

Figure 5. Bimodal size distribution of mature Lake Whitefish in Lake Opeongo, distinguished by sex and DU. There was a gap in mature individuals from 180–190 mm and modes occurred at 149 and 249 mm. Data from OMNRF (unpublished), collected in 2010, 2018, and 2019. Lengths are reported as fork length.

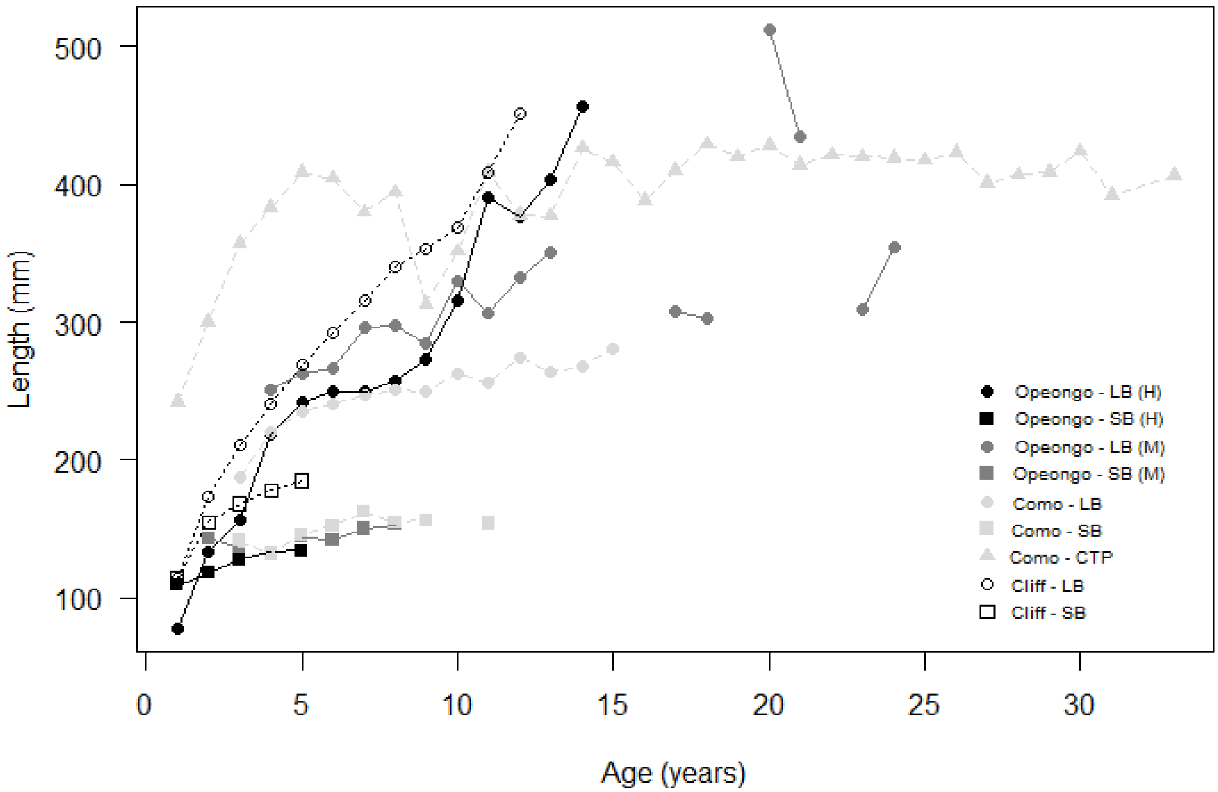

Figure 6. Mean length at age data for large-bodied (LB; circle), small-bodied (SB; square), and contemporary (CTP; triangle) forms of Lake Whitefish from Lake Opeongo (Kennedy (1943) – historic (H), OMNRF unpublished data – modern (M)), Como Lake (Reid et al. 2017), and Cliff Lake (Fenderson 1964). Data are empirical values; data from Kennedy (1943) are standard lengths and ages assessed on scales, OMNRF and Reid et al. (2017) data are fork lengths and ages assessed on otoliths, data from Fenderson (1964) are total length and ages assessed on scales.

Kennedy (1943) noted the growing season for Lake Whitefish on Lake Opeongo began mid-May at the earliest and finished end of September at the latest, and that the large-bodied form grew for a longer part of the growing season, terminating each years' growth later than the small-bodied form. Growth rates were variable year to year (e.g., 1926 and 1927 were particularly fast growing year classes). Mature females in the large-bodied form weighed approximately 2% more than males ($p = 0.04$) but this could be attributed to differences in weights of ovaries compared to testes.

Females from Lake Opeongo (not differentiated by form) had a mean of 7,632 eggs per fish (or up to 27,460 eggs per kg of bodyweight), with a mean gonadosomatic index (ratio of ovary weight to body weight calculated in October and November) of 12.95% (± 2.35 SD) (Ihssen et al. 1981). Eggs were 1.9–2.1 mm in diameter in the ovary and approximately 2.4–2.7 mm in diameter when water hardened with a wet weight of 5.09 mg (± 0.92 SD) (Ihssen et al. 1981, Cucin and Faber 1985).

Cucin and Faber (1985) found that larval Lake Whitefish in Lake Opeongo had a mean total length of 11.32 mm (± 0.61 SD) on May 1st, the earliest capture date, and by June 15th the mean total length was 19.2 mm (± 2.78 SD), but noted that the true mean was likely higher as the larger and older larvae could swim to avoid the tow nets. The authors were unable to distinguish between large- and small-bodied individuals. A survey of larval Lake Whitefish in Chaumont

Bay, Lake Ontario found that larvae grew a mean of 0.12 mm (± 0.04 SE) per day in April and 0.39 mm (± 0.04 SE) per day in May over three years (McKenna and Johnson 2009).

HABITAT AND RESIDENCE REQUIREMENTS

Element 4: *Describe the habitat properties that Lake Whitefish needs for successful completion of all life-history stages. Describe the function(s), feature(s), and attribute(s) of the habitat, and quantify by how much the biological function(s) that specific habitat feature(s) provides varies with the state or amount of habitat including carrying capacity limits, if any*

Lake Opeongo is located within Algonquin Provincial Park in Ontario. The watershed area is 346.1 km^2. The lake has a surface area of 5,860 ha, with a mean depth of 14.6 m and a maximum depth of approximately 50 m (Martin and Fry 1973, Rogers 2009, OMNRF 2020). Approximately 48.3% of the lake is less than 10 m in depth (Challice et al. 2019). The lake consists of three basins, referred to as the East, North, and South arms. The North and East arms connect to the South arm through channels. Water levels on the lake are maintained by a fixed-crest weir at the outlet of Annie Bay. The nearshore of the lake is primarily granite with some areas containing sand beaches or shallow, vegetated bays. The substrate at depth is organic muck (Kennedy 1943). The water is tea stained (Secchi depth of 5.5 m) with pH of 6.8, and total dissolved solids 31.0–35.0 ppm (Martin and Fry 1973, Ihssen et al. 1981, Carl 2007). The fish community contains at least 27 species representing 10 families of fishes (Martin and Fry 1973, Cucin and Faber 1985), and includes Burbot (*Lota lota*), Lake Trout (*Salvelinus namaycush*), Round Whitefish, White Sucker (*Catostomus commersonii*), Yellow Perch, and two introduced species: Smallmouth Bass (*Micropterus dolomieu*; introduced prior to 1920) and Cisco (introduced in 1948; Morbey et al. 2007).

Adult

Summer habitat use by the large- and small-bodied Lake Whitefish in Lake Opeongo was described by Kennedy (1943). Some differences in depth (and temperature) distribution were noted between the two forms throughout the summer season. Adult Lake Whitefish (both forms) were distributed across all depths sampled in May, when temperatures were homogenous through the lake. Both forms moved closer to shore in June; however, large-bodied individuals were captured in approximately 3 m of water (where water temperatures ranged from 7–16°C), and small-bodied individuals were captured in depths between 6 and 12.2 m (7–14°C). In July, both forms were captured in depths from 12–15.2 m (with water temperatures 8–18°C). In August, the large- and small-bodied forms again differed in occupied depths; the large-bodied form concentrated at shallower depths of 9 m (15°C), and the small-bodied form concentrated at 15.2 m (9°C). Kennedy noted that this difference observed in August was largely driven by a single net haul with a large concentration of large-bodied individuals, and another net with a large concentration of small-bodied individuals. In September, both forms were captured together again, occupying depths of 15.2–18.3 m (7–10°C). Lake Whitefish in Lake Opeongo preferentially occupied water warmer than 7 °C when it was available, up to a maximum of 18°C in July and August and 10°C in September. The thermal range for Lake Whitefish in Lake Opeongo reported by Challice et al. (2019) was 7.6–20.0°C with the greatest occupancy observed at 7.7–13.6°C. The authors also noted occupancy was highest where the thermocline contacts the substrate (the washing zone), making use of both the hypolimnion and lower metalimnion, which may provide a more diverse benthic invertebrate community. Dissolved oxygen (DO) has not been found to be limiting in Lake Opeongo; DO was > 7 mg/L at all depths measured (Challice et al. 2019) and was almost always > 8.5 mg/L at sites where large-bodied Lake Whitefish were captured in 2010 and 2019 (OMNRF unpublished data).

Adult Lake Whitefish move into spawning grounds in late October through November, when water temperatures reach 4–7°C (Ihssen et al. 1981). Lake Whitefish generally spawns in depths less than 7.6 m over hard substrates (Scott and Crossman 1998). Ihssen et al. (1981) noted that the lake contains many granite rock ledges and cobble shoals close to shore where spawning likely occurs. Catches of larval Lake Whitefish in both the East and South arms suggest spawning likely occurs at multiple locations around the lake (Cucin and Faber 1985). Martin and Fry (1973) indicated that the East Arm contains the primary spawning grounds for Lake Whitefish.

Winter habitat use in Lake Opeongo is not known, but in Clear Lake, Maine (mean depth of 8.8 m, max depth of 26.2 m) tagged adult Lake Whitefish occupied depths of approximately 15 m (depth range of 8.1–17.7 m) from December through May. After ice out, the fish moved into shallower (< 5 m in depth) warming waters for several weeks, then retreated back to deeper (10–15 m), colder water by summertime (Gorsky et al. 2012).

Juvenile

Little is known about the habitat occupied by juvenile Lake Whitefish in Lake Opeongo. Kennedy (1943) and OMNRF (unpublished data) caught immature individuals with mature large-bodied and small-bodied individuals, suggesting that juveniles can occupy habitats similar to adults. Kennedy (1943) suspected the immature individuals were of the large-bodied form and the immature small-bodied individuals were too small to be captured in the gear. As such, habitat use of the small-bodied juveniles remains unknown. Juvenile Lake Whitefish in other populations are thought to occupy similar habitats as adults as well (Scott and Crossman 1998). Edsall (1999a) found the preferred thermal range for juvenile (age 1) Lake Whitefish was 15.5–19.5 °C in a laboratory setting.

Young of Year

Few larval surveys of Lake Whitefish have been conducted on Lake Opeongo. Ihssen et al. (1981) described larval Lake Whitefish occupying nearshore areas overtop of the spawning grounds for approximately six weeks after hatch when surface water temperatures were 6.5–9.5°C; this is true of larval Lake Whitefish in general (Hart 1930, Freeberg et al. 1990, Jude et al. 1998, McKenna and Johnson 2009, Herbst et al. 2011). The larval fish have limited dispersal abilities at this time, and in larger systems, are sometimes displaced into shore (McKenna and Johnson 2009). After approximately six weeks, an ontogenetic diet shift occurs and larval fish begin to retreat to deeper waters. In some Great Lakes populations, age-0 fish are caught in bottom trawls at shallower depths than adults (Hart 1930, Pothoven et al. 2014); however, the depths occupied by this life stage likely depend on the bathymetry of the system. There are records of age-0 Lake Whitefish captured at depths greater than 20 m in Lake Opeongo (Ihssen et al. 1981). Laboratory studies have shown the preferred thermal range of YOY Lake Whitefish was 12.9–17.8, depending on acclimation temperature (Edsall 1999b).

Cucin and Faber (1985) detected larval Lake Whitefish at most larval sampling sites (East and South arms) in Lake Opeongo, with abundance greatest in the north section of the East Arm. In Cliff Lake, Maine, Chouinard and Bernatchez (1998) found no differences in depth distribution of larval large- and small-bodied Lake Whitefish (confirmed with genetic analysis) during the day or night.

FUNCTIONS, FEATURES, ATTRIBUTES

A description of the functions, features, and attributes associated with the habitat of large- and small-bodied Lake Whitefish in Lake Opeongo can be found in Table 6. The habitat required for each life stage has been assigned a life history function that corresponds to a biological requirement of Lake Whitefish. In addition to the life history function, a habitat feature has been assigned to each life stage. A feature is considered to be the structural component of the habitat necessary for the species. Habitat attributes have also been provided, these are measurable components describing how the habitat features support the life history function for each life stage. This information is provided to guide any future identification of critical habitat for this species. Information is provided for Lake Opeongo DUs where available, and supplemented with general information on Lake Whitefish from elsewhere when necessary.

Table 6. Summary of the essential functions, features, and attributes for each life stage of Lake Whitefish in Lake Opeongo. Habitat attributes from published literature, and those recorded during recent Lake Whitefish captures in Lake Opeongo, have been used to determine the habitat attributes required for the delineation of critical habitat. Information is assumed to be the same for the large- and small-bodied DUs where they are not differentiated.

Life Stage	Function	Feature (s)	Habitat Attribute (s)	
			Scientific Literature	**Critical Habitat**
Spawn to hatch	Spawning (late October through November)	nearshore areas over hard substrates	• water temperatures 4–7°C (Ihssen et al. 1981) • granite ledges and rocky shoals (Ihssen et al. 1981, Cucin and Faber 1985) • depth range approximately 3–5 m (Cucin and Faber 1985); generally, water depths < 8 m (Scott and Crossman 1998) • ~ 10–50 m from shore (Cucin and Faber 1985)	nearshore (up to 50 m offshore) areas over hard substrates (granite ledges and rocky shoals), less than 8 m in depth, especially in East and South arms
	Egg Development (over winter)	hard substrates; cold temperatures; extensive ice cover	•granite or limestone ledges or shoals (with rock, cobble, gravel) free of fine sediments (Hart 1930, Fudge and Bodaly 1984, Freeberg et al. 1990, Jude et al. 1998, McKenna and Johnson 2009) • generally, water temperatures 0.5–8.1°C (Price 1940, Brooke 1975) • generally, cold winters with extensive cover to protect eggs from disturbance/displacement (Freeberg et al. 1990, Jude et al. 1998, McKenna and Johnson 2009)	
	Hatch (days after ice out, late April through May)	warming, productive waters (epilimnion)	• water temperatures 4–8°C (Ihssen et al. 1981, Cucin and Faber 1985)	

Life Stage	Function	Feature (s)	Habitat Attribute (s)	
			Scientific Literature	Critical Habitat
Larval (up to ~ 6 weeks after hatch)	Nursery; feeding	warming, productive waters (epilimnion)	• warming surface waters with temperatures 4–8°C upon hatch, achieving 6.5–12°C (Ihssen et al. 1981, Cucin and Faber 1985), generally, within upper 0.3–1 m (Hart 1930, Reckahn 1970, Freeberg et al. 1990, Herbst et al. 2011)) over depths of 1.5–10 m directly over or near spawning areas (Cucin and Faber 1985) • generally, abundant zooplankton prey (Hart 1930, Freeberg et al. 1990, Cucin and Faber 1985)	warm, productive surface waters over depths up to 10 m (generally same as above)
Age 0 (~50 mm, or when first ontogenetic diet shift occurs)	Feeding	Cool waters of intermediate depths	• unknown in Lake Opeongo • in Great Lakes populations, age 0 individuals move below surface and occupy benthic habitats that are shallower than final adult habitat (Hart 1930, Claramunt et al. 2010, Pothoven et al. 2014)	unknown
Juvenile (age 1 to onset of maturity [~ age 4–5 for large-bodied DU; age 2 for small-bodied DU])	Feeding	cold, deep water in the hypolimnion	• generally, same habitat as adults • laboratory experiments suggest preferred thermal range (age 1) of 15.5–19.5°C; 18.5°C optimum for growth (Edsall 1999a,b)	areas of deep, cold water, not exceeding 20°C
Adult	Feeding	cold, deep water (hypolimnion) with access to pelagic and benthic invertebrates	• water depths ranging from 3–18 m • summer water temperatures 7–14°C, not exceeding 20°C (Kennedy 1943, Challice et al. 2019) • abundant Cladocera, Ephemeroptera larvae (notably in May), Chironomidae, and bivalve *Pisidium* sp. (Sandercock 1964)	areas of deep, cold water, not exceeding 20°C

Life Stage	Function	Feature (s)	Habitat Attribute (s)	
			Scientific Literature	Critical Habitat
Adult (large-bodied DU)	Feeding	cold, deep water (hypolimnion)	• may occupy shallower, warmer water occasionally during summer months (3 m depth with temperatures 7–16° C in June, and 9 m depth and 15° C in August [Kennedy 1943])	unknown
Adult (small-bodied DU)	Feeding	cold, deep water (hypolimnion)	• may occupy deeper, cooler water occasionally during summer months (6–12 m depth with temperatures 7–14° C in June, and 15 m depth and 9° C in August [Kennedy 1943])	unknown

Element 5: *Provide information on the spatial extent of these areas in Lake Whitefish distribution that are likely to have these habitat properties*

It is likely that, with the exception of the few shallow, weedy bays, all of Lake Opeongo provides habitat for Lake Whitefish during at least one life stage or at some time of the year. Challice et al. (2019) reported that 48.3% of the lake is less than 10 m in depth and that 23.3% of the lake is deeper than 20 m and would likely provide thermally suitable summer habitat for juvenile and adult Lake Whitefish. There are many granite ledges and cobblestone shoals (each of a hectare or less in area) of appropriate depths suitable for spawning and egg development around the lake (Ihssen et al. 1981). There is a total of 109.3 km of shoreline, with the nearshore substrate material composed of a mean of 22.2% sand, gravel and small boulder type, and a mean of 34.5% bedrock, rubble and large boulder type (Cucin and Faber 1985); both of these substrate types are likely suitable for spawning and foraging. The South Arm contains the longest shoreline (49 km) and the greatest proportion of bedrock, rubble and large boulders (41.2%; Cucin and Faber 1985). The small bodied DU has not been reported from the North Arm but this is likely due to sampling bias (i.e., insufficient effort and/or unsuitable mesh sizes).

Element 6: *Quantify the presence and extent of spatial configuration constraints, if any, such as connectivity, barriers to access, etc.*

There are no consistently passable connections between Lake Opeongo and other nearby lakes, so Lake Whitefish are effectively constrained to the lake; however, Lake Whitefish may be able to pass over the Annie Bay Dam out of the lake during high water events (Mark Ridgway, OMNRF, pers. comm.). Some tributaries may be accessible for a short length but it is unclear to what extent (if any) Lake Whitefish in Lake Opeongo use these habitats. There are channels connecting each of the arms of Lake Opeongo, and there is no evidence to suggest these prevent or discourage movement between the basins.

Element 7: *Evaluate to what extent the concept of residence applies to the species, and if so, describe the species' residence*

Residence is defined in SARA as a "dwelling-place, such as a den, nest or other similar area or place, that is occupied or habitually occupied by one or more individuals during all or part of their life cycles, including breeding, rearing, staging, wintering, feeding or hibernating". Residence is interpreted by DFO as being constructed by the organism. In the context of the above narrative description of habitat requirements during the life stages of Lake Whitefish, individuals of either DU do not construct residences during their life cycle.

THREATS AND LIMITING FACTORS TO THE SURVIVAL AND RECOVERY OF LAKE WHITEFISH

Element 8: *Assess and prioritize the threats to the survival and recovery of the Lake Whitefish*

THREAT CATEGORIES

A number of threats may negatively impact the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo; however, due to their presence within Algonquin Provincial Park, certain habitat-related threats are limited. The greatest threats are from the introduction of aquatic invasive species that could disrupt food webs and other ecological processes that allow for both DUs to persist sympatrically. There is limited available information to classify threats separately for each DU, but threats were distinguished when supported. Threats were classified according to the IUCN CMP Unified Classification of Direct Threats system (Salafsky et al. 2008). Threats identified as negligible by COSEWIC (2018) were not included in this document.

Human Intrusions and Disturbance

Lake Opeongo is the most visited lake within Algonquin Provincial Park for both recreational angling and backcountry camping. It has 142 campsites, 12 portages, and various park infrastructure including a permit office, staff accommodations, parking lots, outfitters, and the Harkness Laboratory for Fisheries Research (P. Gelok, MOECP, pers. comm.). A 120 m forested buffer is present around the shoreline of the lake (Ontario 2013). Lake Opeongo receives an average of over 2,100 bass and trout angling party nights per year (Mitchell et al. 2020), and is the one of two lakes in Algonquin Provincial Park that permit unlimited horsepower vessels.

Recreational fishing on Lake Opeongo typically targets Lake Trout and Smallmouth Bass (Mitchell et al. 2020); however, Lake Whitefish may be captured incidentally. From creel survey data collected since 1992, a total of 870,334 angler hours were spent fishing Lake Opeongo (the annual average fishing effort was 32,235 hours). A total of 1,138 hours were spent targeting Lake Whitefish (annual average of 42 hours). A total of 358 Lake Whitefish were caught over this time (annual average catch of 13), and 189 of those were harvested (annual average of 7 taken; OMNRF unpublished data). Large-bodied individuals are likely caught more often than small-bodied.

Recreational vessels are known to impact fish and fish habitat, in general (Whitfield and Becker 2014). Mortalities, physiological and behavioural impacts on fishes, as well as habitat disturbances such as increases in turbidity and changes in invertebrate communities have been observed in some studies, but population-level impacts are not well understood (John and Hasler 1956, Yousef et al. 1980, Garrad and Hey 1987, Killgore et al. 2001, Bishop 2007, Rellstab et al. 2007, Graham and Cooke 2008, Gabel et al. 2011, Maxwell et al. 2018).

Major developments are unlikely to occur near the lake due to zoning and other park regulations; however, small construction works or activities related to access points and park infrastructure could be conducted in the future in accordance with the Algonquin Provincial Park Management Plan (Ontario 1998, 2013).

Invasive and Other Problematic Species and Genes

Aquatic invasive species are thought to be the greatest threats facing most sympatric whitefish pairs as they are likely to disrupt the ecological conditions that drive and maintain divergence of the two forms (Mee et al. 2015, Reid et al. 2017, COSEWIC 2018). Two fish species were introduced into Lake Opeongo, Smallmouth Bass in the early 1900’s and Cisco in 1948, but it is unclear what effect these species have had on the two Lake Whitefish DUs. Kennedy (1943) documented the Lake Whitefish species pair after the establishment of Smallmouth Bass, so impacts from this species were likely indirect and negligible. However, Morbey et al. (2007) noted that small Lake Whitefish had declined (as noted in the diet of Lake Trout) in the period of 1937–1943 and hypothesized the decline could be related to competition with Smallmouth Bass for macroinvertebrate prey. It has long been noted that sympatric pairs of Lake Whitefish are only known from lakes where Cisco is absent; small-bodied forms of Lake Whitefish often occupy a limnetic niche similar to Cisco, where the latter would have a competitive advantage (Pigeon et al. 1997, Trudel et al. 2001, Mee et al. 2015). There have been some observations of the small-bodied DU of Lake Whitefish occupying deeper depths than the large-bodied DU in Lake Opeongo (Kennedy 1943), suggesting the possibility it is more benthic and may not compete with Cisco (Mark Ridgway, OMNRF, pers. comm.). Cisco nearly replaced Lake Whitefish in the diet of Lake Trout in the decades following its introduction (Morbey et al. 2007), perhaps releasing some predation pressure. Cisco is also known to predate on Lake Whitefish eggs (Hart 1930). The large- and small-bodied DUs of Lake Whitefish continue to persist in Lake Opeongo despite the possible impacts from these introduced species.

Other aquatic invasive species have impacted sympatric Lake Whitefish pairs elsewhere. It is hypothesized that the introduction of Spiny Waterflea (*Bythotrephes longimanus*) may be responsible for the replacement of the Lake Whitefish pair with a single, larger form in Como Lake, Ontario (Reid et al. 2017). Spiny Waterflea has become the most abundant and largest zooplankton food source in Como Lake and both DUs of Lake Whitefish may have shifted their diet to feed predominantly on this prey item, resulting in more uniform conditions and faster growth for both DUs. It is unclear whether both DUs now grow so rapidly that they are indistinguishable from one another, or whether they have collapsed into a hybrid, but two distinct forms are no longer found (Reid et al. 2017, COSEWIC 2018). The introduction of Rainbow Smelt (*Osmerus mordax*) has also led to a decline in Lake Whitefish populations in many lakes in eastern North America containing either a species pair or a single form, due to competitive interactions at the larval stage and/or predation on newly hatched Lake Whitefish by adult Rainbow Smelt (Loftus and Hulsman 1986, Evans and Waring 1987, Gorsky and Zydlewski 2013, Wood 2016). The nature and result of this interaction appears to be context specific, but generally results in poor recruitment for Lake Whitefish (Evans and Loftus 1987). Spiny Waterflea and Rainbow Smelt are known from lakes around Algonquin Provincial Park, and future introductions into Lake Opeongo are possible via the movement of contaminated recreational boats or through illegal human-mediated introductions, respectively. Additional invaders (e.g., Zebra/Quagga mussels (*Dreissena* spp.)) and species not native to Lake Opeongo (e.g., Northern Pike (*Esox lucius*)) also exist nearby, and may similarly be transferred to Lake Opeongo via contaminated recreational boats or illegal introductions. Owing to the mid-level trophic position of Lake Whitefish in Lake Opeongo, likely in both benthic- and limnetic-oriented food webs, introductions of any aquatic invasive taxa are likely to have effects on Lake Whitefish that could result in homogenization of the two DUs. Further information is needed on the trophic niches of each DU to better understand how future invasive species could disrupt the species pair.

Climate Change and Severe Weather

Warming temperatures and reduced ice cover are two outcomes of climate change most likely to negatively impact Lake Whitefish in Lake Opeongo, based on forecasted and observed changes already occurring in Algonquin Park and limiting factors to the species known from elsewhere (Ridgway and Middel 2020).

Warming water temperatures are likely to directly impact Lake Whitefish in several ways. Lake Whitefish eggs, in general, develop at water temperatures between 0.5–8.1°C, the optimum being at the low end to middle of this range and above which abnormalities and mortalities have been observed under experimental conditions (Price 1940, Brooke 1975). Annual mean air temperatures in the Ontario Great Lakes region are projected to increase by 2.3–7.9°C through the end of the century (McDermaid et al. 2015), possibly placing eggs in a thermally precarious range. Earlier onset of spring can cause a mismatch in timing of larval Lake Whitefish hatching and zooplankton prey abundance (Winder and Schindler 2004, Straile et al. 2007, Jeppeson et al. 2012, Anneville et al. 2009, Pothoven 2020). Reduced ice cover can also decrease egg over-winter survival. Ice cover is thought to provide protection from disturbance associated with wind, wave and current action that may displace eggs from spawning grounds. In larger bays of the Great Lakes, Lake Whitefish egg over-winter survival and subsequent larval density in the spring was found to be significantly greater in colder winters with more extensive ice cover, compared to warmer winters with less ice cover (Freeberg et al. 1990, McKenna and Johnson 2009, Ryan and Crawford 2014). A reduction in ice cover has already been documented on Lake Opeongo in recent decades (Ridgway et al. 2018). Hatching success can therefore be expected to decline as over-winter temperatures increase, ice cover is reduced, and spring arrives earlier. Year class strength will vary because of this, with some year classes being poorly represented or absent.

Warming temperatures may also impact habitat use of all life stages of Lake Whitefish. Earlier warming in the spring may reduce the time that Lake Whitefish are able to feed in productive surface waters without thermal consequences (Gorsky et al. 2012). Lake Whitefish in Lake Opeongo occupy depths where temperatures range from 7–20°C during the summer months, but were most abundant in temperatures from 7.7–13.6°C (Kennedy 1943, Challice et al. 2019). As water temperatures increase, it is thought that lake stratification will last for longer each season, restricting habitat use for coldwater species and prolonging hypoxic conditions where Lake Whitefish are residing during the summer (Sharma et al. 2011, Ridgway and Middel 2020). Guzzo and Blanchfield (2017) found that the quantity of optimal oxythermal habitat for coldwater fishes during summer months has decreased since the 1970's in Boreal Shield lakes. It is hypothesized that lotic coldwater habitat could decrease by 33–86% in the Great Lakes region as a result of climate change, and this is expected to be similar for lentic habitats as well (McKenna 2019). Both the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo could be forced to shift to the same habitat and food sources to avoid thermal stress (Guzzo and Blanchfield 2017), which could lead to niche overlap and, ultimately, loss of the pair.

Other outcomes of climate change could indirectly impact Lake Whitefish in Lake Opeongo as well. Changes in productivity linked to climate change in in-land oligotrophic lakes were thought to be responsible for reduced body condition of Lake Whitefish and Cisco (Rennie et al. 2010). Global increases in harmful algal blooms in recent decades have also been associated with climate change, and cyanobacterial blooms have recently been documented in another Algonquin Park lake (Chapra et al. 2017, Favot et al. 2019, Ridgway and Middel 2020). Algal blooms can detrimentally affect water quality and food webs, and may have a greater impact on pelagic feeders (i.e., certain life stages or DUs of Lake Whitefish in Lake Opeongo) due to bioaccumulation of toxins (Paerl et al. 2001, Sotton et al. 2014, Sukenik et al. 2015).

Cumulative Threats

Threats are often considered independently during threat assessments, but may interact in complex and context-dependent ways. In addition to simple additive effects, stressors in combination can be additive, can compound to amplify impacts (i.e., synergistic responses) or can work antagonistically to dampen impacts relative to any stressor on its own (Schindler 2001, Strayer 2010, Palmer and Yan 2013, Kernan 2015, Jackson et al. 2016, Kovach et al. 2017). It is likely that DUs of Lake Whitefish in Lake Opeongo could be subject to cumulative threats.

Recreational Fishing x Invasive Species or Climate Change

Few studies have investigated the combined impacts of recreational fishing with either invasive species or climate change. Climate change may increase opportunities for recreational fishing, which in-turn may increase the likelihood of human-mediated transport of invasive species (Schindler 2001). Increased potential for the introduction of invasive species, or increased productivity of invasive species owing to climate change, could be coupled with increased harvest potential (incidentally or otherwise) if climate change also results in increased angling opportunities for Lake Whitefish. This situation could result in cumulative impacts stemming from recreational fishing, invasive species, and climate change. Both DUs of Lake Whitefish in Lake Opeongo are most sensitive to perturbations in adult survival when population growth rates are stable or decreasing (Fung et al. 2022). Recreational fishing is most likely to capture adults, so indirect impacts from recreational fishing on top of negative impacts resulting from either of the other two threats may further suppress population growth.

Invasive Species x Climate Change

Climate change can facilitate invasions by enabling range expansion of native species and established invaders into areas they may have been excluded from or suppressed in due to thermal constraints (Schindler 2001, Jackson and Mandrak 2002, Rahel and Olden 2008, Strayer 2010). New invaders and climate change can both alter habitat (biotic and abiotic) conditions and ecosystem functions in a variety of ways (Strayer 2010, Kernan 2015). As more species invade, ecosystems become less resilient to new invaders over time, and, in some cases, invasions of one species may facilitate the invasion of a co-evolved species (Ricciardi and McIsaac 2000). Likewise, increased frequency and intensity of extreme weather events can also make ecosystems less resilient. How the interactions between invasive species and climate change unfold in the context of Lake Opeongo Lake Whitefish is unknown. For example, adult and larval Rainbow Smelt feed on and compete with larval Lake Whitefish, respectively, reducing recruitment. Climate change is likely to reduce egg overwinter survival and may lead to a mismatch in Lake Whitefish hatch and zooplankton abundance in the spring, leading to reduced survival. These impacts in combination could be amplified relative to either threat on its own, leading to greatly reduced recruitment. Alternatively, Rainbow Smelt is also a coldwater species likely to be negatively impacted by climate change (in terms of range expansion, growth, recruitment, survival), and climate change could work to lessen its impacts on Lake Whitefish (Sharma et al. 2011).

THREAT ASSESSMENT

Threats were assessed following guidelines in DFO (2014). Each threat was ranked in terms of the threat Likelihood of Occurrence (LO), threat Level of Impact (LI) and Causal Certainty (CC). The Likelihood of Occurrence was assigned as Known, Likely, Unlikely, Remote or Unknown, and refers to the probability of a specific threat occurring for a given population over 10 years or 3 generations, whichever is shorter. The Level of Impact was assigned as Extreme, High, Medium, Low, or Unknown and refers to the magnitude of the impact caused by a given threat, and the level to which it affects the survival or recovery of the DU (Table 7). The level of certainty associated with each threat was assessed and classified as: 1 = very high, 2 = high, 3 = medium, 4 = low, 5 = very low. The DU-Level Threat Occurrence (traditionally, Population-level; PTO), Threat Frequency (PTF) and Threat Extent (PTE) were also evaluated and assigned a status based on the definitions outlined in Table 7 (rankings in Table 8). The Likelihood of Occurrence and Level of Impact for each DU were subsequently combined in the Threat Risk Matrix (Table 9; rankings in Table 10).

Table 7. Definition and terms used to describe likelihood of occurrence (LO), level of impact (LI), causal certainty (CC), population (in this case, Designatable Unit) -level threat occurrence (PTO), threat frequency (PTF) and threat extent (PTE) reproduced from DFO (2014).

Term	Definition
Likelihood of Occurrence (LO)	
Known or very likely to occur (K)	This threat has been recorded to occur 91–100%
Likely to occur (L)	There is a 51–90% chance that this threat is or will be occurring
Unlikely (UL)	There is 11–50% chance that this threat is or will be occurring
Remote (R)	There is 1–10% or less chance that this threat is or will be occurring
Unknown (U)	There are no data or prior knowledge of this threat occurring or known to occur in the future

Term	Definition
Level of Impact (LI)	
Extreme (E)	Severe population decline (e.g., 71–100%) with the potential for extirpation
High (H)	Substantial loss of population (31–70%) or threat would jeopardize the survival or recovery of the population
Medium (M)	Moderate loss of population (11–30%) or threat is likely to jeopardize the survival or recovery of the population
Low (L)	Little change in population (1–10%) or threat is unlikely to jeopardize the survival or recovery of the population
Unknown (U)	No prior knowledge, literature or data to guide the assessment of threat severity on population
Causal Certainty (CC)	
Very high (1)	Very strong evidence that threat is occurring and the magnitude of the impact to the population can be quantified
High (2)	Substantial evidence of a causal link between threat and population decline or jeopardy to survival or recovery
Medium (3)	There is some evidence linking the threat to population decline or jeopardy to survival or recovery
Low (4)	There is a theoretical link with limited evidence that threat is leading to a population decline or jeopardy to survival or recovery
Very low (5)	There is a plausible link with no evidence that the threat is leading to a population decline or jeopardy to survival or recovery
Population-Level Threat Occurrence (PTO)	
Historical (H)	A threat that is known to have occurred in the past and negatively impacted the population.
Current (C)	A threat that is ongoing, and is currently negatively impacting the population.
Anticipatory (A)	A threat that is anticipated to occur in the future, and will negatively impact the population.
Population-Level Threat Frequency (PTF)	
Single (S)	The threat occurs once.
Recurrent (R)	The threat occurs periodically, or repeatedly.
Continuous (C)	The threat occurs without interruption.
Population- Level Threat Extent (PTE)	
Extensive (E)	71–100% of the population is affected by the threat.
Broad (B)	31–70% of the population is affected by the threat.
Narrow (NA)	11–30% of the population is affected by the threat.
Restricted (R)	1–10% of the population is affected by the threat.

Table 8. Threat Likelihood of Occurrence (LO), Level of Impact (LI), Causal Certainty (CC), Population (in this case, Designatable Unit) -level Threat Occurrence (PTO), Threat Frequency (PTF) and Threat Extent (PTE) for the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo.

	Large-bodied DU						Small-bodied DU					
	LO	LI	CC	PTO	PTF	PTE	LO	LI	CC	PTO	PTF	PTE
Human intrusions and disturbance	K	L	5	H, C, A	R	R	K	L	5	H, C, A	R	R
Invasive and other problematic species and genes	L	H	2	H, C, A	C	E	L	H	2	H,C, A	C	E
Climate change and severe weather	K	L	3	C, A	C	B	K	L	3	C,A	C	B

Human intrusions and disturbances from recreational activities (e.g., fishing, motorized vessel use, camping, visiting) are known to occur in and around Lake Opeongo. Indirect impacts from recreational fishing are likely to have a greater impact on the large-bodied DU, but are likely low as Lake Whitefish are not frequently targeted or incidentally captured by fishers on the lake (OMNRF unpublished data). Impacts from recreational vessels may also have a greater impact on the large-bodied DU (if it regularly occupies shallower waters) and on larval Lake Whitefish, but impacts would mostly occur in littoral areas not generally occupied by this species. These impacts recur seasonally, but would likely only affect a small proportion of the population in the vicinity of the disturbance.

Invasive and other problematic species and genes have already been introduced into the lake, and are, thus, known to occur, but the level of impact of these introduced species appears to be low as both DUs persist. The arrival and subsequent impact of new aquatic invasive species depends on the taxa. This threat was assessed considering the existing introduced species and two invaders that have had substantial impacts on Lake Whitefish pairs elsewhere and are anticipated to arrive to Lake Opeongo based on their current distribution and recent spread. Spiny Waterflea and Rainbow Smelt are already present in other lakes surrounding Algonquin Park, and their level of impact could be extreme should they arrive in Lake Opeongo (e.g., loss of species pair in Como Lake, Ontario (Reid et al. 2017)). Aquatic invasive species would likely have extensive effects on both DUs, whether directly or indirectly.

Effects of climate change and severe weather, including warming temperatures and reduction of ice cover (duration and extent), have already been documented in and around Algonquin Provincial Park (Ridgway et al. 2018); however, the impacts on Lake Whitefish in Lake Opeongo are not well known. Declines and extirpations of Lake Whitefish and Cisco have been observed in lakes in Wisconsin and Minnesota, the species' southern range edge, resulting from climate change (Sharma et al. 2011, Jacobson et al. 2008, Renik et al. 2020). It is expected that egg survival and hatching success will be reduced, habitat shifts will occur for all life stages, and body condition may be reduced as has been observed elsewhere (Freeberg et al. 1990, McKenna and Johnson 2009, Rennie et al. 2010, Ryan and Crawford 2014, Guzzo and Blanchfield 2017). Threats from climate change were considered over a 10 year timeframe (~ 1–2 generations) here. They are current and anticipated to get worse over time, with continuous impacts overall. This threat is likely to affect a broad extent of the population in any given year, but will vary year to year (i.e., some years egg survival may be low because of a warm winter, and other years adult feeding may be reduced because of a warm summer).

Table 9. The Threat Level Matrix combines the Likelihood of Occurrence and Level of Impact rankings to establish the Threat Level for the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo.

		Level of Impact				
		Low	Medium	High	Extreme	Unknown
Likelihood of Occurrence	Known or very likely	Low	Medium	High	High	Unknown
	Likely	Low	Medium	High	High	Unknown
	Unlikely	Low	Medium	Medium	Medium	Unknown
	Remote	Low	Low	Low	Low	Unknown
	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown

Table 10. Threat Level Assessment for the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo resulting from an analysis of both the Threat Likelihood and Threat Impact. The number in brackets refers to the level of certainty associated with the threat impact (1 = Very High; 2 = High; 3 = Medium; 4 = Low; 5 = Very Low).

Threat	Large-bodied DU	Small-bodied DU
Human intrusions and disturbance	Low (5)	Low (5)
Invasive and other problematic species and genes	High (2)	High (2)
Climate change and severe weather	Low (3)	Low (3)

Element 9: *Identify the activities most likely to threaten (i.e., damage or destroy) the habitat properties identified in elements 4–5 and provide information on the extent and consequences of these activities*

The activity most likely to threaten the habitat of the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo is recreational fishing, which can result in disturbances from motorized vessels, degradation of riparian areas, and, most importantly, introductions of aquatic invasive species through contaminated gear and equipment and/or accidental release; any other means of introducing invasive species could also result in negative impacts to habitat. Invasive invertebrates have the potential for the greatest impact to the species pair through changes in food supply. The current invertebrate prey base in Lake Opeongo is supporting four coregonine populations and is likely, in part, responsible for maintaining the coregonine diversity. Any changes in invertebrate abundance or composition are likely to increase competition among the coregonines. The introduction of Spiny Waterflea in Como Lake, Ontario, appears to have resulted in the replacement of the Lake Whitefish pair with a single, larger form (Reid et al. 2017). It is likely that both the large- and small-bodied DUs switched to consuming this abundant invader, homogenizing conditions that originally drove divergence in the species pair. Disturbances to the riparian or littoral areas from recreational fishing and vessels likely have a relatively small impact on habitat overall.

Limiting Factors

Element 10: *Assess any natural factors that will limit the survival and recovery of the Lake Whitefish*

There are several natural abiotic and biotic factors that could limit the survival and recovery of Lake Whitefish DUs in Lake Opeongo. Years with reduced ice cover will likely result in low egg over-winter survival as ice provides protection from disturbance and displacement (Freeberg et al. 1990, Jude et al. 1998, McKenna and Johnson 2009). Food availability for newly hatched larval Lake Whitefish (up to 6 weeks) could also limit their survival and recruitment (Taylor and

Freeburg 1984, Cucin and Faber 1985). Larval Lake Whitefish density closely tracks zooplankton densities in Great Lakes populations and small reductions in zooplankton may result in decreased growth and survival (Freeberg et al. 1990, Hoyle et al. 2011, Pothoven et al. 2020). Other species that occur in Lake Opeongo, in particular Yellow Perch, are known to predate on Lake Whitefish eggs and fry in other locations (Hart 1930). Hart (1930) thought this egg predation was likely opportunistic, but it could lead to reduced larval abundance in years when food is limited and egg predation is high.

In addition to competition with Cisco for pelagic prey, competition with Round Whitefish for benthic prey may be limiting to both DUs. In other Ontario lakes, Carl and McGuiness (2006) found that the catch per unit effort (CPUE) of Lake Whitefish was significantly lower (mean 1.4 CPUE) in lakes with both Cisco and Round Whitefish compared to lakes with just Cisco (mean of 3.0 CPUE) or no other coregonines (mean of 20.5 CPUE) suggesting competition may lead to lower abundances of Lake Whitefish. However, diet studies from lakes in Ontario found that Round Whitefish and Lake Whitefish may eat similar or the same foods, but not at the same time and may differentiate in occupied depths, Lake Whitefish often occupying deeper depths (and a broader depth range overall in Lake Opeongo) to avoid competition (Sandercock 1964, Martin and Fry 1973, Carl and McGuiness 2006, MacPherson et al. 2010).

Lake Whitefish in Lake Opeongo are geographically (and genetically) isolated from other populations and could face impacts related to genetic structure (i.e., drift, inbreeding depression, loss of heterozygosity, bottlenecks, founder effects, etc.) (Lewin et al. 2007). The degree and mechanisms of reproductive isolation between the species pair are not known, and the genetic integrity of the pair could be especially vulnerable following severe events that result in die-offs or limit reproduction.

Element 11: *Discuss the potential ecological impacts of the threats identified in element 8 to the target species and other co-occurring species. List the possible benefits and disadvantages to the target species and other co-occurring species that may occur if the threats are abated. Identify existing monitoring efforts for the target species and other co-occurring species associated with each of the threats and identify any knowledge gaps*

Ecological impacts from recreational fishing activities on Lake Opeongo are most important for Lake Trout and Smallmouth Bass for which there are active fisheries, and may be less important for Lake Whitefish, Yellow Perch and Burbot, which are infrequently targeted and incidentally captured (OMNRF unpublished data). Martin and Fry (1973) suggested that recreational fishing doubled the mortality rate of Lake Trout in Lake Opeongo and that year class strength is correlated with fishing pressure; however, some of these impacts appear to have been offset by the introduction of Cisco as forage. Changes in exploitation of Lake Trout could lead to changes in prey size and abundance (Shuter et al. 2016).

The impacts of aquatic invasive species on Lake Whitefish and co-occurring species would depend on the taxa, but could be direct through competition or predation, or indirect through changes in prey availability, nutrient cycling, damage to habitat, or introduction of diseases and parasites. Preventing the introduction of new aquatic invasive species would benefit the whole fish community by preventing changes in food webs or habitat conditions. Removing existing introduced Cisco may benefit one or both Lake Whitefish DUs by reducing competition, but could negatively impact Lake Trout that predominantly consume Cisco (Morbey et al. 2007), which in-turn could increase predation pressure on the Lake Whitefish DUs. Lake Trout began consuming Cisco shortly after its introduction and resulted in larger Lake Trout that mature later (Martin and Fry 1973, Shuter et al. 2016). Removing existing Smallmouth Bass may provide a benefit to Lake Trout through reduced competition, and may benefit littoral fishes and benthic macroinvertebrate prey.

Climate change threatens all aquatic organisms and the effects are wide-ranging, difficult to quantify, and often cumulative with other stressors. Fishes can be impacted in behaviour and physiology through increased air and water temperatures, changes in water levels, reduced ice cover, increased severe weather events (both in frequency and intensity), increased disease prevalence, and changes in food web dynamics (Lemmen et al. 2004). Reducing impacts of climate change would likely provide the greatest benefit to coldwater fishes such as Lake Whitefish, Lake Trout, and Burbot in Lake Opeongo (Casselman 2002, Chu et al. 2005, Sharma et al. 2011).

Occasional monitoring of the fish community by OMNRF is conducted and creel survey data (dating back to 1936 when fishing pressure commenced) are collected from Lake Opeongo that would likely detect new introduced fishes, and may detect changes in the fish community resulting from impacts of disturbance, non-fish aquatic invasive species, and climate change.

SCENARIOS FOR MITIGATION OF THREATS AND ALTERNATIVES TO ACTIVITIES

Element 16: *Develop an inventory of feasible mitigation measures and reasonable alternatives to the activities that are threats to the species and its habitat (as identified in element 8 and 10)*

Threats to species survival and recovery can be reduced by implementing mitigation measures to reduce or eliminate potential harmful effects that could result from works or undertakings associated with projects or activities on Lake Opeongo (large and small-bodied Lake Whitefish habitat). In previous RPAs, the DFO Program Activity Tracking for Habitat (PATH) database was queried for a variety of works, undertakings, and activities that occurred within a species known distribution during the previous five years that could harm or destroy its habitat. In the case of Lake Opeongo, no activities were identified in the vicinity of the lake. In a case where an activity threatens the habitat of the large- and small-bodied DUs of Lake Whitefish, habitat-related threats can be linked to the Pathways of Effects developed by DFO's Fish and Fish Habitat Protection Program (FFHPP) in Coker et al. (2010). The document provides guidance on mitigation measures for 18 Pathways of Effects for the protection of aquatic species at risk in the Central and Arctic Region (Coker et al. 2010). Coker et al. (2010) should be referred to when considering mitigation and alternative strategies for habitat-related threats. Additional mitigation and alternative measures related to non-habitat related threats (i.e., invasive species) are listed below.

Invasive and Other Problematic Species and Genes

Existing introduced species, Cisco and Smallmouth Bass, may negatively affect the large- and small-bodied DUs of Lake Whitefish in Lake Opeongo, and new aquatic invasive species, such as Spiny Waterflea and Rainbow Smelt, could pose significant threats should they arrive.

Mitigation

- Promote public awareness campaigns for anglers and visitors to the park (i.e., surrounding bait legislation and proper cleaning, draining, and drying of vessels and equipment), and encourage the use of existing invasive species reporting systems (e.g., EDDMapS, Invading Species Awareness Program Hotline, iNaturalist).
- Conduct early detection surveillance or monitoring for invasive species that may negatively impact Lake Whitefish or alter food web dynamics in the lake.
- Implement a rapid response plan if invasive species are detected aimed at eradication or control (Locke et al. 2010).

- Boat washing stations, other vessel restrictions/conditions of use
  - Lake Opeongo is one of two lakes in Algonquin Provincial Park to allow unlimited horsepower vessels (36 other lakes allow limited power vessels) (Ontario 2013); it is more likely to receive Aquatic Invasive Species (AIS) through accidental spread from contaminated vessels.

Alternatives

- Unauthorized introductions
  - There are no alternatives for unauthorized introductions because these should not occur.
- Authorized introductions
  - Use only native species.
  - Do not introduce Lake Whitefish from other populations.
  - Follow the National Code on Introductions and Transfers of Aquatic Organisms for all aquatic organism introductions (DFO 2017)

Element 17: *Develop an inventory of activities that could increase the productivity or survivorship parameters (as identified in elements 3 and 15)*

The mitigation measures outlined above are in line with the goal of increasing survivorship and reducing impacts to Lake Whitefish DUs from the threats of invasive and other problematic species and genes. Both the large- and small-bodied DUs are most sensitive to perturbations in adult survival (Fung et al. 2022), but information regarding how threats impact adult survival is limited. Options for improving productivity should be evaluated on their own merit.

Element 18: *If current habitat supply may be insufficient to achieve recovery targets (see element 14), provide advice on the feasibility of restoring the habitat to higher values. Advice must be provided in the context of all available options for achieving abundance and distribution targets*

Habitat does not appear to be limiting to either the large-bodied or small-bodied DUs of Lake Whitefish in Lake Opeongo (Fung et al. 2022). The area of Lake Opeongo (58.6 km^2) is greater than the minimum area for population viability of approximately 42.0 km^2 for the large-bodied and approximately 3.5 km^2 for the small-bodied DU.

SOURCES OF UNCERTAINTY

Population abundance and trends through time are lacking for both DUs, but particularly for the small-bodied DU. This could be rectified with standardized monitoring of both the large- and small-bodied DUs of Lake Whitefish (using appropriate, size-selective gears) where age and maturity data are collected. There is some evidence to suggest that the sympatric pair of Lake Whitefish in Lake Opeongo may not conform to the same habitat and trophic niches observed for species pairs elsewhere. Habitat models evaluating depth, water temperature and dissolved oxygen coupled with diet studies would help resolve the niches of the large- and small-bodied DUs in Lake Opeongo. Such studies would also provide a baseline for evaluating impacts of future aquatic invasive species. Reproductive isolation between the two DUs is inferred based on morphological and life history (and possibly behavioural) differences, but genetic analysis would confirm the DU structure and what degree of genetic differentiation separates them. There is a lack of knowledge on DU-specific life history parameters like fecundity, and the available information on other parameters such as growth, maturity, age-length relationships, meristics/morphometrics, and sex ratios from Kennedy (1943) pre-dates the introduction of

Cisco. Additionally, data were collected in the 1980's on the two Lake Whitefish forms (Evans and Ihssen 1993) that show patterns of age and growth for the small-bodied population that differ from those in the historic 1930's data (Kennedy 1943) or the modern 2010's data (OMNRF unpublished data); these data should be evaluated in the future if they become available. It is unclear whether both DUs occupy all three arms of the lake; small-bodied individuals have not been detected in the North Arm, but this may be a bias in sampling. Threats from human disturbances, aquatic invasive species and climate change likely impact Lake Whitefish in Lake Opeongo but there is poor empirical information to evaluate the consequences and magnitudes of these threats.

ACKNOWLEDGEMENTS

The authors wish to thank Mark Ridgway, Allan Bell, and Trevor Middel from the Ontario Ministry of Natural Resources and Forestry for providing survey data, analysis, and context from Lake Opeongo.

REFERENCES CITED

Anneville, O., Souissi, S., Molinero, J.C. and Gerdeaux, D. 2009. Influences of human activity and climate on the stock-recruitment dynamics of whitefish, *Coregonus lavaretus*, in Lake Geneva. Fish. Manage. Ecol. 16(6): 492–500.

Barnes, M.A., and Power, G. 1984. A comparison of otolith and scale ages for western Labrador lake whitefish *Coregonus clupeaformis*. Environ. Biol. Fishes 10(4): 297–299.

Bernatchez, L., Vuorinen, J.A., Bodaly, R.A., and Dodson, J.J. 1996. Genetic evidence for reproductive isolation and multiple origins of sympatric trophic ecotypes of whitefish (*Coregonus*). Evolution 50(2): 624–635.

Bishop, M.J. 2007. Impacts of boat-generated waves on macroinfauna: towards a mechanistic understanding. J. Experim. Mar. Biol. Ecol. 343(2): 187–196.

Bodaly, R.A. 1979. Morphological and ecological divergence within the Lake Whitefish (*Coregonus clupeaformis*) species complex in Yukon Territory. J. Fish. Res. Board Can. 36: 1214–1222.

Bodaly, R.A., Clayton, J.W., and Lindsey, C.C. 1987. COSEWIC status report on the Squanga Whitefish, *Coregonus lavaretus*, in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, ON. 44 p.

Bodaly, R.A., Vuorinen, J., and Macins, V. 1991. Sympatric presence of dwarf and normal forms of lake whitefish *(Coregonus clupeaformis)* in Como Lake, Ontario. Can. Field Nat. 105(1): 87–90.

Brooke, L.T. 1975. Effect of different constant incubation temperatures on egg survival and embryonic development in Lake Whitefish (*Coregonus clupeaformis*). Trans. Am. Fish. Soc. 104(3): 555–559.

Carl, L.M., and McGuiness, F. 2006. Lake whitefish and lake herring population structure and niche in ten south-central Ontario lakes. Environ. Biol. Fishes 75: 315–323.

Carl, L.M. 2007. Lake trout demographics in relation to burbot and coregonine populations in the Algonquin Highlands, Ontario. Environ. Biol. Fishes 83(2): 127–138.

Casselman, J.M. 2002. Effects of temperature, global extremes and climate change on year-class production of warmwater, coolwater, and coldwater fishes in the Great Lakes basin. *In* Fisheries in a Changing Climate. Edited by N.A. McGinn. Am. Fish. Soc. Symposium 32, Bethesda, MD. 39–60 pp.

Challice, A.R., Milne, S.W., and Ridgway, M.S. 2019. Does habitat occupancy by lake trout and lake whitefish in large lakes match published thermal habitat envelopes? Ecol. Freshw. Fish 28(4): 611–623.

Chapra, S.C., Boehlert, B., Fant, C., Bierman, V.J., Henderson, J., Mills, D., Mas, D.M.L., Rennels, L., Jantarasami, L., Martinich, J., Strzepek, K.M., and Paerl, H.W. 2017. Climate change impacts on harmful algal blooms in U.S. Freshwaters: a screening-level assessment. Environ. Sci. Technol. 51: 8933–8943.

Chouinard, A., and Bernatchez, L. 1998. A study of trophic niche partitioning between larval populations of reproductively isolated whitefish (*Coregonus* sp.) ecotypes. J. Fish Biol. 53(6): 1231–1242.

Chu, C., Mandrak, N.E., and Minns, C.K. 2005. Potential impacts of climate change on the distributions of several common and rare freshwater fishes in Canada. Diversity Distrib. 11(4): 299–310.

Claramunt, R.M., Muir, A.M., Johnson, J., and Sutton, T.M. 2010. Spatio-temporal trends in the food habits of age-0 lake whitefish. J. Great Lakes Res. 36(Suppl.1): 66–72.

Coker, G. A., Ming, D.L., and Mandrak, N.E. 2010. Mitigation guide for the protection of fishes and fish habitat to accompany the species at risk recovery potential assessments conducted by Fisheries and Oceans Canada (DFO) in Central and Arctic Region. Version 1.0. Can. Manuscr. Rep. Fish. Aquat. Sci. 2904: vi + 40 p.

COSEWIC. 2005. COSEWIC assessment and update status report on the lake whitefish (Lake Simcoe population) *Coregonus clupeaformis* in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, ON. vii + 36 p.

COSEWIC. 2012. COSEWIC guidelines for recognizing designatable units [online]. (accessed September 4, 2020)

COSEWIC. 2018. COSEWIC assessment and status report on the Whitefish *Coregonus* spp., European Whitefish - Squanga Lake small-bodied population (*Coregonus lavaretus*), Lake Whitefish - Squanga Lake large-bodied population (*Coregonus clupeaformis*), European Whitefish - Little Teslin Lake small-bodied population (Coregonus *lavaretus*), Lake Whitefish - Little Teslin Lake large-bodied population (*Coregonus clupeaformis*), European Whitefish - Dezadeash Lake small-bodied population (*Coregonus lavaretus*), European Whitefish - Dezadeash Lake large-bodied population (*Coregonus lavaretus*), Lake Whitefish - Lake Opeongo small-bodied population (*Coregonus clupeaformis*), Lake Whitefish - Lake Opeongo large-bodied population (*Coregonus clupeaformis*), Lake Whitefish - Como Lake small-bodied population (*Coregonus clupeaformis*) and the Lake Whitefish - Como Lake large-bodied population (*Coregonus clupeaformis*) in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa, ON. xxxix + 42 p.

Cucin, D. and Faber, D.J. 1985. Early life studies of Lake Whitefish (*Coregonus clupeaformis*), Cisco (*Coregonus artedii*) and Yellow Perch (*Perca flavescens*) in Lake Opeongo, Ontario. Ontario Fish. Tech. Rep. Ser. 16: 27 p.

DFO. 2007. Revised protocol for conducting recovery potential assessments. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2007/039.

DFO. 2014. Guidance on Assessing Threats, Ecological Risk and Ecological Impacts for Species at Risk. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2014/013. (*Erratum*: June 2016)

DFO. 2017. National Code on Introductions and Transfers of Aquatic Organisms. Fisheries and Oceans Canada, Ottawa, ON. ii + 41 p.

DFO. 2018. Freshwater Landings, 2018 [online]. (accessed January 1, 2021)

DFO. 2021. Recovery Potential Assessment for six designatable units of whitefish (Coregonus spp.) in Yukon Lakes. DFO Can. Sci. Advis. Sec. Sci. Resp. 2021/009.

Doyon, J.F., Shetagne, R., and Verdon, R. 1998. Different mercury bioaccumulation rates between sympatric populations of dwarf and normal lake whitefish (*Coregonus clupeaformis*) in the La Grande Complex watershed, James Bay, Quebec. Biogeochemistry 40: 203–216.

Edsall, T.A. 1999a. The growth-temperature relation of juvenile Lake Whitefish. Trans. Am. Fish. Soc. 128(5): 962–964.

Edsall, T.A. 1999b. Preferred temperatures of juvenile Lake Whitefish. J. Great Lakes Res. 25(3): 583–588.

Evans, D.O., and Loftus, D.H. 1987. Colonization of inland lakes in the Great lakes region by Rainbow Smelt, *Osmerus mordax*: their freshwater niche and effects on indigenous fishes. Can. J. Fish. Aquat. Sci. 44: 249–266.

Evans, D.O., and Waring, P. 1987. Changes in the multispecies, winter angling fishery of Lake Simcoe, Ontario, 1961-83: invasion by Rainbow Smelt, *Osmerus mordax*, and the roles of intra- and interspecific interactions. Can. J. Fish. Aquat. Sci. 44: 182–197.

Evans, D.O., and Ihssen, P.E. 1993. Ecological and genetic diversity of two sympatric stocks of Lake Whitefish, *Coregonus clupeaformis*, in Algonquin Park, Ontario. Conference on The Role of Parks in Conservation of Biodiversity. Algonquin Park, Ontario. September 27, 1993.

Favot, E.J., Ruhland, K.M., DeSellas, A.M., Ingram, R., Paterson, A.M., and Smol, J.P. 2019. Climate variability promotes unprecedented cyanobacterial blooms in a remote, oligotrophic Ontario Lake: evidence from paleolimnology. J. Paleolimnol. 62: 31–52.

Fenderson, O.C. 1964. Evidence of subpopulations of Lake Whitefish, *Coregonus clupeaformis*, involving a dwarfed form. Trans. Am. Fish. Soc. 93(1): 77–94.

Freeberg, M.H., Taylor, W.W., and Brown, R.W. 1990. Effect of egg and larval survival on year-class strength of Lake Whitefish in Grand Traverse Bay, Lake Michigan. Trans. Am. Fish. Soc. 199(1): 92–100.

Fudge, R.J.P., and Bodaly, R.A. 1984. Postimpoundment winter sedimentation and survival of lake whitefish (*Coregonus clupeaformis*) eggs in Southern Indian Lake, Manitoba. Can. J. Fish. Aquat. Sci. 41: 701–705.

Fung, S.R., van der Lee, A.S., and Koops, M.A. 2022. Recovery Potential Modelling of Lake Whitefish (*Coregonus clupeaformis*) in Lake Opeongo, Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2022/043. iv + 28 p.

Gabel, F., Stoll, S., Fischer, P., Pusch, M.T., and Garcia, X.F. 2011. Waves affect predator-prey interactions between fish and benthic invertebrates. Oecologia 165: 101–109.

Garrad, P.N., and Hey, R.D. 1987. Boat traffic, sediment resuspension and turbidity in a broadland river. J. Hydrol. 95(3–4): 289–297.

Goodchild, C.D. 2001. The status of the Mira River population of Lake Whitefish, *Coregonus clupeaformis*, in Canada. Can. Field Nat. 115(4): 623–634.

Gorsky, D., Zydlewski, J., and Basleu, D. 2012. Characterizing seasonal habitat use and diel vertical activity of Lake Whitefish in Clear Lake, Maine, as determined with acoustic telemetry. Trans. Am. Fish. Soc. 143(3): 761–771.

Gorsky, D., and Zydlewski, J. 2013. Experimental evaluation of size-dependent predation by adult post-spawned Rainbow Smelt on larval Lake Whitefish. N. Am. J. Fish. Manage. 33(1): 163–169.

Graham, A.L., and Cooke, S.J. 2008. The effects of noise disturbance from various recreational boating activities common to inland waters on the cardiac physiology of a freshwater fish, the largemouth bass (*Micropterus salmoides*). Aquat. Conserv. Mar. Freshw. Ecosystems 18(7): 1315–1324.

Guzzo, M.M., and Blanchfield, P.J. 2017. Climate change alters the quantity and phenology of habitat for lake trout (*Salvelinus namaycush*) in small Boreal Shield lakes. Can. J. Fish. Aquat. Sci. 74: 871–884.

Hart, J.L. 1930. The spawning and early life history of the whitefish *Coregonus clupeaformis* (Mitchill), in the Bay of Quinte, Ontario. Contrib. Can. Fish. Biol. 7: 165–214.

Herbst, S.J., and Marsden, J.E. 2011. Comparison of precision and bias of scale, fin ray, and otolith age estimates for lake whitefish (*Coregonus clupeaformis*) in Lake Champlain. J. Great Lakes Res. 37(2): 386–389.

Herbst, S.J., Marsden, J.E., and Smith, S.J. 2011. Lake Whitefish in Lake Champlain after commercial fishery closure and ecosystem changes. N. Am. J. Fish. Manage. 31(6): 1106–1115.

Holm, E., Mandrak, N.E., and Burridge, M. 2009. The ROM field guide to freshwater fishes of Ontario. Royal Ontario Museum Science, Toronto, ON. 464 p.

Hoyle, J.A., Johannsson, O.E., and Bowen, K.L. 2011. Larval Lake Whitefish abundance, diet and growth and their zooplankton prey abundance during a period of ecosystem change on the Bay of Quinte, Lake Ontario. Aquat. Ecosyst. Health 14(1): 66–74.

Ihssen, P.E., Evans, D.O., Christie, W.J., Reckhan, J.A., and DesJardine, R.L. 1981. Life history, morphology, and electrophoretic characteristics of five allopatric stocks of Lake Whitefish (*Coregonus clupeaformis*) in the Great Lakes Region. Can. J. Fish. Aquat. Sci. 38: 1790–1807.

Jackson, D.A., and Mandrak, N.E. 2002. Changing fish biodiversity: predicting the loss of cyprinid biodiversity due to global climate change. *In* Fisheries in a Changing Climate. Edited by N.A. McGinn. Am. Fish. Soc. Symp. No. 32 Bethesda, MD. 89–98 pp.

Jackson, M.C., Loewen, C.J.G., Vinebrooke, R.D., and Chimimba, C.T. 2016. Net effects of multiple stressors in freshwater ecosystems: a meta-analysis. Global Change Biol. 22(1): 180–189.

Jacobson, P.C., Cross, T.K., Zandlo, J., Carlson, B.N., and Pereira, D.P. 2008. The effects of climate change and eutrophication on cisco *Coregonus artedi* abundance in Minnesota lakes. Advanc. Limnol. 63: 417–427.

Jeppeson, E., Mehner, T., Winfield, I.J., Kangur, K., Sarvala, J., Gerdeaux, D., Rask, M., Malmquist, H.J., Holmgren, K., Volta P., Romo, S., Eckmann, R., Sandstrom, A., Blanco, S., Kangur, A., Ragnarsson Stabo, H., Tarvainen, M., Ventela, A., Sondergaard, M., Lauridsen, T., and Meerhoff, M. 2012. Impacts of climate warming on the long-term dynamics of key fish species in 24 European lakes. Hydrobiologia 694: 1–39.

John, K.R., and Hasler, A.D. 1956. Observations on some factors affecting the hatching of eggs and the survival of young shallow-water Cisco, *Leucichthys artedi* LeSueur, in Lake Mendota, Wisconsin. Limnol. Oceanogr. 1: 176–194.

Jude, D.J., Tesar, F.J., and Tin, H.T. 1998. Spring distribution and abundance of larval fishes in the St. Mary's River, with a note on potential effects of freighter traffic on survival of eggs and larvae. J. Great Lakes Res. 24: 569–581.

Kennedy, W.A. 1943. The Whitefish, *Coregonus clupeaformis* (Mitchill), of Lake Opeongo, Algonquin Park, Ontario. On. Fish. Res. Lab. No. 62: 25 p.

Kernan, M. 2015. Climate change and the impact of invasive species on aquatic ecosystems. Aquat. Ecosyst. Health 18(3): 321–333.

Kerr, S.J. 2010. Fish and Fisheries Management in Ontario: A Chronology of Events [online]. Biodiversity Branch. Ontario Ministry of Natural Resources. Peterborough, ON. (accessed November 1, 2020)

Killgore, K.J., Maynord, S.T., Chan, M.D., and Morgan, R.P. 2001. Evaluation of propeller-induced mortality on early life stages of selected fish species. N. Am. J. Fish. Manage. 21: 947–955.

Kovach, R.P., Al-Chokhachy, R.K., Whited, D.C., Schmetterling, D.A., Dux, A.M., and Muhlfeld, C.C. 2017. Climate, invasive species and land use drive population dynamics of a cold-water specialist. J. Applied Ecol. 54(2): 638–647

Landry, L. Vincent, W.F., and Bernatchez, L. 2007. Parallel evolution of lake whitefish dwarf ecotypes in association with limnological features of their adaptive landscape. Euro. Soc. Evol. Biol. 20(3): 971–984.

Landry, L., and Bernatchez, L. 2010. Role of epibenthic resource opportunities in the parallel evolution of lake whitefish species pairs (*Coregonus* sp.). J. Evol. Biol. 23(12): 2602–2613.

Lemmen, D.S., and Warren, F.J. 2004. Climate change impacts and adaptation: a Canadian perspective. Climate Change Impacts and Adaptation Program 2004. Ottawa, ON. 174 p.

Lewin, W.C., Arlinghaus, R., and Mehner, T. 2007. Documented and potential biological impacts of recreational fishing: insights for management and conservation. Rev. Fish. Manage. 14(4): 305–367.

Lindsey, C.C. 1981. Stocks are chameleons: plasticity in gill rakers of coregonid fishes. Can. J. Fish. Aquat. Sci. 38: 1497–1506.

Locke, A., Mandrak, N.E., and Therriault, T.W. 2010. A Canadian Rapid Response Framework for Aquatic Invasive Species. Can. Sci. Advis. Sec. Res. Doc. 2010/114 iv + 30 p.

Loftus, D.H., and Hulsman, P.F. 1986. Predation on larval Lake Whitefish (*Coregonus clupeaformis*) and Lake Herring (*C. artedii*) by adult Rainbow Smelt (*Osmerus mordax*). Can. J. Fish. Aquat. Sci. 43: 812–818.

Lu, G., and Bernatchez, L. 1999. Experimental evidence for reduced hybrid viability between dwarf and normal ecotypes of lake whitefish (*Coregonus clupeaformis* Mitchill). Proc. R. Soc. Lond. B 265: 1025–1030.

Macpherson, A., Holmes, J.A., Muir, A.M., and Noakes, D.L.G. 2010. Assessing feeding competition between lake whitefish *Coregonus clupeaformis* and round whitefish *Prosopium cylindraceum*. Current Zool. 56(1): 109–117.

Martin, N.V., and Fry, F.E.J. 1973. Lake Opeongo: The ecology of the fish community and man's effects on it. Great Lakes Fishery Commision Tech. Rep. No. 24: v + 34 p.

Maxwell, R.J., Zolderdo, A.J., de Bruijn, R., Brownscombe, J.W., Staaterman, E., Gallagher, A.J., and Cooke, S.J. 2018. Does motor noise from recreational boats alter parental care behaviour of a nesting freshwater fish. Aquat. Conserv: Mar. Freshw. Ecosyst. 28(4): 969–978.

McDermaid, J., Fera, S., and Hogg, A. 2015. Climate change projections for Ontario: an updated synthesis for policymakers and planners. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Climate Change Research Report CCRR-44: vi + 27 p.

McKenna, J.E., and Johnson, J.H. 2009. Spatial and temporal variation in distribution of larval lake whitefish in eastern Lake Ontario: signs of recovery? J. Great Lakes Res. 35(1): 94–100.

McKenna, J.E. 2019. The Laurentian Great Lakes: a case study in ecological disturbance and climate change. Fish Manag. Ecol. 26: 486–499.

Mee, J.A., Bernatchez, L., Reist, J.D., Rogers, S.M., and Taylor, E.B. 2015. Identifying designatable units for intraspecific conservation prioritization: a hierarchical approach applied to the lake whitefish species complex (*Coregonus* spp.). Evol. App. 8(5): 423–441.

Mitchell, K., Challice, A., Lacombe, N., Taylor, C., Glenn, F., Middel, T., and Ridgway, M. 2020. Assessing recreational angling in Algonquin Provincial Park. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Technical Report TR-35: vi + 37 p.

Morbey, Y.E., Vascotto, K., and Shuter, B.J. 2007. Dynamics of piscivory by Lake Trout following a Smallmouth Bass invasion: a historical reconstruction. Trans. Am. Fish. Soc. 136(2): 477–483.

Ohlund, G., Bodin, M., Nilsson, K.A., Ohlund, S.O., Mobley, K.B., Hudson, A.G., Peedu, M., Brannstrom, A., Bartels, P., Praebel, K., Hein, C.L., Johansson, P., and Englund, G. 2020. Ecological speciation in European whitefish is driven by a large-gaped predator. Evol. Lett. 4(3): 243–256.

OMNRF (Ontario Ministry of Natural Resources and Forestry). 2020. Harkness Laboratory of Fisheries Research: Lake Opeongo [online]. (Accessed November 1, 2020)

Ontario. 1998. Algonquin Provincial Park Management Plan. Ontario Ministry of Natural Resources and Forestry, Ontario Parks, Algonquin Provincial Park, ON. MNR 5016. vii + 86 p.

Ontario. 2013. Algonquin Provincial Park Management Plan Amendment. Ontario Ministry of Natural Resources and Forestry, Ontario Parks, Algonquin Provincial Park, ON. MNR 52727-0. 28 p.

Paerl, H.W., Fulton, R.S., Moisander, P.H., and Dyble, J. 2001. Harmful freshwater algal blooms with an emphasis on cyanobacteria. Sci. World 1: 76–113.

Palmer, M.E., and Yan, N.D. 2013. Decadal-scale regional changes in Canadian freshwater zooplankton: the likely consequence of complex interactions among multiple anthropogenic stressors. Freshw. Biol. 58: 1366–1378.

Pigeon, D., Chouinard, A., and Bernatchez, L. 1997. Multiple modes of speciation involved in the parallel evolution of sympatric morphotypes of Lake Whitefish (*Coregonus clupeaformis*, Salmonidae). Evol. 51(1): 196–205.

Pothoven, S.A., Hook, T.O., and Roswell, C.R. 2014. Feeding ecology of age-0 lake whitefish in Saginaw Bay, Lake Huron. J. Great Lakes Res. 40(Suppl.1): 148–155.

Pothoven, S.A. 2020. The influence of ontogeny and prey abundance on feeding ecology of age-0 Lake Whitefish (*Coregonus clupeaformis*) in southeastern Lake Michigan. Ecol. Freshw. Fish 29(1): 103–111.

Price, J.W. 1940. Time-temperature relations in the incubation of the whitefish, *Coregonus clupeaformis* (Mitchill). J. Gen. Phys. 449–468.

Rahel, F.J., and Olden, J.D. 2008. Assessing the effects of climate change on aquatic invasive species. Cons. Biol. 22: 521–533.

Reckahn, J.A. 1970. Ecology of young lake whitefish (*Coregonus clupeaformis*) in South Bay, Manitoulin Island, Lake Huron. *In* Biology of coregonid fishes. Edited by C.C. Lindsey and C.S. Woods. University of Manitoba Press, Winnipeg, MB. pp. 437–460.

Reid, S.M., Parna, M., and Reist, J.D. 2017. Collapse of Lake Whitefish *Coregonus clupeaformis* (Mitchill, 1818) species pair in Como Lake, Ontario. J. Appl. Ichthyol. 33(5): 933–939.

Rellstab C., Maurer, V., Zeh, M., Burgi, H.R., and Spaak, P. 2007. Temporary collapse of the *Daphnia* population in turbid and ultra-oligotrophic Lake Brienz. Aquat. Sci. 69: 257–270.

Renik, K.M., Jennings, M.J., Kampa, J.M., Lyons, J., Parks, T.P., and Sass, G.G. 2020. Status and distribution of Cisco (*Coregonus artedi*) and Lake Whitefish (*Coregonus clupeaformis*) in inland lakes of Wisconsin. Northeastern Natur. 27(3): 469–484.

Rennie, M., Sprules, G., and Vaillancourt, A. 2010. Changes in fish condition and mercury vary by region, not *Bythotrephes* invasion: a result of climate change? Ecography 33: 471–482.

Ricciardi, A., and McIsaac, H.J. 2000. Recent mass invasion of the North American Great Lakes by Ponto-Caspian species. Trends Ecol. Evol. Rev. 15: 62–65.

Ridgway, M., and Middel, T. 2020. From aquatic connectivity to aquatic conservation in Algonquin Provincial Park. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Information Report IR-20: 41 p.

Rogers, S.M., and Bernatchez, L. 2007. Genetic architecture of ecological speciation and the association with signatures of selection in natural Lake Whitefish (*Coregonus* sp. Salmonidae) species pairs. Mol. Biol. Evol. 24: 1423–1438

Rogers, S.M. 2009. Designatable units at an appropriate scale for the Lake Whitefish (*Coregonus clupeaformis*). Special Report prepared for the Committee on the Status of Endangered Wildlife in Canada, Ottawa, ON. iii + 67 p.

Ridgway, M., D. Smith and T. Middel. 2018. Climate warming projections for Algonquin Provincial Park. Ontario Ministry of Natural Resources and Forestry, Science and Research Branch, Peterborough, ON. Science and Research Information Report IR-1: 23 p. + append.

Ryan, K.M., and Crawford, S.S. 2014. Distribution and abundance of larval lake whitefish (*Coregonus clupeaformis*) in Stokes Bay, Lake Huron. J. Great Lakes Res. 40: 755–762.

Salafsky, N., Salzer, D., Stattersfield, A.J., Hilton-Taylor, C., Neugarten, R., Butchart S.H.M., Collen, B., Cox, N., Master, L.L., O'Connor, S., and Wilkie, D. 2008. A standard lexicon for biodiversity conservation: unified classifications of threats and actions. Conserv. Biol. 22: 897–911.

Sandercock, F.K. 1964. A contribution to the ecology of the whitefishes *Prosopium cylindraceum* and *Coregonus clupeaformis* of Algonquin Park, Ontario. M.Sc. thesis, Department of Zoology, The University of British Columbia, Vancouver B.C.

Sandstrom, S. J. and N. Lester. 2009. Summer Profundal Index Netting Protocol; a Lake Trout Assessment Tool. Ontario Ministry of Natural Resources. Peterborough, Ontario. Version 2009.1: 22 p. + Appendices

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Can. J. Fish. Aquat. Sci. 58: 18–29.

Scott, W.B., and Crossman, E.J. 1973. Freshwater fishes of Canada. Bull. Fish. Res. Board Can. No. 184. 1998 Reprint. 996 p.

Sharma, S., Vander Zanden, M.J., Magnuson, J.J., and Lyons, J. 2011. Comparing climate change and species invasions as drivers of coldwater fish population extirpations. PLoS ONE 6: e22906: 9 p.

Shuter, B.J., Giacomini, H.C., de Kerckhove, D., and Vascotto, K. 2016. Fish life history dynamics: shifts in prey size structure evoke shifts in predator maturation traits. Can. J. Fish. Aquat. Sci. 73: 693–708.

Sotton, B., Guillard, J., Anneville, O., Maréchal, M., Savichtcheva, O., and Domaizon, I. 2014. Trophic transfer of microcystins through the lake pelagic food webs: evidence for the role of zooplankton as a vector in fish contamination. Sci. Total Environ. 466–467: 152–163.

Straile, D., Eckmann, R., Jungling, T., Thomas, G., and Loffler, H. 2007. Influence of climate variability on whitefish (*Coregonus lavaretus*) year-class strength in a deep, warm monomictic lake. Glob. Change Conserv. Ecol. 151: 521–529.

Strayer, D.L. 2010. Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshw. Biol. 55: 152–174.

Sukenik, A., Quesada, A., and Salmaso, N. 2015. Global expansion of toxic and non-toxic cyanobacteria: effect on ecosystem functioning. Biodivers. Conserv. 24: 889–908.

Taylor, W.W., and Freeberg, M.H. 1984. Effect of food abundance on larval lake whitefish *Coregonus clupeaformis* Mitchill, growth and survival. J. Fish Biol. 25: 733–741.

Trudel, M., Tremblay, A., Schetagne, R., and Rasmussen, J.B. 2001. Why are dwarf fish so small? An energetic analysis of polymorphism in lake whitefish (*Coregonus clupeaformis*). Can. J. Fish. Aquat. Sci. 58: 394–405.

Vuorinen, J.A., Bodaly, R.A., Reist, J.D., Bernatchez, L., and Dodson, J.J. 1993. Genetic and morphological differentiation between dwarf and normal size forms of Lake Whitefish (*Coregonus clupeaformis*) in Como Lake, Ontario. Can. J. Fish. Aquat. Sci. 50: 210–216.

Winder, M. and Schindler, D.E. 2004. Climatic effects on the phenology of lake processes. Glob. Change Biol. 10: 1844–1856.

Whitfield, A.K., and Becker, A. 2014. Impacts of recreational motorboats on fishes: a review. Mar. Poll. Bull. 83: 24–31.

Wood, J. 2016. Current status of Lake Whitefish in Maine; an update to MDIFW's 2001 whitefish assessment. Maine Department of Inland Fisheries and Wildlife, Fisheries and Hatcheries Division, Fishery Final Report Series No. 14-01. ii + 60 p.

Yousef, Y.A., McLellon, W.M., and Zebuth, H.H. 1980. Changes in phosphorus concentrations due to mixing by motorboats in shallow lakes. Wat. Res. 14: 841–852.

Yule, D.L., Stockwell, J.D., Black, J.A., Cullis, K.I., Cholwek, G.A., and Myers, J.T. 2008. How systematic age underestimation can impede understanding of fish population dynamics: lessons learned from a Lake Superior Cisco stock. Trans. Am. Fish. Soc. 137: 481–495.