Assessment of the fish populations beneficial use impairment in the Hamilton Harbour Area of Concern

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Assessment of the fish populations beneficial use impairment in the Hamilton Harbour Area of Concern

by

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ABSTRACT

Midwood, J.D., Balshine, S., Beech, S., Boston, C.M., Brown, E., Budgell, E., Court, A. Croft-White, M.V., Gardner Costa, J., Lake, C., Larocque, S.M., Mehdi, H., Rebalka, A., Reddick, D.T., Turner, N.A., Theijsmeijer, T., Vanden Byllaardt, J. 2024. Assessment of the fish populations beneficial use impairment in the Hamilton Harbour Area of Concern. Can. Tech. Rep. Fish. Aquat. Sci. 3628: xxi + 315 p. https://doi.org/10.60825/bah3-m048

Fish populations in the Hamilton Harbour Area of Concern (Hamilton Harbour AOC) were assessed as impaired under beneficial use impairment (BUI) #3 – *Degradation of Fish and Wildlife Populations.* We used multiple lines of evidence to evaluate the two criteria listed under BUI #3. The first criterion relates to community structure and declines in Common Carp (*Cyprinus carpio*) catch and biomass plus regional similarities in the density of pelagic forage fishes are positive signs. However, many native species indicated either a decline or no change, and catch rates were typically lower than regionally similar areas. Overall, the fish community continues to be more indicative of eutrophic rather than mesotrophic conditions and remains impaired. The second criterion is focused on Index of Biotic Integrity (IBI) scores, which remained below the target of 55-60. Most nearshore fish community metrics were lower than regional reference areas and trends in IBI and metric values either showed no change or were declining, indicating that fish populations remain impaired. Several factors that may limit improvements to the fish community were identified: seasonal hypoxia, aquatic invasive species, poor water quality, limited habitat supply, and impaired habitat conditions. Additional work is recommended to quantify the extent of their effects. Recommendations on monitoring actions and analysis are presented to support future assessments of fish populations.

RÉSUMÉ

Midwood, J.D., Balshine, S., Beech, S., Boston, C.M., Brown, E., Budgell, E., Court, A. Croft-White, M.V., Gardner Costa, J., Lake, C., Larocque, S.M., Mehdi, H., Rebalka, A., Reddick, D.T., Turner, N.A., Theijsmeijer, T., Vanden Byllaardt, J. 2024. Assessment of the fish populations beneficial use impairment in the Hamilton Harbour Area of Concern. Can. Tech. Rep. Fish. Aquat. Sci. 3628: xxi + 315 p. https://doi.org/10.60825/bah3-m048

Les populations de poissons du secteur préoccupant du port de Hamilton ont été évaluées comme étant altérées relativement aux critères d'altération d'utilisation bénéfique (AUB) n^{o} 3 – *dégradation des populations de poissons et d'animaux sauvages*. Nous avons utilisé plusieurs sources de données pour évaluer les trois critères énumérés dans l'AUB n^{o} 3. Le premier critère a trait à la structure de la communauté, et bien que l'on observe des signes positifs tels qu'une diminution des prises et de la biomasse de carpe commune (*Cyprinus carpio*) et des similitudes régionales dans la densité des poissons fourrages pélagiques, de nombreuses espèces indigènes ont montré un déclin ou n'ont montré aucun changement, et les taux de prises étaient généralement inférieurs à ceux de régions similaires. Dans l'ensemble, la communauté de poissons continue d'indiquer davantage des conditions eutrophes que des conditions mésotrophes, et demeure altérée. Le deuxième critère est axé sur les scores de l'indice d'intégrité biotique, qui sont demeurés inférieurs à la cible établie à 55-60. Les valeurs mesurées chez les communautés de poissons de la zone littorale étaient pour la plupart inférieures à celles des zones de référence régionales et aux tendances de l'indice d'intégrité biotique, et elles ne montraient aucun changement ou étaient largement en baisse, ce qui indique que les populations de poissons demeurent altérées. Plusieurs facteurs susceptibles de limiter l'amélioration de l'état de la communauté de poissons ont été cernés, notamment l'hypoxie saisonnière, les espèces aquatiques envahissantes, la mauvaise qualité de l'eau, la faible disponibilité de l'habitat, et l'état altéré de l'habitat. Nous recommandons que d'autres travaux soient réalisés afin de quantifier l'étendue des effets de ces facteurs. Des recommandations en matière d'analyse et de mesures de surveillance sont présentées pour appuyer les futures évaluations des populations de poissons.

RATIONALE FOR BUI STATUS

Recommended Beneficial Use Impairment Status: Impaired

Our objectives were to use multiple studies and fish monitoring programs to assess the status of fish populations, describe trends in fish populations since the initial listing of the AOC, and recommend future actions to improve fish populations in order to understand their dynamics more accurately. Several lines of evidence were reviewed to assess the two delisting criteria listed for the fish component of beneficial use impairment (BUI) #3 – *Degradation of Fish and Wildlife Populations* in the Hamilton Harbour Area of Concern (Hamilton Harbour AOC; Table 1). The objective of criterion FP-1 was to evaluate whether the fish community had become more representative of a mesotrophic environment with a balanced food-web composition that includes top predators and native fishes. This criterion was assessed by exploring three sets of data. Temporal trends were explored in species catch (FP-1A) in the Hamilton Harbour AOC and regional reference areas were modelled using Fisheries and Oceans Canada's (DFO) boat electrofishing dataset; complementary information on catch and observed spatial movements were integrated from a variety of other data sources. Temporal changes in the overall fish community and the presence of fish species within the harbour and adjacent watersheds were also explored (FP-1B). Finally, pelagic prey fish density and biomass were assessed using split-beam hydroacoustic surveys and mid-water trawling, which were compared to other areas within western Lake Ontario (section FP-1C). To evaluate whether Index of Biotic Integrity (IBI) scores were meeting the 55-60 target (Criterion FP-2), temporal trends in IBI and fish community metrics in the Hamilton Harbour AOC and regional reference areas were assessed using the DFO electrofishing dataset (section FP-2A) and the Ontario Ministry of Natural Resources and Forestry (OMNRF) trap net dataset (section FP-2B). The statuses of both criteria (FP-1 and FP-2) were assessed independently and then used to evaluate the overall status of the BUI. Based on the assessment for the two delisting criteria (see sections FP-1 and FP-2), BUI #3 for fish populations is currently deemed impaired (Table 1).

Table 1. *Summary of the evaluated status and rationale for this status for the two delisting criteria for the fish population component of BUI#3 in the Hamilton Harbour AOC.*

Delisting Criterion	Delisting Line of Evidence	Status	Rationale for BUI Status
FP–1 Shift from a fish community indicative of eutrophic environments (e.g., White Perch, Alewife, bullheads, and carp) to a self-sustaining community more representative of a mesotrophic environment with a balanced trophic composition that includes top predators (e.g., Northern Pike, Largemouth Bass, and Walleye) and other native species (e.g., Suckers, Yellow Perch, and sunfishes).	FP–1A – Species-Specific Trends (multiple data sources)	Impaired (unchanged)	Catches of the majority of native species monitored using boat electrofishing have declined or remained unchanged since the AOC was first listed. Offshore pelagic species are key contributors to total catch and biomass in nearshore catches and are reflective of littoral habitat impairment; native Gizzard Shad have increased and are now among the most abundant species. Catch of native fishes is significantly lower in the Hamilton Harbour AOC than at similar reference areas in eastern Lake Ontario. Trap net data indicated that non-native fishes and species indicative of degraded, eutrophic conditions are hyperabundant in the Hamilton Harbour AOC.
	FP–1B – Overall Fish Community (multiple data sources)	Impaired (unchanged)	The Hamilton Harbour fish community is unique and distinct from other Lake Ontario embayments. Fifty-five different fish species were detected in the harbour and watersheds between 1985 and 2012, only 43 have been observed between 2013 and 2021.
Overall status: Impaired	FP–1C – Pelagic Prey Fish	**Supporting evidence**	There were no clear differences in density or biomass of pelagic fishes relative to the available regional comparison sites, particularly at the west end of the Hamilton Harbour AOC. These results support the interpretation of the status of FP-1 and FP-2.
FP–2. Attain an Index of Biotic Integrity (IBI) of 55-60 for Hamilton		Impaired (unchanged)	IBI scores are below the targets (55-60) and continue to be indicative of an impaired sheltered embayment.

Delisting Criterion	Delisting Line of Evidence	Status	Rationale for BUI Status
Harbour and maintain the target score for two sequences of monitoring carried out a minimum of every three years. The IBI incorporates components of native species richness, numbers and biomass; piscivore biomass; non-native species; and reflects water quality and the quality of fish habitat. **Overall status: Impaired**	FP–2A – Fish Community Metrics (DFO Electrofishing)		Majority of fish community metrics still indicate impairment in the fish community. Fish community metrics related to catch, richness and production are now comparable to or lower than what was observed when the system was first listed and assessed.
	FP–2B – Fish Community Metrics and Population Trends (OMNRF Trap Netting)	Impaired (unchanged)	IBI scores in the Hamilton Harbour AOC were categorized as “fair” throughout the sampling period and were lower than IBI scores at unimpaired reference sites, indicative of an impaired sheltered embayment. The proportion of piscivore biomass (PPB) was lower than at other sheltered embayments with relatively lower catches of Smallmouth and Largemouth Bass; mean PPB was greater than 20% in 3/10 survey years. The proportion of total fish community biomass represented by specialist species (PSPE) is lower than other sheltered embayments with lower catches of native species including Bluegill, Pumpkinseed, Black Crappie, and Yellow Perch; mean PSPE over 40% has not been observed.

AOC = Area of Concern

BUI = Beneficial Use Impairment

DFO = Fisheries and Oceans Canada

FP = Fish Population

OMNRF = Ontario Ministry of Natural Resources and Forestry
IBI = Index of Biotic Integrity

HISTORY OF THE FISH POPULATIONS BENEFICIAL USE IMPAIRMENT

Hamilton Harbour is a large (22 km^2), protected embayment situated at the western end of Lake Ontario with a watershed encompassing over 500 km^2 (Figure 1). The harbour resides within the traditional territories of the Erie, Neutral, Huron-Wendat, Haudenosaunee and Mississaugas. This land is covered by the Dish With One Spoon Wampum Belt Covenant (1701), an agreement to share and care for the resources around the Great Lakes, and the Between the Lakes Purchase, Treaty 3 (1792).

Figure 1. Map showing infilled shoreline and tributaries of Hamilton Harbour in orange hatched. There are additional areas infilled after 1915 and as such does not capture infills that occurred prior to this date (source unknown).

Four large creek systems drain into Hamilton Harbour: Spencer Creek (including Chedoke Creek, Ancaster Creek, and Borer's Creek), Indian Creek, Grindstone Creek, and Red Hill Creek. Historically, the embayment contained extensive wetlands, aquatic vegetation, gravel and cobble shoals, and numerous tributaries, particularly along the southern shoreline (City of Hamilton 2023a; an example of the amount of infilling in the south shore: Figure 1). These habitats supported diverse and productive fisheries, including year-round coldwater fisheries in the deeper portions of the harbour (Whillans 1979).

Bowlby et al. (2009) documented, in great detail, the conditions of the natural (e.g., physiography, climate, soils) and anthropogenic (e.g., land use, watercourse barriers) environments that influence the harbour. Here we highlight some historical and present-day conditions that have led to the current state of fish populations in the Hamilton Harbour Area of Concern (AOC.

Species extirpation from the harbour started in the early 1800s as European settlers began to exploit the abundant fisheries in the system. Development continued in the 1900s, increasing human population around the watershed. The receiving waters were impacted by increased runoff and nutrients from sewage, resulting in poorer water clarity and quality. Conversion of natural lands to agriculture within the watersheds of the harbour increased sedimentation into the water, and removal and siltation of larger aggregate material in the harbour negatively affected important spawning shoals for many species of fish such as Lake Herring (*Coregonus* sp.; Holmes 1988). Bowlby et al. (2009) also extensively documented shifts and declines of coolwater and warmwater fishes for various species (see Appendix A for species thermal guild assignments and scientific names). Infilling aquatic habitats, particularly along the south shore, resulted in an 85% loss of the wetland habitat in the system (Whillans 1982) and the industrial development on these infilled areas contributed to significant contamination of the substrates. Industrial developments, including one of the busiest ports on the Great Lakes, and steel production, now cover 46% of Hamilton Harbour’s 45-kilometer shoreline (Bay Area Restoration Council 2012).

Anthropogenic stress continues to influence Hamilton Harbour to this day as human populations within the watershed have increased and contributed additional inputs from wastewater into the ecosystem. The City of Hamilton has experienced between 3.7% and 6.1% population growth every five years since 1996 (Statistics Canada 2022). While extensive efforts are underway to upgrade wastewater treatment and reduce the effluent that enters the harbour (City of Hamilton 2023b), the well-documented conditions of eutrophication within Hamilton Harbour remain (Visha et al. 2021). In addition to increased wastewater loadings, wastewater bypasses (untreated sewage entering directly into the harbour; City of Hamilton 2023c) further degrade water quality in the system.

Many of the challenges faced at the inception of the Hamilton Harbour AOC are still present (e.g., sediment toxicity, eutrophication, habitat loss) and, with additional new or lake-wide stressors, recovery of fish populations has become more difficult. The arrival of novel aquatic invasive species (AIS) [e.g., Round Goby (*Neogobius melanostomus*), Rudd (*Scardinius erythrophthalmus*) and expansion of existing AIS [e.g., Goldfish (*Carassius auratus)*], the persistence of historic pollutants (e.g., polyfluoroalkyl substances (PFASs)), the emergence of new pollutants (e.g., hormone disrupters like estradiols), and even climate change, complicate the recovery of fish and fish habitat. Knowledge gaps remain in understanding some of these stressors and their interactions amongst each other and resulting effects on fish populations.

The loss and degradation of important fish and wildlife habitat and poor water quality were all contributing factors to the designation of Hamilton Harbour as an AOC (listed in 1985 and then formalized in 1987; HHRAP 1992a). Several beneficial use impairments (BUI), including fish and wildlife populations (BUI#3) in the harbour, were deemed to be impaired at that time. Currently, the wildlife populations component of BUI#3 is in review for redesignation from impaired to not-impaired status (HHRAP 2022), while the fish populations component remains impaired and requires assessment.

The International Joint Commission (IJC) has created generic fish populations delisting criteria for all AOCs that state that an AOC can delist: "*when environmental conditions support healthy, self-sustaining communities of desired fish and wildlife at predetermined levels of abundance that would be expected from the amount and quality of suitable physical, chemical and biological habitat present*," (International Joint Commission 1991, p. 5). This guidance also notes the need for consistency, aligning with Great Lakes Fishery Commission goals, and if community structure data are unavailable, toxicity data can be used (International Joint Commission 1991). The Hamilton Harbour AOC is fortunate to have abundant information on fish communities that have supported the development and refinement of delisting targets and criteria. The Hamilton Harbour Remedial Action Plan (HHRAP) was developed in 1989 and included actions to remediate fish populations and habitat. The first was developed through Fish and Wildlife Committee workshops in 1990, where experts in marsh restoration and fisheries enhancement put forth remedial options in a report titled "A plan for restoration of fish and wildlife habitat in Hamilton Harbour and Cootes Paradise" (HHRAP 1990). Two important reports expanded the plan in 1992. The "Stage 1 Environmental Conditions and Problem Definition Report" (HHRAP 1992a) outlined the nature and scope of the 11 of 14 potential environmental problem BUIs and the accompanying "Stage 2 Goals, Options, and Recommendations Report" offered solutions (HHRAP 1992b).

The AOC-specific delisting criteria for Hamilton Harbour's fish populations were developed in consultation with the community and adapted from the original IJC delisting guideline. Although the current criteria have been simplified, the original 1992 Stage 2 goals for fish populations (HHRAP 1992b) stated that the fish community should have the following structure:

a) Shift from a fish community indicative of eutrophic environments, such as White Perch, Alewife, bullheads, and Common Carp to a self-sustaining community more representative of a mesotrophic environment containing Northern Pike, bass, Yellow Perch, and sunfish

b) Attain a littoral fish biomass of 200 – 250 kg/ha
c) Increase the species richness from 4 species to 6-7 species per transect.
d) Increase the native species biomass from 37% to 80-90% of the total biomass.
e) Reduce the spatial variability in fish biomass within the harbour.
f) Proposed nearshore fish community of Hamilton Harbour:

Category	**Littoral Biomass (kg/ha)**
Piscivore (Northern Pike, bass)	40 - 60
Specialists (insectivores like Pumpkinseeds, Yellow Perch)	70 - 100
Generalists (omnivores like Common Carp, Brown Bullheads)	30 - 90

The original delisting criteria (a-f), including the percent of fisheries biomass allocated to the three trophic groups, were based on a comparison of electrofishing data collected from Hamilton Harbour, the Bay of Quinte, and Severn Sound in 1990. At the time, all three areas were designated as Great Lakes AOCs, but there were regions within the Bay of Quinte and Severn Sound that had relatively unimpaired fish assemblages comparable to reference locations (Minns et al. 1994; Brousseau et al. 2011). Since then, fish populations in the more degraded areas of the Bay of Quinte and Severn Sound have improved and the fish population BUI in both areas has been redesignated to not-impaired. Severn Sound was delisted as an AOC in 2003, but the Bay of Quinte AOC has not yet been delisted despite the recovery of fish and wildlife populations and habitat, due to continuing eutrophication issues.

Indices of Biotic Integrity are a widely used means of integrating aspects of a biotic community (e.g., abundance, richness) into a single score that can indicate the biotic community or the health of an ecosystem. A fish-based Index of Biotic Integrity (IBI) was developed to assess the condition of littoral areas in the Great Lakes (Minns et al. 1994). Fish community composition (e.g., abundance of native fishes, proportion of piscivore biomass, number of non-native fishes) is used in this IBI to derive an overall score that can help compare ecosystem conditions among areas, track changes through time, and establish population goals (Minns et al. 1994; Brousseau et al. 2011; Boston et al. 2016). In 2002, a new line of evidence was established for fish populations in the Hamilton Harbour AOC and it used the fish IBI to add a quantitative measure (HHRAP 2003); the additional IBI-based goal was:

g) Attain an IBI score of 55-60 for Hamilton Harbour.

A public forum that included all Hamilton Harbour stakeholders was held in 2012 to revisit the delisting criteria for all of the harbour's BUIs and, as a group, delisting criteria were discussed and further refined. One of the results of the process was recognizing that the IBI score was a suitable replacement for multiple delisting targets (a to f above; HHRAP 2012) for fish populations since many of these elements were metrics used to derive the IBI. Based on these 2012 revisions, the criteria we use in current assessment of BUI#3 is when the nearshore fish community has the following structure:

a) Shift from a fish community indicative of eutrophic environments (e.g., White Perch, Alewife, bullheads, and carp) to a self-sustaining community more representative of a mesotrophic environment with a balanced trophic composition that includes top predators (e.g., Northern Pike, Largemouth Bass and Walleye) and other native species (e.g., Suckers, Yellow Perch, and sunfishes).
b) Attain an Index of Biotic Integrity (IBI) of 55-60 for Hamilton Harbour and maintain the target score for two sequences of monitoring carried out a minimum of every three years. The IBI incorporates components of native species richness, numbers and biomass; piscivore biomass; non-native species, and reflects water quality and the quality of fish habitat.
(HHRAP 2019, p 8)

In addition, Hamilton Harbour has three other BUIs that address fish impairment including: BUI#1 Restrictions on Fish (Impaired) and Wildlife Consumption (Requires Further Assessment), BUI#4 Fish Tumours or Other Deformities (Requires Further Assessment), and BUI#14 Degradation of Fish and Wildlife Habitat (Impaired) (HHRAP 2019). These BUIs will need to be addressed before the Hamilton Harbour AOC can be delisted. The habitat BUI (#14) is being assessed concurrently and will not be redesignated during this assessment period because aquatic vegetation and other habitat targets have not been achieved. The Fish Tumours BUI (#4) will be assessed in 2023 allowing for a year to pass since the completion of environmental dredging and containment of contaminated sediment at the Randle Reef site. A further round could occur in 2027 pending the results of 2023.

The HHRAP has completed extensive work to address declining fish populations and water quality. For fish populations, members of the HHRAP have implemented several habitat improvement projects (currently being compiled in BUI#14's habitat assessment). For example, construction of the Red Hill Valley Parkway along Red Hill Creek included the rebuilding of the central stream channel and improvements to the Red Hill Creek marsh area. Windermere Basin and lower Red Hill Creek have been dredged multiple times (Portt and Associates 2003) and were altered in 2012 into a managed wetland system to provide better habitat for fish and colonial waterbirds (City of Hamilton 2022). Cootes Paradise had a fish barrier/passage structure installed in 1996 at the entrance to the harbour to exclude Common Carp and pass native fishes. Installation of this fishway also coincided with several habitat improvement projects in the wetland (Theysmeyer and Court 2021). There have also been several habitat improvement projects in the harbour, such as the Waterfront Trail improvement (2000), the LaSalle Park Fish and Wildlife Restoration Project (1994), and the Northeast Shoreline Fish and Wildlife Restoration Project (1994), which provide shoal areas for fish (Gardner Costa et al. 2020). Fish population dynamics around some of these habitat improvements, particularly islands (Maynard et al. 2022), were recently assessed (Maynard et al. 2022) and explored in more detail in FP-1B of this report. Future habitat creation or restoration works may focus on the western portion of the harbour, such as the area around Carroll's Point, since it was recognized as having the greatest potential for recovery due to comparatively lower levels of contaminated substrate and submerged aquatic vegetation persisting in waters <2.5 m (Holmes 1988). In contrast, there are limited opportunities for habitat rehabilitation along the south shore of the harbour due to extensive infilling, shoreline hardening, and substrate toxicity.

To improve water quality, the Region of Halton upgraded the Skyway Wastewater Treatment Plant in 2016 from secondary to tertiary treatment (K. O'Connor, HHRAP, Hamilton, ON, personal communication 2023). Woodward Wastewater Treatment Plant (WWTP) is currently upgrading capacity and moving from secondary to tertiary treatment (Hamilton 2023b). The City of Hamilton has continued the Sewer Lateral Cross-Connection Program, inspecting and repairing sewer connections improperly connected to the stormwater collection system to reduce wastewater bypass. The City of Hamilton inspected 47 kilometres of storm sewer in 2022, corrected 54 cross connections (for a total of 450 completed cross connection repairs so far), diverting more than 100 million liters of sewage from the stormwater system to the treatment plant (City of Hamilton 2023b). The combined sewer system is a significant challenge for the city and continues to be a priority in infrastructure planning, like many other large cities. In 2019 and 2021, despite years of improvement, over four billion liters of bypass from the combined sewer system and Woodward WWTP were discharged into Hamilton Harbour (City of Hamilton 2023c), representing approximately 1.6% of the harbour volume (Halfon 1996). This does not include the volume from normal operation of any of the three WWTPs discharging into Hamilton Harbour. Woodward WWTP, for example, discharged 95.81 billion liters of treated water in 2021 with 1.75% bypassed directly to receiving waters of Hamilton Harbour (City of Hamilton 2023c). Bypasses were typically combined sewer overflows with a few secondary bypasses (City of Hamilton 2023c).

The Hamilton Harbour AOC is a dynamic system and, as noted, conditions have changed since initial listing with some improvements to habitat and wastewater treatment as well as major ecological changes from the introduction of novel invasive species (e.g., zebra mussels and Round Goby) and climate change (e.g., storm intensity, warmer water temperatures, or fluctuating water levels). We preface our assessment with these changes within the Hamilton Harbour AOC to provide context to the BUI's current status and caution readers to be wary of Pauly's (1995) shifting baseline syndrome in terms of forgetting positive progress that has been made in the harbour and the large-scale changes that have affected all of Lake Ontario since the Hamilton Harbour AOC designation. In the former case, stakeholders may be more pessimistic about what we can do to resolve the challenges the harbour faces since conditions still appear degraded. In the latter case, regional shifts in fish community composition and health (i.e., throughout Lake Ontario) may mean we must temper some of our expectations regarding population recovery. Balancing these two factors will be critical to ensuring assessments of fish population recovery are true to the intent of the original designation of fish populations as impaired in the Hamilton Harbour AOC.

In this assessment of BUI#3 for the Hamilton Harbour AOC, our objectives were to use multiple studies and fish monitoring programs to assess the status of fish populations, describe any trends since the listing of the AOC, and recommend future actions to improve fish populations and understand their dynamics more accurately. Specifically, we assessed both fish population and IBI trends over time, which were divided into time stanzas that reflected significant ecological changes in Lake Ontario and/or Hamilton Harbour. Time stanzas have the benefit of allowing comparison among AOCs and similar areas in Lake Ontario when sampling effort is limited and direct year-to-year comparisons are not possible. Four time stanzas correspond to four significant eras and are detailed in Turner et al. (in review). Stanza P1 (pre-1994) reflects when the Hamilton Harbour AOC was first listed, and when fish populations in reference areas (e.g., Bay of Quinte) were also listed as impaired. It also covers the Dreissenia invasion of the Great Lakes. Stanza P2 (1995-2004) reflects a post-Dreissenia period and covers the completion of the Cootes Paradise Fishway (1997), which was designed to exclude adult Common Carp from the marsh. Stanza P3 (2005-2012) marks the invasion of Round Goby into the Great Lakes. Lastly, P4 (2013-2021), is the current stanza and starts the year after there was successful establishment of stocked Walleye (*Sander vitreus*) in Hamilton Harbour. P4 also aligns with the start of declines in fish catch in the Toronto and Region AOC (Midwood et al. 2022).

The assessment is divided into three major parts.
Part one, Fish Populations (FP-1) assesses criterion 1: "Shift from a fish community indicative of eutrophic environments … to a self-sustaining community more representative of a mesotrophic environment…" and is split into three sections:

1) FP-1a – species-specific trends,
2) FP-1b – fish community trends, and
3) FP-1c – pelagic prey fish surveys.

Part two, FP-2 assesses criterion 2: "Attain an Index of Biotic Integrity (IBI) of 55-60…" with two subsections:

1) FP-2a – electrofishing, and

2) FP-2b – trap-netting.

Part three is a general discussion that captures common themes and provides key messages and recommendations.

SUMMARY OF STATUS OF FP-1

Multiple lines of evidence were used to assess whether the Hamilton Harbour Area of Concern (AOC) fish community has shifted from one indicative of eutrophic environments to one more representative of mesotrophic conditions with balanced trophic composition (including top predators). First, nearshore trends in catch of specific species since initial listing were assessed (section FP-1A), and while declines in Common Carp and Brown Bullhead (*Ameiurus nebulosus*) are a positive sign, declines in Smallmouth Bass (*Micropterus dolomieu*), sunfishes, and White Sucker (*Catostomus commersoni*) and no change in catches of Northern Pike (*Esox Lucius*) and Largemouth Bass (*Micropterus salmoides*) indicate continued impairment. Declines in catches of some native species [i.e., Largemouth Bass, Smallmouth Bass, Walleye, and Yellow Perch (*Perca flavescens)*] were also found at reference embayments in eastern Lake Ontario but generally, catches in these areas were still higher than in the Hamilton Harbour AOC. Two novel non-native species, Rudd and Round Goby, have become established since the AOC was listed, and Goldfish have increased in catch since the mid-2000s. Offshore, pelagic species are key contributors to total catch and biomass in littoral areas of the Hamilton Harbour AOC with Gizzard Shad (*Dorosoma cepedianum*), a native, offshore species characteristic of degraded, eutrophic conditions, now one of the most abundant species. In trap net surveys, non-native species [e.g., Common Carp, Rudd, and White Perch (*Morone americana*)], as well as species indicative of degraded, eutrophic conditions (e.g., Brown Bullhead), were found to be hyperabundant in the Hamilton Harbour AOC compared to similar embayments. Overall, the fish community in Hamilton Harbour remains impaired and is unique and distinct from other embayments in Lake Ontario (section FP-1B). Recent trends in species presence indicate declines in richness since 2013 in Hamilton Harbour, Cootes Paradise, and the Cootes Paradise Fishway, as well as in the watersheds draining into the harbour (the sole exception being the Red Hill Creek watershed). Within Hamilton Harbour specifically, 55 species were detected between 1985 and 2012, and 43 species from 2013 to 2022. These trends are consistent with overall declines in species richness noted under criterion FP-2. Finally, in the main basin of the harbour, hydroacoustic surveys and mid-water trawling suggested that while there was seasonal and spatial variability within the AOC, fish density and biomass were comparable to other similar ecotypes in western Lake Ontario (section FP-1C).

Despite some limited positive findings, such as declines in Common Carp catch and biomass, as well as regional similarities in the density of pelagic forage fishes, results from the current assessment of this criterion suggest that the fish community is still more indicative of eutrophic conditions and thus remains impaired. Throughout this report, several potential factors that may be limiting improvements to the fish community were identified such as persistent hypolimnetic hypoxia, negative effects from established and novel aquatic invasive species, an impaired benthic environment, poor water quality, legacy contaminants, limited habitat supply, and impaired habitat condition, among others. The extent of the effect of these stressors and ongoing ecosystem degradation is unclear, but undoubtedly, these factors interact to limit improvements in the condition of the fish community and the abundance of native fishes. Developing a conceptual framework for how these stressors and limitations act to restrict fish populations would help identify the most likely drivers of impairment, and consequently, the stressors towards which remediation efforts should be focused.

CRITERION FP-1A: SPECIES-SPECIFIC

SUMMARY

Multiple data sources were used to assess trends in species catch and catchability in the Hamilton Harbour Area of Concern (AOC) and compare values with those from other sheltered embayments in Lake Ontario. Results indicating declines in Common Carp for the Hamilton Harbour AOC are a positive trend; however, few other species identified as targets indicated population recovery (e.g., Centrarchids). Walleye were a notable exception, with population increases driven by stocking efforts, while no other piscivore increased in catch between the initial listing and the most recent time stanza. Gizzard Shad also showed marked increases in catch; however, as a native, predominantly pelagic offshore species characteristic of degraded, eutrophic conditions, their increases do not necessarily indicate a systemic improvement. Similarly, increased catch of non-native Goldfish and White Perch and the arrival of non-native Rudd and Round Goby since the Hamilton Harbour AOC was first listed further point to fish population degradation. Based on species-specific patterns, fish populations in the Hamilton Harbour AOC remain impaired.

KEY MESSAGES

- In the Hamilton Harbour AOC, the majority of native species declined in the catch or remained unchanged between P1 (pre-1994) and P4 (2013-2021; Table 2).
- Except for stocked Walleye, top predator (e.g., Northern Pike, Largemouth Bass) populations in Hamilton Harbour have declined or are lower in numbers at Hamilton compared to east reference embayments (East-Ref).
- Multiple lines of evidence show that Common Carp have declined in abundance at the Hamilton Harbour AOC, including in electrofishing catches throughout the harbour, at the Cootes Paradise Fishway, and in Cootes Paradise since the initial listing; despite these declines, they are still important contributors to the total biomass of fishes in the harbour.
- Two novel invasive fishes (Round Goby and Rudd) became established in the Hamilton Harbour AOC since the initial listing, and the invasive Goldfish has increased in the catch of all monitoring programs since the mid-2000s.
- Offshore pelagic species are key contributors to total catch and biomass in Hamilton Harbour. Gizzard Shad, a native, predominantly offshore species characteristic of degraded, eutrophic conditions, is one of the more abundant species in the harbour catch that has increased over time, particularly in the west harbour zone.
- White Perch, a non-native pelagic eutrophic species, declined in Hamilton Harbour over time (P1-P4) in electrofishing catches but increased in the catch between P3 and P4 in trap net surveys (Table 3). White Perch were

hyperabundant in the Hamilton Harbour AOC trap net surveys compared to East-Ref.
- By harbour zone, species richness and total catch were highest in the west followed by the north and then east, demonstrating that clear spatial differences exist and are likely related to habitat supply.
- At regional reference embayments, declines in native species abundance at East-Ref were also noted between P1 and P4, but in general, the catch of native species was significantly higher at East-Ref than at the Hamilton Harbour AOC. In contrast, fish assemblages at west reference embayments (West-Ref) were more similar to Hamilton Harbour.
- In trap net surveys, the catch of non-native species (e.g., Common Carp, Rudd, and White Perch) and species indicative of degraded, eutrophic conditions (e.g., Brown Bullhead) were found to be hyperabundant in the Hamilton Harbour AOC compared to East-Ref but native species catches were depressed (e.g., Centrarchidae, Yellow Perch).

REMAINING CONCERNS AND UNCERTAINTY

- Given the low population size for most native and piscivorous species (e.g., Northern Pike), a review of sustainable levels and sources of mortality is necessary to reduce pressure on these already marginal populations.
- It is unclear which factor(s) are limiting the natural recruitment of Walleye in the AOC and further exploration of potential recruitment limitations (e.g., habitat, siltation, water quality, and/or forage base) is warranted.
- Competitive interactions between invasive and native species for habitat and prey resources in Hamilton Harbour are understudied; for example, the impacts of increasing Goldfish and Rudd populations on native species and aquatic habitat (i.e., removal of aquatic macrophytes).
- For specialist foraging guilds (e.g., invertivores), the amount and type of available prey remain largely unknown and understudied.
- It is unclear the extent to which habitat supply and condition limit species presence and abundance both within the Hamilton Harbour AOC and relative to similar areas in Lake Ontario.

FUTURE MONITORING

- Creel surveys for recreational species (e.g., top predators) in the Hamilton Harbour AOC should be conducted to determine the magnitude of angling pressure on species of interest.
- DFO and MNRF should continue to assess similar sheltered embayments across Lake Ontario to provide baseline reference information for the Hamilton Harbour AOC.
- Spatial surveys that target benthic invertebrates in the Hamilton Harbour AOC would provide the data needed to assess prey resources for littoral invertivore

fish species that are in decline; the last spatial survey to assess benthic invertebrates was conducted in 2014 (Milani and Grapentine 2016) at deeper, offshore locations in the harbour. A more comprehensive survey that includes littoral sites (see DFO's 2002-2003 benthic surveys) would be informative.

RECOMMENDED ACTIONS

- Given the low capture rates of top predators (Largemouth Bass, Smallmouth Bass, Northern Pike) across various gear types (electrofishing, trap netting, Royal Botanical Gardens Fishway, and wetland monitoring), attempts should be made to mitigate sources of mortality until such populations make a reasonable recovery. For example, non-lethal sampling methods should be explored for aging (scales, spines, fin clips) and contaminant load for consumption guidelines (muscle biopsy, blood).
- A detailed assessment of habitat availability and suitability among Hamilton Harbour AOC zones and sampling regions in Lake Ontario is warranted; this would help identify the type of species and life stage including the abundance that would be expected/predicted to occur based on zonal habitat conditions.
- Trap net data should be assessed on the same zonal basis as electrofishing data to make data interpretation more comparable.

BACKGROUND

Following the loss of major wetland and shoreline areas, industrialization, and water quality impairment, many species of fish in Hamilton Harbour experienced dramatic declines in abundance or local extirpation, which contributed to its listing as an Area of Concern (AOC) in 1985 (Kelso and Aquatic Habitat Toronto 1996). Following the listing of Hamilton Harbour as an AOC, several delisting criteria were developed to guide and assess changes over time and provide science-based advice and evidence to determine when the system was no longer impaired. The number of delisting criteria for fish populations was reduced to two main criteria in 2012. The first delisting criterion for fish populations was more general and identified specific shifts in the fish community that were deemed desirable, "*…from [one] indicative of eutrophic environments (e.g., White Perch, Alewife, bullheads, and carp) to a self-sustaining community more representative of a mesotrophic environment with a balanced trophic composition that includes top predators (e.g., Northern Pike, Largemouth Bass, and Walleye) and other native species (e.g., Suckers, Yellow Perch, and sunfishes)*" (HHRAP 2019; pg. 8). The second criterion was more specific, identifying an Index of Biotic Integrity (IBI) target range of 55-60 sustained for a minimum of three consecutive years. Initial fish community assessments for the Hamilton Harbour AOC noted increases in multiple species in the early 1990s following the reduction of total phosphorus, increased water clarity, habitat creation, and restoration projects (Smokorowski et al. 1998; Brousseau and Randall 2008; Boston et al. 2016). However, from 2006-2012, general declines in the fish community and overall IBI scores were documented; these declines were attributed in part to Round Goby establishment (Balshine et al. 2005) and the reversal of previous phosphorus reduction and water clarity (Boston et al. 2016). An updated IBI assessment can be found elsewhere in this report (see sections FP-2A and FP-2B). The objective of this section is to assess species-specific trends in their likelihood of capture in a transect (herein “catchability”) and catch (i.e., numbers) within the Hamilton Harbour AOC at three spatial zones (west, north, and east) using multiple long-term datasets.

Furthermore, we compared species-specific data from the Hamilton Harbour AOC with other sheltered embayments located in eastern (Bay of Quinte and West Lake) and western (Jordan’s Harbour and Frenchman’s Bay) Lake Ontario to determine if changes in species catchability and catch were specific to the Harbour Harbour AOC or the result of larger lake-wide changes (e.g., changing baselines). Species of interest were identified and included groups of species that would ideally increase (top predators and native littoral species) or decrease (undesirable, offshore, and non-native/invasive species) in the catch (Table 2). The analyses and data syntheses in this section will aid in the assessment of the status of fish populations within the Hamilton Harbour AOC as well as the development of recommended actions that may be required to meet delisting targets related to fish abundance, productivity, and community structure.

DATE SOURCES AND METHODS

Electrofishing (DFO) Turner et al. (in review)

Long-term, summer (May-August) electrofishing data were collected and compiled by Fisheries and Oceans Canada (DFO). Sampling occurred in 19 of the past 33 years (1988-2021) at fixed transect locations at 1.5 m water depths in Hamilton Harbour and at similar sheltered embayments in Lake Ontario (East-Ref – Bay of Quinte and West Lake; West-Ref – Frenchman’s Bay and Jordan Harbour – both of which have degraded water quality similar to the Hamilton Harbour AOC; Cvetkovic and Chow-Fraser 2011) following a standardized protocol (see Brousseau et al. 2005 for detailed methods). Like section FP-2A, temporal trends in individual species catches were analyzed across four different time stanzas (P1: pre-1994, P2: 1995-2004, P3: 2005-2012, and P4: 2013-2021). Mean numbers of individuals captured per transect (i.e., catch) were compared among time stanzas within the Hamilton Harbour AOC overall (i.e., all transects combined) or by harbour zone (west, north, and east; Figure 2). Individual species catches from the Hamilton Harbour AOC were compared with eastern (East-Ref; P1-P4) and western (West-Ref; P3 and P4 time stanzas only) reference areas. All analyses were completed using hurdle models (Mullahy 1986) that had time stanzas and location (Hamilton-overall, Hamilton-zones, East-Ref, and West-Ref) as fixed effects and transect and sampling period (day or night) as random effects. The first step in these models explored species catchability (i.e., probability of encountering the species in a transect) and the second step modelled the mean number of individuals captured when that species was encountered. For data-limited species, it was not always possible to model by harbour zone, so for those species, data were combined to assess harbour-wide trends or in rarer cases assessed visually when modelling was not possible. High-level summaries relevant to the assessment of the status of fish species catch and catchability are provided here but can also be found in some detail in Turner et al. (in review). All model outputs not described in detail below can be found in Appendix B.

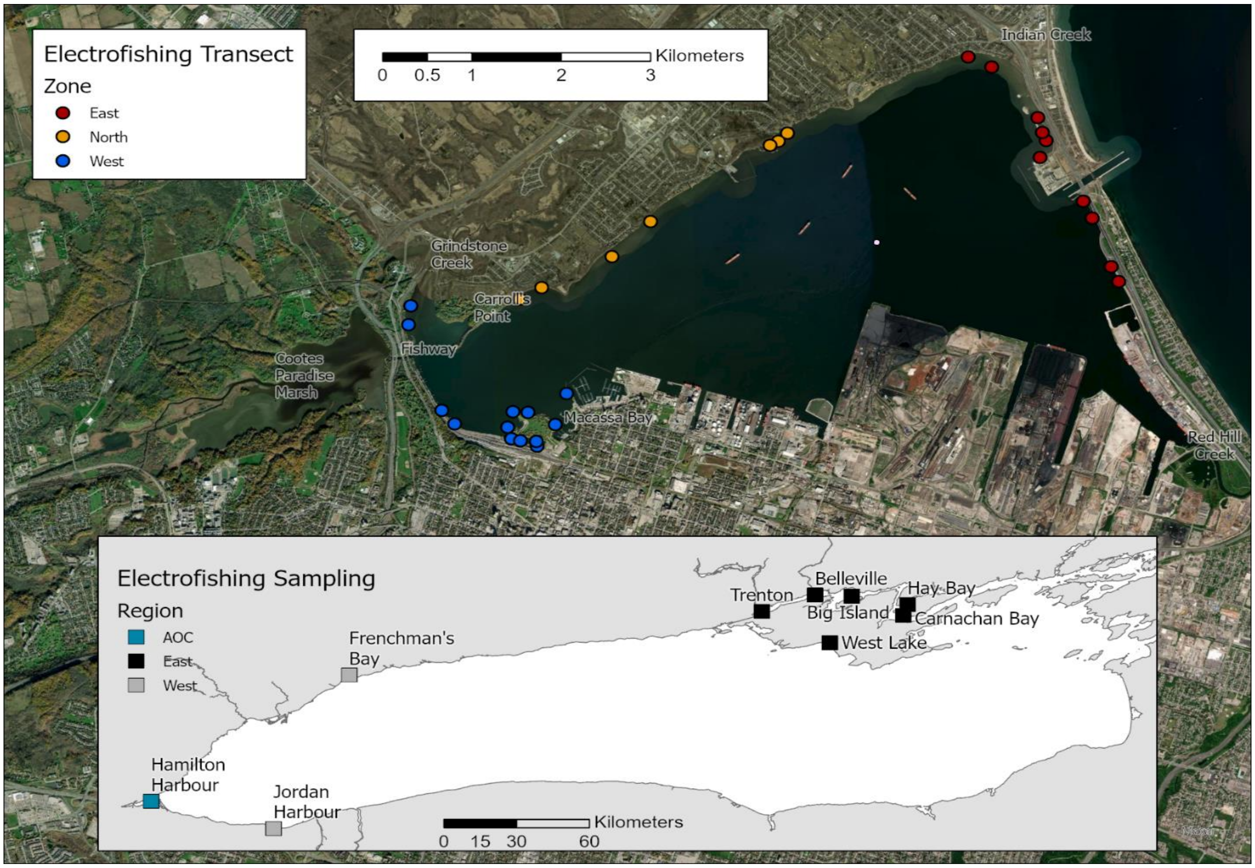

Figure 2. *Electrofishing sampling locations in the Hamilton Harbour Area of Concern (AOC) broken down by zone (east = red, north = orange, west = blue). Bottom inset shows the location of regional reference areas in Lake Ontario.*

Trap Netting (MNR) Nearshore Fish Community Index Netting (NSCIN) FP-2B and Appendix D

Data were collected and summarized from a long-term trap netting program (Nearshore Fish Community Index Netting) by the Ontario Ministry of Natural Resources and

Forestry (MNRF) on Lake Ontario embayments (Stirling 1999). The dataset covers roughly 15 years (2006-2021) of sampling effort across various littoral Lake Ontario embayments including Hamilton Harbour and east regional reference locations. Sampling locations within an embayment were randomly selected annually; however, standard trap net criteria were applied (water depth, orientation to shoreline, and distance between nets). Trap net surveys began on August 1st and continued until surface water temperatures reached an average of 13°C; the minimum size of fish available for capture is approximately 90 mm in length and excludes smaller species such as native minnows and juvenile life stages of most species (See section FP-2B for more details; Stirling 1999). Additionally, the program lethally samples up to 30 individuals of species of interest, including top predators, to assess age (e.g., otoliths), diet, and contaminant loadings for fish consumption guidelines (refer to Beech and Brown 2021 for more details). Trap net sampling data have been summarized and provided in the species-specific sections below; data in the text are reported as catch per unit effort (CPUE; i.e., mean number of fish/trap net). These data have not been included in the hurdle models and no statistical analysis has been completed.

Fall fyke netting (DFO) Budgell et al. (2023)

In the fall of 2020 and 2021, DFO conducted community surveys to identify areas of Northern Pike recruitment and nursery areas used by young-of-year (YOY) and juvenile pike. Sampling methods used a combination of gear types, including fyke nets, light traps, and seine nets, depending on the year and area sampled. Sampling locations included Cootes Paradise, Grindstone Creek, Spencer Creek, Red Hill Creek, and Hamilton Harbour. For a more detailed methodology, refer to (Budgell et al. 2024).

Population estimates (DFO) Larocque et al. (2023)

A capture-mark-recapture (CMR) study was conducted on top predators (Northern Pike, Largemouth Bass, Smallmouth Bass, and Walleye) in Hamilton Harbour from 2017 to 2021 using Passive Integrated Transponder (PIT) technology. PIT tagging and recapture events occurred during boat electrofishing community surveys and the Cootes Paradise Fishway. CMR population abundances were estimated for adults of each species for the study period and both capture methods. See Larocque et al. 2023 for more details.

Minnow traps (McMaster University) McCallum et al. (2014); Young et al. (2010); and Appendix E

Round Goby were sampled at six locations (Desjardins Canal, Grindstone Creek, LaSalle Park, Fisherman’s Pier, Pier 27, and Sherman Inlet) across Hamilton Harbour using minnow traps between 2002 and 2022. At each location, six minnow traps were set for 24 hours twice a month between April and November; four traps were baited (25g of corn) and two were un-baited (see Appendix F; McCallum et al. 2014; Young et al. 2010 for detailed methods).

Stormwater management ponds (DFO)

The City of Hamilton was identified as a hotspot for the release of unwanted aquarium pets into the natural environment (Chan et al. 2019). In 2021 and 2022, 30 stormwater management ponds (SWMP) managed by the City of Hamilton were surveyed to identify the presence-absence of non-native species and critical factors of invasive species arrival, survival, and subsequent dispersal into natural waterways from SWMP. Ponds selected for the study addressed a range of physical characteristics and factors that could affect arrival and dispersion (Chan et al. 2019). SWMP within the City of Hamilton were found in nine different watersheds including major tributaries to Hamilton Harbour (Red Hill, Spencer, Borer's, and Grindstone creeks).

Acoustic telemetry (DFO) Larocque et al. (2024)

Eleven species of fish [Bowfin (*Amia calva*), Common Carp, Freshwater Drum (*Aplodinotus grunniens*), Goldfish, Largemouth Bass, Longnose Gar (*Lepisosteus osseus*), Northern Pike, Smallmouth Bass, Walleye, White Sucker, and Yellow Perch] were acoustically tagged in Hamilton Harbour, following procedures described in Brooks et al. (2019). Each species was analyzed across seasons to determine residency outside and within the harbour, depth use, and general habitat associations. Similar analyses were done when focusing on the spawning window for each species. For detailed methods see Larocque et al. (2024).

Monitoring in Cootes Paradise and Grindstone Creek (Royal Botanical Gardens) Appendix G

Fishway Operation (1996 – 2022): The fishway operates seasonally using a minimum of one and up to six inbound and outbound cages at a time to facilitate the migration of fish impacted by the barrier into and out of Cootes Paradise and associated tributaries. Operation begins each spring after ice out and typically continues until the salmon run is over in the autumn. Inbound cages are first lifted, emptied into a holding tank, and then identified, counted, and sorted as they exit the tank. Native fish are allowed passage into the marsh while non-native species (e.g., Common Carp, Goldfish, and Rudd) are sent back into the harbour. The same process repeats for the outbound cages, with the only difference being that all fish are sent back to the harbour side. The frequency of lifts is dependent on the time of year and number of observed fish. As mentioned, all fish are counted as they pass through the fishway and categorized as either incidental (<25 cm) or large (>25 cm; refer to Theijsmeijer, 2022 for more details).

Pike Trap Monitoring (2001 – 2022): Monitoring for young-of-the-year (YOY) Northern Pike occurred in June of each sampling year and involved the deployment of customized plexiglass box traps (1 ft x 2 ft with a 15 ft lead) from herein referred to as 'pike traps', set for an overnight period (24 hr) in appropriate habitat conditions (< 1.0 m of water). Historically, monitoring focused on the upper floodplain ponds of Grindstone Creek Marsh as it was deemed the primary spawning habitat for Northern Pike in Hamilton Harbour and was subject to specific HHRAP restoration projects (HHRAP

1991). For more details, refer to specific HHRAP restoration projects (Theysmeyer and Court 2021)

Index Electrofishing Monitoring (1994 – 2022): A boat electrofishing monitoring program was initiated in 2010 (late August time frame) to assess fish populations in Cootes Paradise and the Grindstone Creek marshes/ponds. Before 2010, monitoring occurred seasonally from May to October. On average, a total of twenty-six transects 50 m in length were sampled using either a modified boat sampling approach, employing punt electrofishing equipment in Cootes Paradise, and an additional thirteen 50 m transects were sampled either by wading or canoe with the same modified punt electrofishing unit in Grindstone. All captured fish were identified by species and measured.

Carp Removal (2000–2022): Each year, carp removal efforts are made to eradicate Common Carp from the entire Royal Botanical Gardens (RBG) coastal wetland system. This is accomplished through electrofishing, seining, and/or gill netting. In Cootes Paradise, this occurs annually from May to December. In the Grindstone Creek Marsh ponds, carp removal efforts typically occur twice annually: once in the summer and once in autumn, usually with a seine net and electrofishing gear.

RESULTS

Table 2. *Desired response for species catch* (arrows indicate ↑ *= increasing,* ↓ *= decreasing,* — *= no change, NA = no available data) in the Hamilton Harbour Area of Concern between time stanza P1 (pre-1994) and P4 (2013-2021) for boat electrofishing only. Response for the entire Hamilton Harbour AOC (HH Overall), among harbour zones (West, North, and East), and at reference embayments in eastern Lake Ontario (East-Ref), as well as overall Hamilton Harbour AOC catchability (HH catchability), and East-Ref catchability.*

		pre-1994 vs. 2013-2021 Electrofishing						
Species	Desired Response	HH Overall	West	North	East	East-Ref	HH Catchability	East-Ref Catchability
Piscivores								
Northern Pike	↑	—	NA	NA	NA	—	—	↓
Largemouth Bass	↑	—	—	—	—	↓	—	↑
Smallmouth Bass	↑	↓	↓	↓	↓	↓	NA	NA
Walleye (stocked)*	↑	↑	↑	↑	↑	↓	NA	NA
Native specialists								
White Sucker	↑	↓	NA	NA	NA	—	↓	↑
Centrarchidae **	↑	↓	—	—	—	↑	↓	—
Bluegill	↑	—	NA	NA	NA	—	—	↑
Pumpkinseed	↑	↓	NA	NA	NA	—	↓	—
Yellow Perch	↑	—	—	—	—	↓	—	—
Native Minnows								
Emerald Shiner	↑	—	—	—	—	NA	↓	NA
Spottail Shiner	↑	—	—	—	—	NA	↓	NA
Generalists, Offshore, and Non-natives								
Brown Bullhead	↓	↓	↓	↓	↓	—	↓	—
Gizzard Shad	↓	↑	↑	—	—	↓	↑	—
Alewife	↓	↓	↓	↓	↓	—	↓	↓
White Perch	↓	—	—	—	—	↑	↓	—
Common Carp	↓	↓	↓	—	↓	—	↓	—
Goldfish*	↓	↑	↑	↑	↑	NA	NA	NA
Rudd*	↓	↑	↑	↑	↑	NA	NA	NA
Round Goby*	↓	↑	↑	↑	↑	↑	NA	NA

*Based on visual assessment of the data (no statistical analysis).

**Includes: Pumpkinseed, Bluegill, Black Crappie, Rock Bass

Table 3. *Observed responses at Hamilton Harbour AOC by individual monitoring programs between time stanzas P3 (2006-2012) and P4 (2013-2021), which includes boat electrofishing (HH Efish), trap nets, (HH Trap net), and Royal Botanical Gardens (RBG) Fishway (HH RBG). Regional reference areas also included East reference embayments for electrofishing (East-Ref Efish), and trap netting (East-Ref Trap net), as well as west reference embayments for electrofishing (West-Ref Efish). Arrows indicate* ↑ *= increasing,* ↓ *= decreasing,* — *= no change, NA = no available data.*

	2006-2012 vs. 2013-2021					
Species	HH Efish	HH Trap net*	HH RBG*	East-Ref Efish	East-Ref Trap net*	West-Ref Efish
Piscivores						
Northern Pike	—	↓	↑ ***	—	↓	—
Largemouth Bass	↓	—	↓	↓	—	—
Smallmouth Bass	↓*	↓	↓	↓*	↓	—*
Walleye	↑*	↑	NA	↓*	↓	—
Native specialists						
White Sucker	—	—	↑	—	↓	—
Centrarchidae **	—	NA	NA	—	NA	—
Bluegill	—	↑	NA	—	↓	—*
Pumpkinseed	—	—	NA	—	↓	—
Yellow Perch	↓	↓	↓	↓	—	—
Native Minnows						
Emerald Shiner	↑	NA	NA	—	NA	↓
Spottail Shiner	—	NA	NA	—	NA	NA
Generalists, Offshore, and Non-natives						
Brown Bullhead	↓	↑	↓	—	↓	—
Gizzard Shad	↑	↓	↑	—	↓	↑
Alewife	—	—	NA	↓	↑	—
White Perch	—	↑	↑	↑	↓	—
Common Carp	↓	—	↓	—	—	—
Goldfish	↑*	↑	↑	—*	NA	↑*
Rudd	↑*	↑	↑	—*	—	↑*
Round Goby	↓*	NA	NA	NA	NA	NA

*Based on visual assessment of the data (no statistical analysis).

**Species include: Pumpkinseed, Bluegill, Black Crappie, Rock Bass

*** Number of Northern Pike increased at the RBG fishway between P3 and P4 but were down from P2 (1995-2005). Assessment of adult and juvenile numbers by RBG indicates a decline in Northern Pike populations. 1136 juvenile Northern Pike were stocked into Cootes Paradise in 2014 (P4)

SUMMARY STATUS OF NORTHERN PIKE

Key messages

The population of Northern Pike in Hamilton Harbour is small relative to other top predators and there are indications from multiple data sources (RBG, MNRF, DFO) that there has been a decline in the population since initial listing.

Current catch /regional reference /temporal trends

Northern Pike were captured infrequently (< 1.0) during electrofishing surveys at both the Hamilton Harbour AOC and regional reference embayments (East-Ref and West-Ref). Due to low capture rates, electrofishing models used combined data from the entire harbour instead of zones. Models indicated no change in the catch across all of the four time stanzas at both the Hamilton Harbour AOC and East-Ref embayments (Figure 3). However, while the probability of catching a Northern Pike in Hamilton Harbour has remained unchanged and close to zero (P1-P4), at East-Ref embayments, there was a significant decline in catchability between P1 and P3, and P1 and P4 (Figure 4). There were no differences noted in the catch or catchability at the West-Ref embayments between P3 and P4. Data from the trap net program showed that the catch of Northern Pike declined by ~50% between P3 and P4 at both the Hamilton Harbour AOC (0.89 and 0.46 CPUE, respectively) and East-Ref embayments (0.85 vs. 0.44 CPUE; Appendix D). A recent population estimate study suggested that the Northern Pike population in Hamilton Harbour is small (~160 adults), which was low relative to estimates for other top predators (Larocque et al. 2023).

To better understand Northern Pike movement patterns and habitat preferences within the Hamilton Harbour AOC, 24 adult Northern Pike were tagged with acoustic transmitters and tracked between April 2016 and April 2020 (Larocque et al. 2024). All Northern Pike remained resident to the harbour during the study period and were primarily located in the west end. Northern Pike moved shallower (~0.5 m) in the spring, presumably to spawn, and were concentrated in the west end of the harbour near Macassa Bay, Cootes Paradise, and throughout the Grindstone Creek system. During the summer, Northern Pike moved into deeper (~1-2 m) waters and were mainly located in the west end near Macassa Bay and Piers 5-7. During the autumn and winter, Northern Pike were found deeper offshore (~1.5-3.5 m) but still in the west end of the harbour (Larocque et al. 2024).

Approximately 400 adult Northern Pike were transferred into the Hamilton Harbour in 1988 to help boost the population (Bowlby et al. 2009). In 2014, the RBG transplanted 1136 juvenile Northern Pike (~30-38 cm) from a local source into Cootes Paradise across multiple locations (Wilton et al. 2015). Electrofishing surveys conducted in Cootes Paradise, pre-and post- construction of the Cootes Paradise Fishway, showed marginal changes in Northern Pike abundance (0.04-0.07 individuals/transect; Theijsmeijer and Court 2021). Similarly, at Grindstone Creek marshes/ponds, there was little change (0.15- 0.06 individuals/transect) following the establishment of the berms and passive fish barriers at the entrance to the ponds designed to exclude Common Carp (Theysmeyer and Court 2021). In general, despite efforts to boost population numbers from stocking in 1988 and 2014 and carp exclusion, the catch of Northern Pike has declined in monitoring programs run by the Royal Botanical Gardens in Cootes Paradise and Grindstone Creek wetlands (Appendix F).

Multiple juvenile Northern Pike surveys were conducted in recent years (2016-2021) to look for evidence of recruitment and to identify potential nursery habitats throughout the harbour. DFO conducted comprehensive surveys in the fall of 2020 and 2021 at Cootes Paradise, the Grindstone Creek marshes, Spencer Creek, and Red Hill Creek (see Budgell et al. In Review for complete methods). Efforts resulted in capturing just a single juvenile Northern Pike at the Red Hill Creek/Van Wagners marsh area (Budgell et al. 2024). Juvenile Northern Pike surveys undertaken by RBG and McMaster University were more successful; the McMaster survey captured a total of 19 juveniles (2016-2018) in Cootes Paradise and Red Hill Creek between June and October and the RBG captured 34 in Grindstone, Cootes Paradise, lower Spencer Creek, and West Pond (2018-2020) during spring sampling. Furthermore, trap net data indicated the capture of age 1 Northern Pike in 8 of 10 sampling years (Appendix D).

Although juvenile Northern Pike catches were low, results here confirm natural recruitment within the harbour system, albeit at very low levels. Differences in Northern Pike catch (YOY, juvenile, adult) throughout the harbour are likely related to differences in sampling time, location, and gear type (active vs. passive), as well as variable spring water levels, which dictate spawning success in any given year (i.e. access and increased availability of spawning/nursery habitat; Minns et al. 1996).

In general, results from the various assessment programs indicate that a small population of Northern Pike with limited recruitment exists in the Hamilton Harbour AOC. These numbers are particularly low compared to other top predators in the system. However, mean catch estimates from both trap netting and electrofishing appear to be similar at Hamilton Harbour AOC and East-Ref embayments, suggesting that Northern Pike abundance may be low or in decline across other sheltered Lake Ontario embayments. Statistical analyses of electrofishing data showed a decline in the catchability of Northern Pike at East-Ref embayments in P3 and P4, which would be consistent with a decline in the abundance of Northern Pike between P3 and P4 in trap net datasets in both Hamilton Harbour and East-Ref embayments. Acoustic telemetry data revealed that Northern Pike were mainly concentrated in the west zone of the harbour. Of note, none of the acoustically tagged Northern Pike moved into the Red Hill

Creek system during this period, despite Northern Pike being captured there routinely in previous years in multiple surveys. This suggests Northern Pike associated with Red Hill Creek rarely, if ever, frequent the more heavily sampled portions of Hamilton Harbour (i.e., the main harbour). Northern Pike populations have declined in Lake Ontario due to historical overharvesting and habitat degradation/loss. Management efforts to support this species have focused on habitat restoration and there are limited opportunities for such restoration in the Hamilton Harbour AOC (Casselman and Lewis 1996; Minns et al. 1996). There have been no indications that the resident population of Northern Pike in the Hamilton Harbour AOC has improved since initial listing; these trends suggest a decline in adult catch over time at both the harbour and East-Ref sheltered embayment areas in Lake Ontario.

Recommendations

Recommendations for Northern Pike include quantifying habitat availability for all life history stages, specifically, assessing the availability of nursery and spawning habitat and how it might fluctuate due to varying spring water levels (flooding), vegetation type, and overall size of spawning habitat (i.e., crowding; (Minns et al. 1996; Crane et al. 2015). Evaluating habitat quality is also important to ensure factors like temperature, dissolved oxygen, or turbidity are not outside the preferred ranges for Northern Pike at different life phases (Pierce 2012). A creel survey of anglers in Hamilton Harbour would provide a means to collect data to estimate mortality and consumption of Northern Pike locally. Given their marginal population size, a reduction or cessation of lethal sampling by scientific agencies should be considered to aid in the recovery of this species. Exploring non-lethal aging options such as anal fin clips may be substituted for lethal sampling in the future to help in the assessment of year classes (Oele et al. 2015).

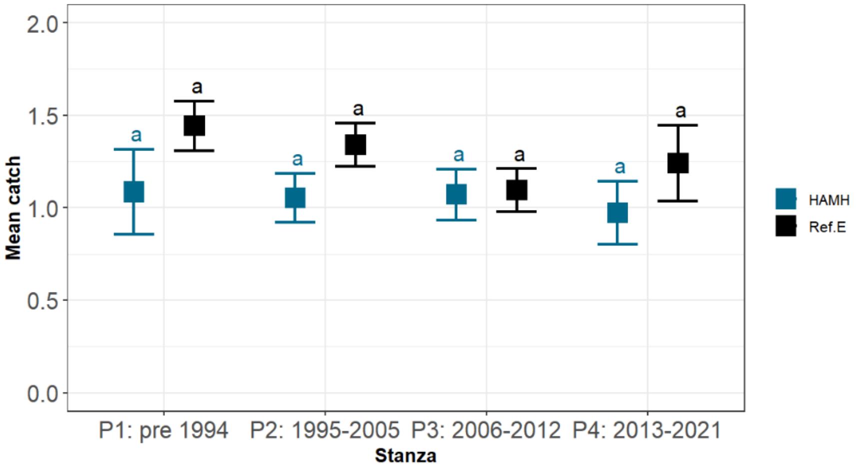

Figure 3. *Temporal changes in modelled mean ± SE Northern Pike from boat electrofishing surveys within the Hamilton Harbour AOC and east regional reference areas (Ref.E). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

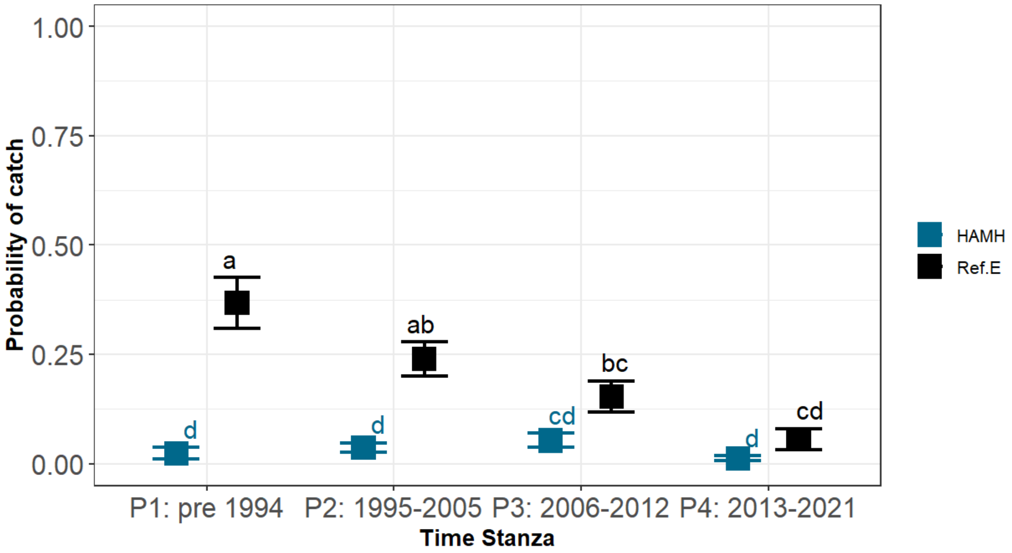

Figure 4. *Temporal changes in modelled mean ± SE Northern Pike probability of capture from boat electrofishing surveys within the Hamilton Harbour AOC and east regional reference areas (Ref.E). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY STATUS OF WALLEYE

Key messages

Recent Walleye stocking efforts have created successful angling opportunities and re-establishing an adult population for this species in Hamilton Harbour. However, there has been limited evidence for any natural recruitment indicating that conditions may not be suitable for egg and/or larval survival that would sustain a population. Telemetry tracking of stocked individuals revealed that most of the tagged Walleye migrated out of the harbour during the summer and early fall but returned in the late fall and early winter. The population size in the harbour is currently unknown, however, encounters are relatively common.

Current catch /regional reference /temporal trends

Surviving stocked Walleye numbers increased in electrofishing catches at Hamilton Harbour between P1 and P4. Prior to stocking in 2012 (P1-P3), Walleye were captured infrequently in the harbour and individuals captured may have been the result of previous stocking efforts that occurred in the 1990s (Section FP-2B; Bowlby et al. 2009). In P4, Walleye were stocked in 2012, 2013, 2014, 2015, 2016, and 2018 and were first detected in trap net surveys in 2014 (age 2 fish). Walleye captured in trap net surveys in P4 indicated the most successful stocking events occurred in 2012, 2016, and 2018, which were the years with the largest stocking events of summer fingerlings (Appendix D).

The catch of Walleye in electrofishing surveys remained low (< 0.5/transect) in P4 but has increased with each stocking event. In P4, Walleye were captured across all harbour zones and were most abundant in the west zone of the harbour (Figure 5). At East-Ref, Walleye catch declined following P1 (2.63 per transect), and the catch was lower (<1.0/transect) in subsequent time stanzas. No Walleye were captured at West-Ref. In trap nets, Walleye catch increased between P3 and P4 (0.42 vs. 3.56 CPUE) following stocking in the Hamilton Harbour AOC but declined at East-Ref between P3 and P4 (3.05 v. 2.27 CPUE), similar to electrofishing trends.

Acoustically tagged adult Walleye (N=37) were tracked over five years and demonstrated both resident and migratory behaviour, where a large number of individuals moved out of the harbour (N=27); this pattern was repeated across multiple years (Brooks et al. 2019; Larocque et al. 2024). During winter, Walleye had a greater residency to the north shore, west, and central basin at deeper waters (~11 m) and moved into shallower waters (~2.5-4.5 m) across the harbour in the spring, presumably to spawn. Resident Walleye moved towards the east zone of the harbour at shallower depths (~2.5-4.5 m) during the summer and re-dispersed across the harbour by fall at deeper depths (~7 m; Larocque et al. 2024). No Walleye entered Cootes Paradise or were detected attempting to access other riverine areas (Larocque et al. 2024).

Results gathered here indicate that stocking efforts (~4.5 million life stage from 2012-2022; see Appendix D) within the Hamilton Harbour AOC have been successful at establishing a new population of adult individuals, albeit the status of natural recruitment is currently unknown. While adult Walleye have been documented spawning at multiple locations in Hamilton Harbour during four consecutive spring spawning surveys (2016-2019) and fertilized eggs have been found (J. Midwood, unpublished data), there has been limited and unconfirmed evidence of natural recruitment in electrofishing or trap net surveys. Both trap net and electrofishing data from the Hamilton Harbour AOC indicated that Walleye from stocking have increased in the catch since the time of stocking, while catch at East-Ref has declined. Walleye have been shown to display both resident and migratory movement behaviors in Hamilton Harbour (Brooks et al. 2019; Larocque et al. 2024) and the Bay of Quinte (Bowlby and Hoyle 2011; Hoyle et al. 2017; Elliott et al. 2022) and despite greater capture efficacy in trap nets compared to electrofishing (Boston et al. 2016), the timing of trap net surveys (early August) may only represent the resident portion of the Walleye population being sampled in both areas. Movement throughout Hamilton Harbour appears to be seasonally dependent and is likely related to thermal-optical habitat availability (Lester et al. 2004), dissolved oxygen requirements of Walleye (Brooks et al. 2022), and availability of prey fish species (Bowlby and Hoyle 2011; Hoyle et al. 2017).

A recently completed IBI targeting report found that further addition of Walleye to the Harbour AOC alone would not be sufficient to improve IBI values to reach the delisting targets (Gardner Costa et al. 2022). A shift in the fish community as a whole is required to reach delisting targets, and therefore, efforts to increase the abundance of a variety of species may be warranted. An increasing Walleye population maintained by stocking in Hamilton Harbour could indirectly affect other native species through competition with other top predators or predation on native and non-native fishes. Research is required to determine the effects of stocked Walleye on fish communities in Hamilton Harbour. Therefore, future additions of Walleye to the system should be monitored closely and research should be undertaken to explore their potential effects on native species and other top predators in the Hamilton Harbour AOC.

Recommendations

DFO has completed preliminary Walleye larval fish and egg surveys, finding limited evidence of fertilized eggs and no larval fishes. Further effort will be required, and it is recommended that efforts continue to determine the status of natural Walleye recruitment throughout Hamilton Harbour. The establishment of stocked summer fingerlings would suggest challenges to recruitment for early life stages. Assessing the overall availability of habitat for Walleye, including spawning habitat, identified through spawning surveys or acoustic telemetry, will inform future enhancement of these areas to facilitate natural recruitment into the system. The future of Walleye stocking would be best guided by an understanding of the current adult population from both stocked and wild recruitment, the overall carrying capacity of the harbour to support Walleye, and the goals to improve the proportion of piscivores in the fish community. Further investigation into stable isotope analysis and stomach content analysis may provide insight into the prey base of Hamilton Harbour Walleye and how the trophic structure of the fish community may have changed post-stocking.

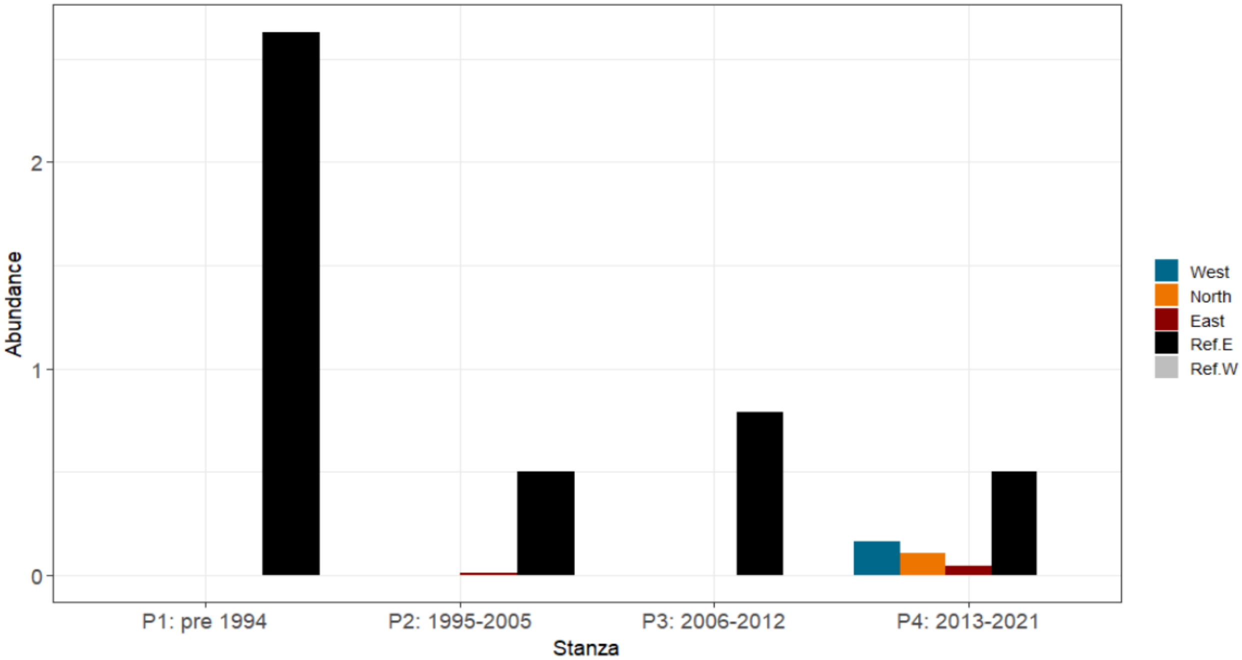

Figure 5. *Temporal changes in mean Walleye abundance from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east) and east (Ref.E) and west (Ref.W) regional reference areas. There was insufficient capture of Walleye to support statistical analysis.* Therefore, the *values presented are based on mean catch per transect across electrofishing surveys.*

SUMMARY STATUS OF LARGEMOUTH BASS

Key messages

The catch of Largemouth Bass in Hamilton Harbour has not changed over time despite indications of improvement within the time series. However, the probability of catching a Largemouth Bass over time has increased in the west zone of the harbour compared to the north and east zones since the 1990s. Trap net surveys suggest that the catch of Largemouth Bass in Hamilton is low compared to East-Ref embayments. Largemouth Bass are more abundant in electrofishing catches relative to other top predators in the harbour, but the population is likely limited by habitat availability for all life stages of this species.

Current catch /regional reference/temporal trends

Electrofishing models indicated no significant change in Largemouth Bass catch between P1 and P4 in the Hamilton Harbour AOC. Within the time series, Largemouth Bass catch increased significantly between P1 and P2, followed by significant declines in P3 and P4 driven by lower catches in the west zone (Figure 6). Similarly, at East-Ref locations, there was no change in Largemouth Bass catch between P1 and P4, but in contrast to the Hamilton Harbour AOC, catch was highest during P3 before declining significantly in P4 (Figure 6). The mean catch of Largemouth Bass was similar in P3 and P4 for the overall Hamilton Harbour AOC and at both East-Ref and West-Ref locations, indicating no differences among these areas (Figure 6). However, the probability of catching bass was significantly greater from P2-P4 at the west zone of the harbour and East-Ref embayments than at the north and east zones of the Hamilton Harbour AOC (Figure 7). In trap nets, the CPUE of Largemouth Bass was similar in both P3 and P4 at the Hamilton Harbour AOC (mean CPUE of 0.25 and 0.26, respectively) and at unimpaired East-Ref embayments (3.97 and 4.01, respectively) but, unlike electrofishing catches, the CPUE at reference embayments was orders of magnitude higher. The number of Largemouth Bass caught at the Cootes Paradise Fishway has declined 5-10-fold over the last three years (Appendix G).

Acoustically tagged Largemouth Bass (N = 25) were generally resident year-round within the Hamilton Harbour AOC, with only two fish detected leaving the harbour in more than four years of continuous tracking. The spatial distribution of Largemouth Bass within the AOC aligned with observed electrofishing-based catch and encounter rates, with bass detected primarily in the west zone of the harbour year-round. Tagged individuals were found in slightly deeper waters (~1-2 m) during the fall and winter and in shallower waters (~0.5 m) around Macassa Bay in the spring and summer. During the spawning window (May 1-July 15), Largemouth Bass were also detected to a lesser extent along the north shore and in Cootes Paradise. A recent, harbour-wide mark-recapture study (2017-2021) on Largemouth Bass (N = 241) estimated a population of

~2000 adults (Larocque et al. 2023), which is not an insignificant population relative to other top predator species (e.g., Northern Pike population estimates from the same study) estimates. This population estimate can be used as a baseline for future comparisons and/or be linked to estimates of habitat supply that should be developed to determine whether potential densities align with observed catch rates.

Collectively, results indicate that while there is a larger population of Largemouth Bass relative to other top predators, they are spatially limited and primarily found in the shallow, littoral waters of the west zone of the Hamilton Harbour AOC. Since initial listing as an AOC, there was a temporary increase in Largemouth Bass capture in P2 driven by an increase at the west end; however, while values in the west end have declined in P4, they remain comparable to those observed at East-Ref and West-Ref. In contrast, the probability of catching a bass at the north and east zones of the harbour are now significantly lower than at East-Ref embayments.

Both electrofishing and trap net monitoring programs provided vital information about the existing Largemouth Bass population in the Hamilton Harbour AOC. The differences in Largemouth Bass catches between electrofishing and trap net datasets are likely due to several factors, including differences in sampling locations within the harbour, gear biases (passive vs. active), differences in reference embayments (east vs. west), and habitat supply for this species in the Hamilton Harbour AOC. Unequal spatial distribution of Largemouth Bass (and related catch rates) likely contributed to differences between electrofishing and trap netting results in P3 and P4 since trap net values are for the whole AOC and lower catch rates in the east and north zones may act to reduce overall estimates. The noted use of shallow areas, like Macassa Bay, and the known site fidelity of this species (Larocque et al. 2023), suggests that some Largemouth Bass habitats may not be as accessible with trap nets compared to boat electrofishing, and this could further reduce catch estimates. The datasets share two sheltered reference embayments at the eastern end of Lake Ontario, but the trap net dataset has an additional three sites at the east end and none in the more heavily developed western end outside of Toronto Harbour. Observed spatial patterns also make apparent that habitat supply for Largemouth Bass is not equally available in all zones of the harbour. Limited availability of suitable warmwater habitat at the east end of the harbour has been noted previously (Maynard et al. 2022), but a more comprehensive assessment of habitat supply is warranted. However, the assessment of fish populations in the Hamilton Harbour AOC has focused on whole-harbour trends, and trap net results show that the CPUE of Largemouth Bass is well below values observed in embayments in eastern Lake Ontario (East-Ref).

Recommendations

Species-specific recommendations for Largemouth Bass include surveying bass spawning nests across harbour zones to look for evidence of disruption to recruitment, which may indicate the extent to which spawning habitat is limited. An unpublished spawning nest assessment was conducted by DFO in the 1990s and could be used as a baseline for future assessments of this survey. This species experiences heavy angling pressure (shore-based) at the west/south-west end of the harbour where they are most abundant. Largemouth Bass were reported within the top 10 fish on the Hamilton Harbour consumption report (HH RAP Fish Consumption Report); further creel survey data may help to provide further insight.

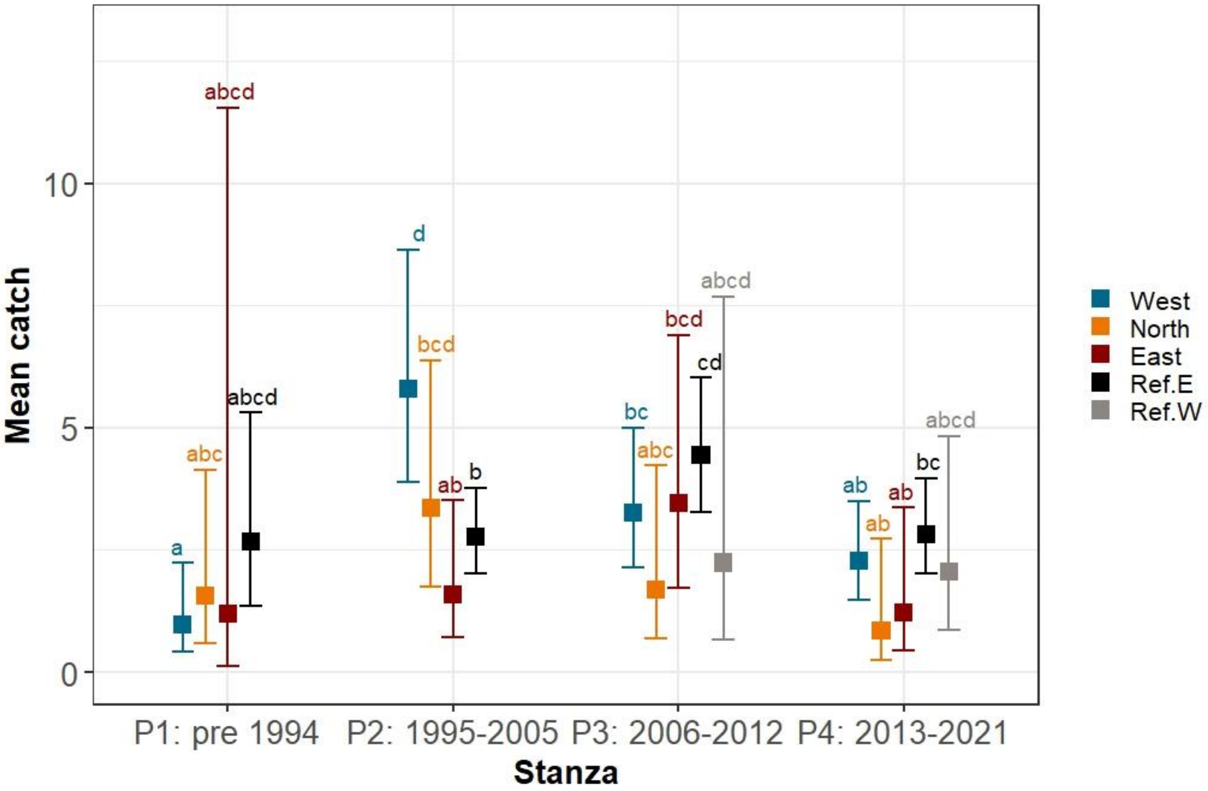

Figure 6. *Temporal changes in modelled mean ± SE Largemouth Bass catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

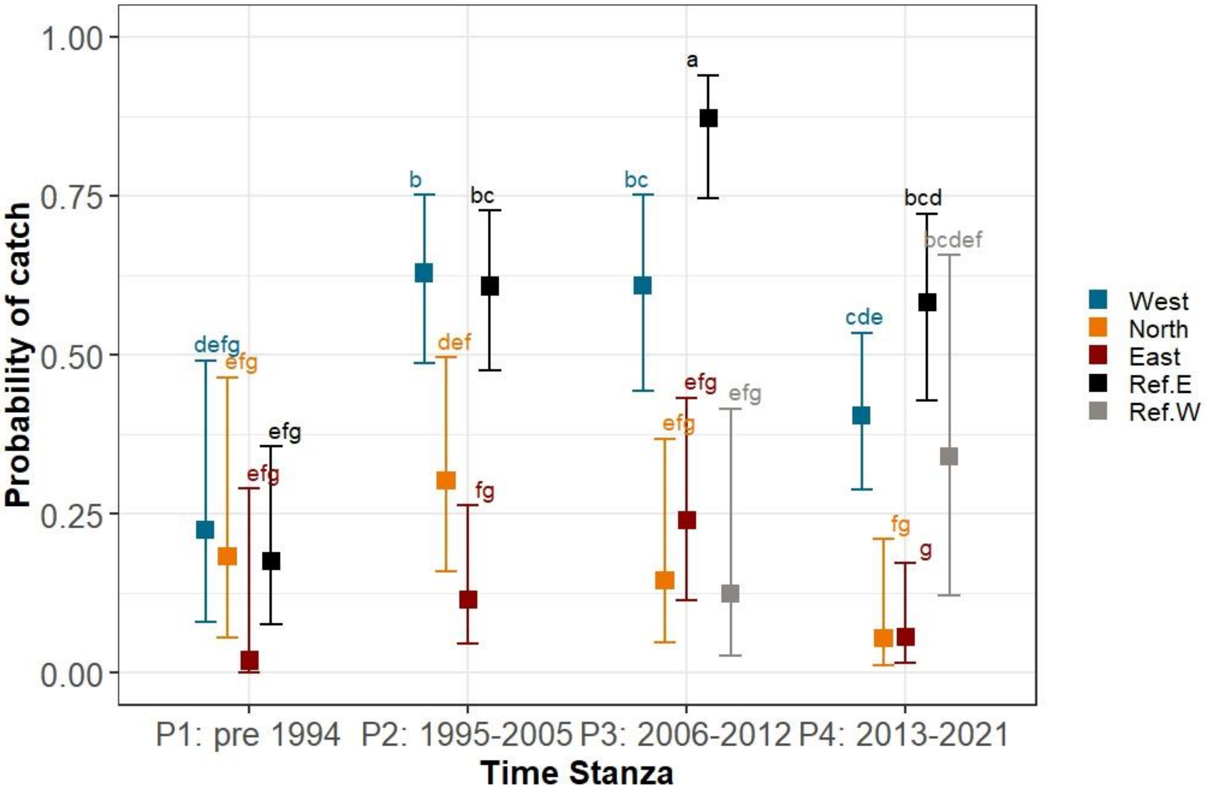

Figure 7. *Temporal changes in modelled Largemouth Bass catchability from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east) east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY STATUS OF SMALLMOUTH BASS

Key message

Smallmouth Bass are rarely captured in electrofishing or trap net surveys in Hamilton Harbour and acoustic telemetry found that tagged individuals were resident to the harbour and spatially limited to the west end. Smallmouth Bass have declined at reference locations in Lake Ontario since the early 1990s.

Current catch /regional reference /temporal trends

Smallmouth Bass were rarely captured (<1.0/transect) in Hamilton Harbour during routine electrofishing surveys. The mean catch declined between 1988 and 2021 as none were captured at any harbour electrofishing transects in P4 (Figure 8). At East-Ref, catch was also low (<1.0/transect) and declined between P1 (0.79/transect) and P4 (0.02/transect; Figure 8). At West-Ref, Smallmouth Bass were only captured during P3 (Figure 8). In trap net surveys, the CPUE of Smallmouth Bass was also low (<1.0) and declined between P3 and P4 in Hamilton Harbour (0.12 vs. 0.06) and East-Ref (0.95 vs. 0.33).

Between 2017 and 2021, 14 Smallmouth Bass were captured and tagged in Hamilton Harbour as part of a mark-recapture population estimate study, with recaptures yielding an estimate of approximately 50 adult individuals (Larocque et al. 2023). In addition, the movements of six acoustically tagged Smallmouth Bass were tracked between June 2017 and April 2020; none of the tagged fish left the harbour suggesting that the population is localized. Smallmouth Bass were found to reside year-round near Piers 5-7 close to their tagging locations; from May to September, bass were detected on average at depths of < 0.5 m but moved to deeper waters (5-7 m) in the autumn and winter.

The results suggest small, local population exists in Hamilton Harbour primarily in the west zone. In eastern Lake Ontario, Smallmouth Bass populations have been monitored through index gill netting programs since 1976, with greater capture rates using gill nets than either electrofishing or trap netting. In gill net surveys, Smallmouth Bass abundance peaked in the 1980s (P1 and earlier) and reached an all-time low in 2001 (3.0 CPUE; Hoyle 2000; Hoyle and Yuille 2016). Our results using littoral sampling gear (i.e., electrofishing and trap nets) show similar trends with Smallmouth Bass having low abundance at sheltered Lake Ontario embayments compared to gill net surveys, which found that abundance peaked in P1, declined in P2, increased in P3 slightly, and declined again in P4. Other alternate data sources confirm that Smallmouth Bass populations are declining in Lake Ontario (Ontario Ministry of Natural Resources and Forestry (OMNRF) 2020).

Habitat supply and water quality may be limiting the abundance and spatial distribution of Smallmouth Bass in Hamilton Harbour. Smallmouth Bass are considered moderately intolerant to turbidity and the size of a population can be stunted under turbid conditions (Trebitz et al. 2007). Sedimentation of rocky substrates in areas of the harbour subject to riverine inputs (Grindstone, Indian, and Red Hill Creeks) could be inhibiting spawning opportunities and ultimately recruitment success. Although the growth and condition of Smallmouth Bass in Lake Ontario increased following Round Goby establishment (P3) and an increase in the catch was noted in other Lake Ontario monitoring surveys in P3 (Reyjol et al. 2010; Hoyle and Yuille 2016; Ontario Ministry of Natural Resources and Forestry 2020), gobies may also negatively impact the species through egg and larval fish predation as they utilize overlapping habitats (Leblanc et al. 2020).

Recommendations

Recommendations for Smallmouth Bass include harbour-wide spring nest surveys to assess spawning numbers and available spawning habitats. This could also be guided by preliminary acoustic telemetry data. This species was recently listed in the top 5 species on the Hamilton Harbour consumption report. More detailed creel surveys may help us better understand the effects of angling pressure on this species. Furthermore, given the small population estimate and low catch of Smallmouth Bass confirmed by multiple gear types, a reduction or cessation of lethal scientific sampling by agencies should be considered to alleviate any additional mortality pressure.

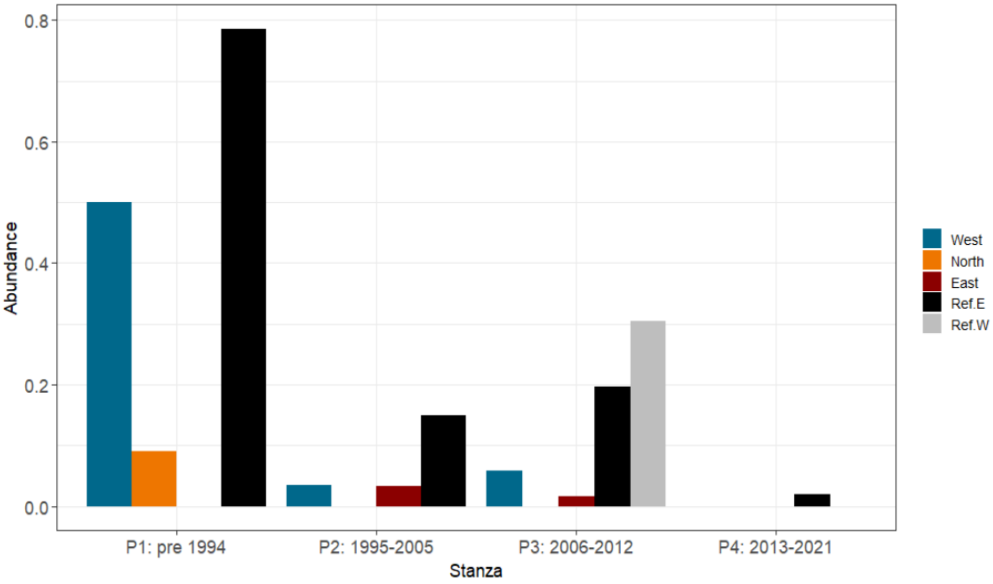

Figure 8. *Temporal changes in Smallmouth Bass catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east) and east (Ref.E) and west (Ref.W) regional reference areas. There was insufficient capture of Smallmouth Bass to support statistical analysis. Therefore, values presented are based on mean catch per transect across electrofishing surveys.*

SUMMARY STATUS OF OTHER SUNFISHES (CENTRARCHIDAE; PUMPKINSEED, BLUEGILL, BLACK CRAPPIE, AND ROCK BASS)

Key message

The overall catch of other species belonging to the family Centrarchidae in Hamilton Harbour has declined since the initial listing. The same trend was not seen at East-Ref embayments. Catch of Centrarchidae was higher at East-Ref embayments for all four species.

Current catch /regional reference /temporal trends

Centrarchid sunfishes declined significantly in electrofishing catches between P1 and P4 at Hamilton Harbour, whereas, across the East-Ref embayments, they significantly increased (Figure 9). In P1, the CPUE was similar at all sites, but between P1 and P2, the CPUE increased significantly at East-Ref embayments and Hamilton Harbour (>50%; Figure 9), driven by higher catches in the west zone of Pumpkinseed (*Lepomis gibbosus*) specifically (Figure 10 and Figure 11). The increase in the catch during P2 was concurrent with the expansion of submerged macrophytes in embayments across Lake Ontario (Leisti et al. 2012). Catch declined between P2 and P3 at both Hamilton and the East-Ref (Figure 9); P4 noted further declines in the sunfish catch in the Hamilton Harbour AOC but catch at East-Ref embayments remained stable. The mean catch of centrarchids at West-Ref embayments showed no change between P3 and P4, similar to Hamilton Harbour AOC, and was significantly lower than mean catches at East-Ref embayments (Appendix B). The probability of catching a centrarchid significantly declined between P1 and P4 across the Hamilton Harbour AOC but remained similar in East-Ref areas; it was also significantly higher in the East-Ref areas across all four-time stanzas (Appendix B).

Similar to electrofishing catches, the CPUE of sunfishes in trap net surveys at sheltered reference embayments in P3 and P4, were orders of magnitude higher for most centrarchid species [e.g., Black Crappie (*Pomoxis nigromaculatus*), Bluegill (*Lepomis macrochirus*), and Pumpkinseed] compared to Hamilton Harbour. In trap nets, the CPUE of Black Crappie and Pumpkinseed declined between P3 and P4 but the CPUE of Bluegill and Rock Bass (*Ambloplites rupestris*) increased between the two time stanzas (Table 12 in FP-2B). At East-Ref embayments, a similar decline in the CPUE between P3 and P4 was also noted for Black Crappie and Pumpkinseed while Rock Bass CPUE increased. Both electrofishing and trap net data showed a decline in Pumpkinseed over time but in contrast to the electrofishing data, trap net CPUE of Bluegill increased between the latter two time stanzas.

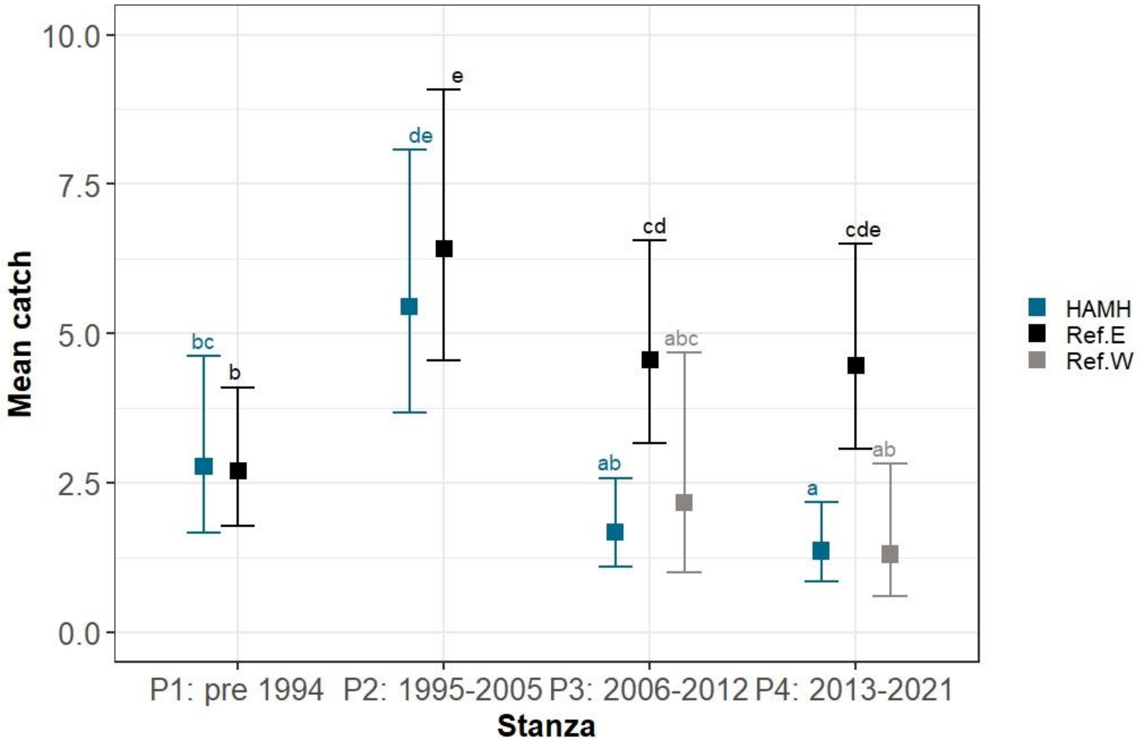

Figure 9. *Temporal changes in modelled combined sunfish species (Pumpkinseed, Bluegill, Black Crappie, and Rock Bass) catch from boat electrofishing surveys within the Hamilton Harbour AOC, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

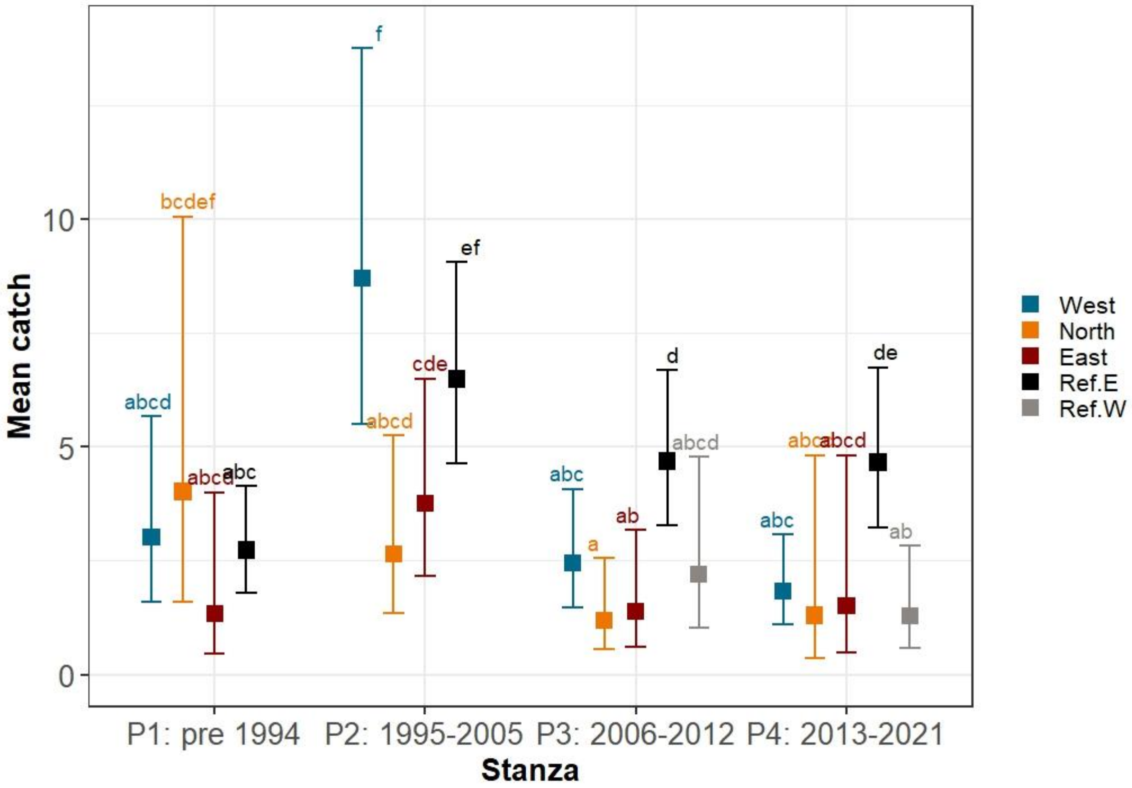

Figure 10. *Temporal changes in modelled combined sunfish species (Pumpkinseed, Bluegill, Black Crappie, and Rock Bass) catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY STATUS OF PUMPKINSEED AND BLUEGILL

Key message

A significant decline in Hamilton Harbour Pumpkinseed catch occurred from P2 to P3 and remained lower than P1 levels in both P3 and P4 while the Bluegill catch remained unchanged among time stanzas. However, both species declined in catchability between the third and fourth time stanzas indicating that recent changes in conditions in the harbour or other population-level effects are driving declines. Pumpkinseed are known to feed on molluscs and are less efficient at eating dreissenid mussels than Round Goby, therefore, foraging overlap could be a source of competition between the two species. Such competition between Round Goby and Bluegill is less likely given the differences in foraging strategy between Bluegill and Pumpkinseed (Andraso 2005).

Current catch /regional reference /temporal trends

To further understand centrarchid trends in Hamilton harbour among the time stanzas, the two most abundant sunfish, Bluegill and Pumpkinseed, were examined in greater detail. There were no changes in Bluegill catch between P1 and P4 at Hamilton Harbour or East-Ref embayments (Figure 12). The mean catch of Bluegill was ≤ 2.5/transect at Hamilton Harbour AOC in all time stanzas, but the catch at East-Ref embayments more than doubled between P1 to P2 (Figure 12). The mean catch of Bluegill was significantly higher at East-Ref embayments than at Hamilton Harbour overall from P2 to P4. (Figure 12). While the catch of Bluegill in Hamilton Harbour did not change over time, the probability of catching a Bluegill was significantly higher in P2 and P3, before declining in P4 back to P1 levels (Figure 13).

In contrast, Pumpkinseed catches in the Hamilton Harbour AOC were significantly different between P1 and P4 (Figure 11). A significant increase in Pumpkinseed catches at the Hamilton Harbour AOC and East-Ref embayments occurred between P1 and P2 followed by a significant decline between P2 and P3, which remained unchanged in P4 and lower than P1 levels (Figure 11). Catch was similar between the East-Ref embayments and Hamilton Harbour during P1 and P2, but the mean catch in the harbour was significantly lower during P3 and P4 than at East-Ref embayments (Figure 11). The catch of Pumpkinseed at West-Ref was similar to that of the Hamilton Harbour AOC during P3 and P4 and similar to East-Ref during P3 but significantly lower in P4 (Appendix B). The probability of catching a Pumpkinseed declined significantly from P2 to P4 in the harbour (Figure 14).

Recommendations

Centrarchids residing in the west end of the harbour have likely been impacted by water quality and increased eutrophication issues in the most recent time stanza affecting habitat and food resources. A comprehensive benthic invertebrate survey of the harbour would help with future assessments to better understand food availability for a number of species belonging to this family. Investigating recruitment success and condition of habitat for various life stages also seems pertinent with observed declines in several species. Continued monitoring of catch following upgrades to wastewater treatment facilities is recommended. Furthermore, macrophyte abundance and diversity can be highly variable on an annual basis due to changes in water levels and water clarity; conducting routine macrophyte surveys would provide further insight into varying Centrarchidae abundance throughout the harbour. It is important to note that improvements in Centrarchid populations, both in terms of total catch and richness, are key to meeting other Hamilton Harbour AOC fish population objectives (see Section FP-2A).

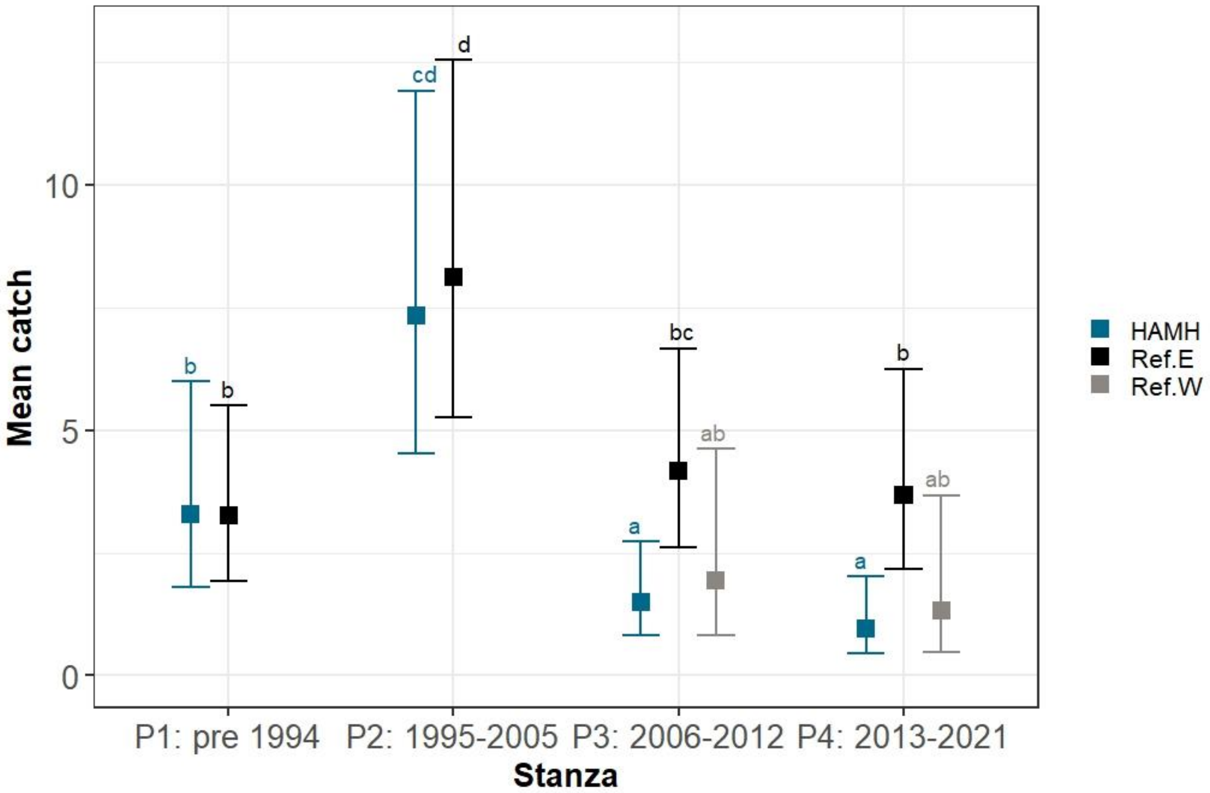

Figure 11. *Temporal changes in modelled Pumpkinseed catch from boat electrofishing surveys within the Hamilton Harbour AOC, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

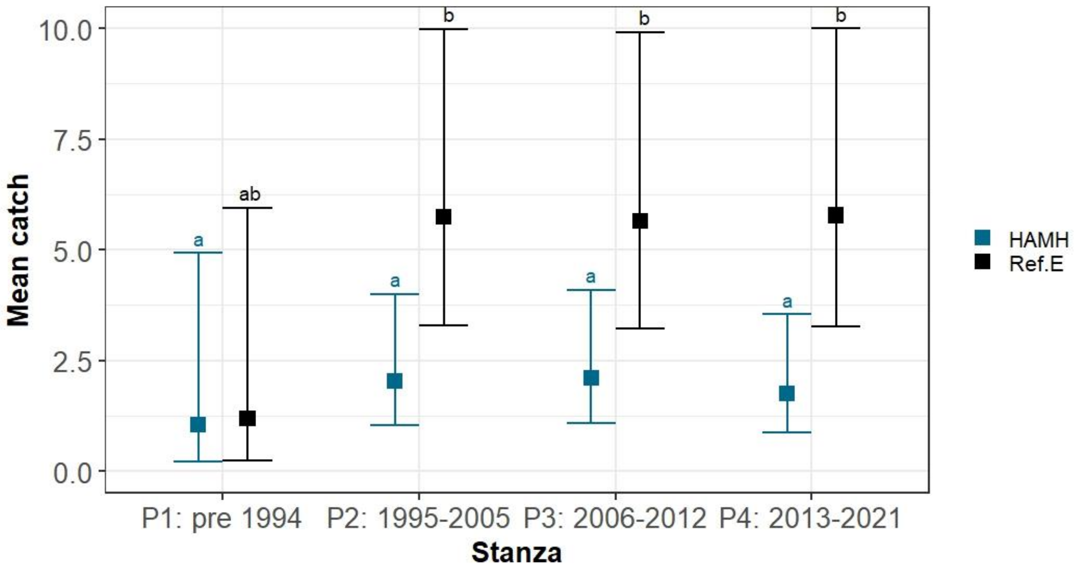

Figure 12. *Temporal changes in modelled Bluegill catch from boat electrofishing surveys within the Hamilton Harbour AOC and east regional reference areas (Ref.E). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

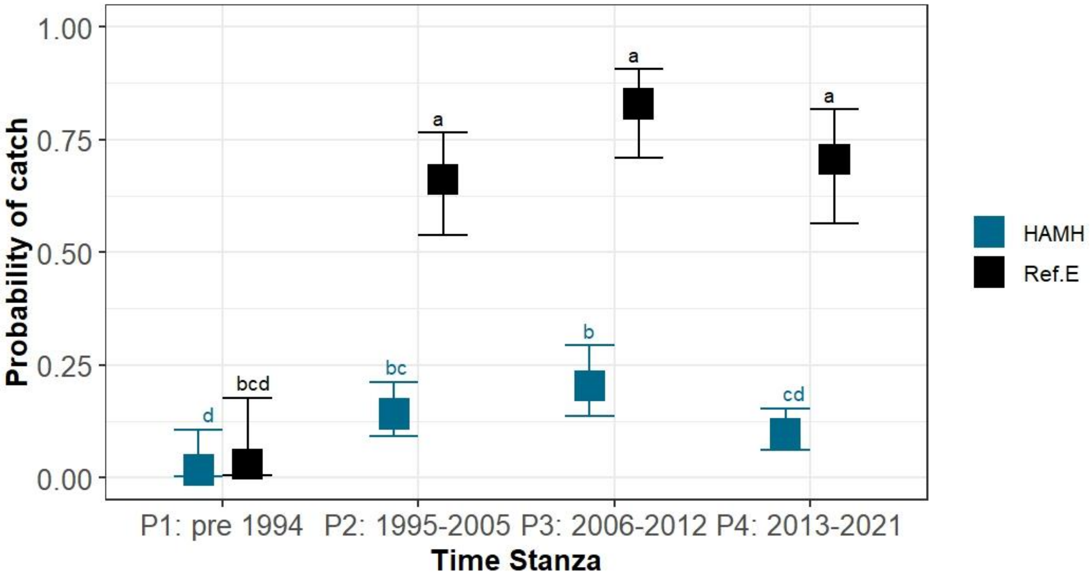

Figure 13. *Temporal changes in modelled Bluegill catchability from boat electrofishing surveys within the Hamilton Harbour AOC and east regional reference areas (Ref.E). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

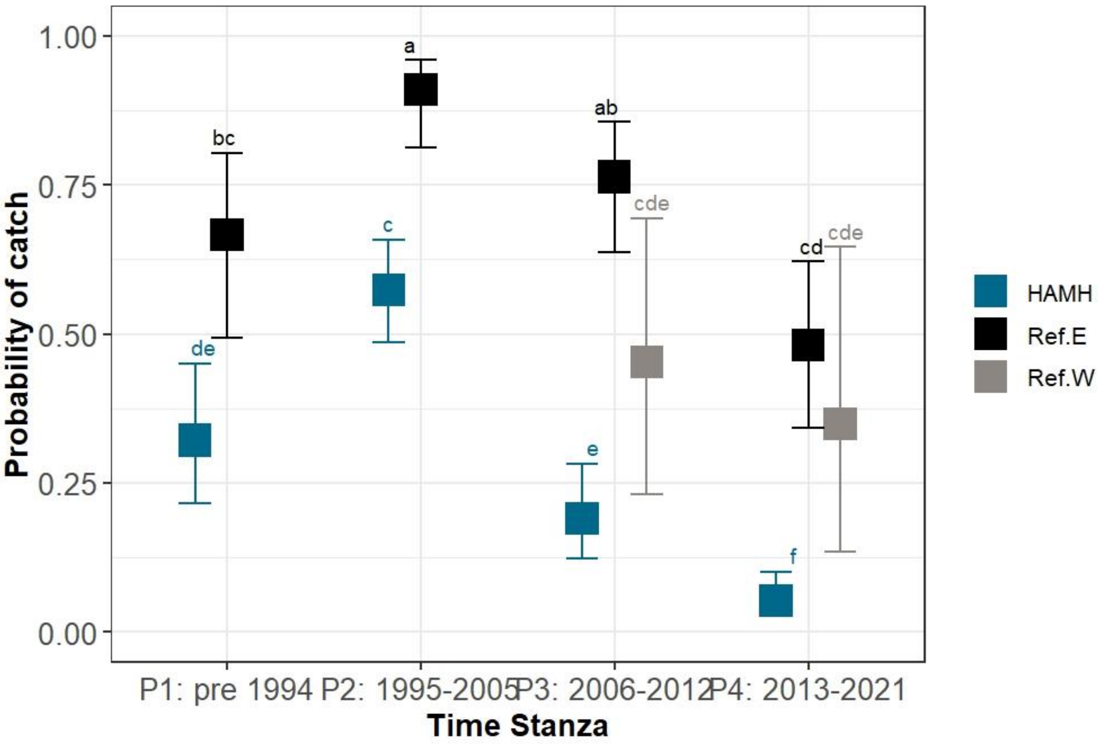

Figure 14. *Temporal changes in modelled Pumpkinseed catchability from boat electrofishing surveys within the Hamilton Harbour AOC, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY STATUS OF YELLOW PERCH

Key message

There has been no change in the catch of Yellow Perch in Hamilton Harbour over time and the mean catch was lower in the harbour than at East-Ref in electrofishing surveys throughout the time series. There was similarly no change from P3 to P4 in Yellow Perch catch at the West-Ref.

Current catch /regional reference /temporal trends

In Hamilton Harbour, electrofishing models indicated no significant changes in Yellow Perch catch between P1 and P4, but the catch was significantly higher in P2 and P3 than in P4 (Figure 15), indicating a change within the time series. At individual harbour zones, the only significant difference in the time series occurred at the west zone with a decline in catch from P2 to P4 (Appendix B). Yellow Perch catches were significantly higher at East-Ref in all time stanzas; however, like Hamilton Harbour, there was a significant decline in the CPUE between P3 and P4 (Figure 15).

The probability of capturing a Yellow Perch during electrofishing between P1 and P4 remained low in Hamilton Harbour and high at East-Ref (Figure 16). Within the time series, the probability of catching a Yellow Perch in Hamilton was significantly higher during P2 and P3 than during P1 and P4, which was consistent with catch models (Figures 15 and 16). At the East-Ref embayments, the probability of capture was similar in all time stanzas (Figure 16). This result differed from electrofishing catch models, where we noted a significant decline in abundance in P4 from P2 at reference embayments, indicating that the probability of capturing a Yellow Perch did not change but the overall catch declined. At West-Ref, there was no change in mean catch between P3 and P4. In P4, the catch at West-Ref was higher than at the east zone of Hamilton Harbour but more similar to catches from the west and north zones in the same time period (Figure 17).

NSCIN trap net surveys indicated that Yellow Perch were less abundant in Hamilton Harbour compared to East-Ref embayments in P3 and P4, consistent with the trend from electrofishing models. Yellow Perch catch declined in trap nets across the harbour between P3 and P4 (1.29 vs. 0.58), similar to trends seen in electrofishing data; however, there was no change at East-Ref embayments between the two latter time stanzas (2.42 vs. 2.3), which differed from electrofishing model results.

In 2016, 10 adult Yellow Perch (175-295 mm fork length) were captured in the west end of Hamilton Harbour, fitted with acoustic transmitters, and tracked for 10 months (Larocque et al. 2024). All tagged individuals remained within Hamilton Harbour and were primarily detected in the western area of the harbour, close to their tagging location but demonstrated seasonal movements throughout the harbour. During the spring, tagged individuals were detected in the west end of the harbour near Macassa Bay, Bayfront Park, Cootes Paradise, Grindstone Creek, and along the north shore. During the summer, tagged perch were detected primarily in the west end close to vegetated areas by Macassa Bay and Bayfront Park. In autumn, Yellow Perch moved around the harbour and were detected along the south shore of the central basin and in the east end before moving back towards the west end for the winter where they were detected in deeper, offshore waters. Although acoustic telemetry indicated that Yellow Perch were frequently associated with the west end of Hamilton Harbour, these results may be biased because all individuals were tagged in the west. This is further reinforced through electrofishing models which did not find any differences in catch across the three harbour zones in P3 and P4 (Figure 17; although there was variation in the probability of capture among zones during P2; Figure 16). Previous studies have indicated that Yellow Perch have a limited home range but do demonstrate some larger seasonal movements linked to life history traits like spawning, overwintering, and foraging (0.54-2.20 ha; Fish and Savitz 1983). In general, the west end of the harbour has more suitable habitat for perch including shallow water, and submerged aquatic vegetation (Fish and Savitz 1983; Lane et al. 1996; Scott and Crossman 1998; Matley et al. 2022), but further work is needed to confirm habitat supply across the harbour.

Trends in the catches between P3 and P4 at East-Ref embayments were different between electrofishing and trap net data, which could be attributed to gear biases that select for different life stages (larval and juvenile vs. adult) of this species, timing of surveys, and locations sampled. Other index netting surveys (i.e., trawling) conducted in the upper Bay of Quinte supported the trend in trap net catches at sheltered embayments; between P3 and P4, the catch of Yellow Perch was similar or increased (e.g., Belleville and Trenton; Ontario Ministry of Natural Resources and Forestry 2022). However, declines in Yellow Perch abundance in P4 were documented in other Lake Ontario surveys (Hoyle and Yuille 2016; Ontario Ministry of Natural Resources and Forestry 2022), in particular, at open coast (e.g., Kingston Basin) and exposed embayment areas (e.g., Toronto Harbour; Midwood et al. 2022). The decline of Yellow Perch at Hamilton Harbour and sheltered reference embayments in electrofishing catches, and the decline in trap net catch at exposed embayments from P3 to P4, may be an indication of a greater lake-wide trend or could be the result of local stressors.

Local stressors that could negatively impact Yellow Perch populations in P4 include predation on YOY and juveniles via top predators and proximity to large piscivorous bird populations (Burnet et al. 2002; Rudstam et al. 2004). In addition, declines in Yellow Perch abundance were documented from 2014 to 2016 at several Lake Ontario locations following two, long consecutive winters and unseasonably cool summers (Honsey et al. 2016).

Recommendations

Specific recommendations for Yellow Perch include the investigation of local stressors on population demographics and habitat availability. Assessing recruitment within Hamilton Harbour may be enlightening as there has been low abundance with no change since the initial listing of the harbour. A decline in Yellow Perch catch across multiple Lake Ontario areas has been noted (Hoyle and Yuille 2016; Ontario Ministry of Natural Resources and Forestry 2022) and should be considered when assessing trends in the Hamilton Harbour population. If more detailed spatial information is required for Yellow Perch, effort should be made to capture and tag fish throughout the Harbour, including the east and north zones.

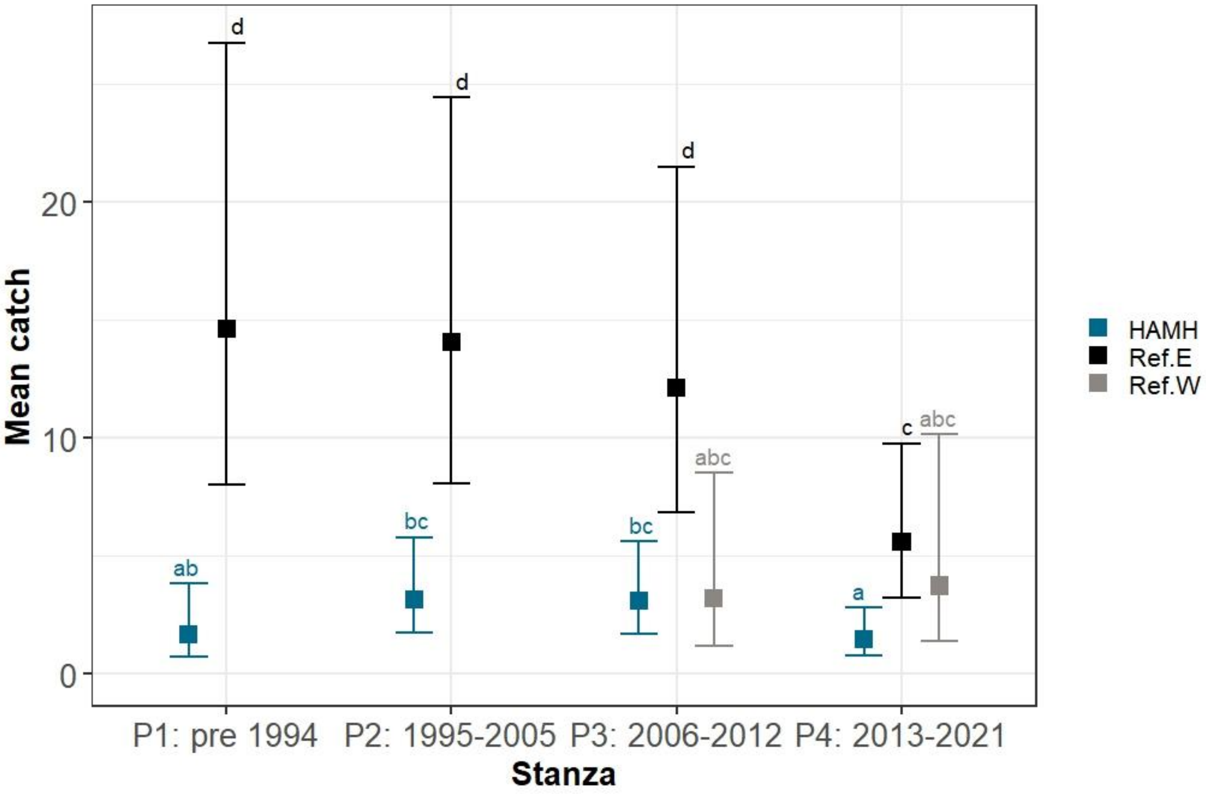

Figure 15. *Temporal changes in modelled mean ± SE Yellow Perch from boat electrofishing surveys within the Hamilton Harbour AOC, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

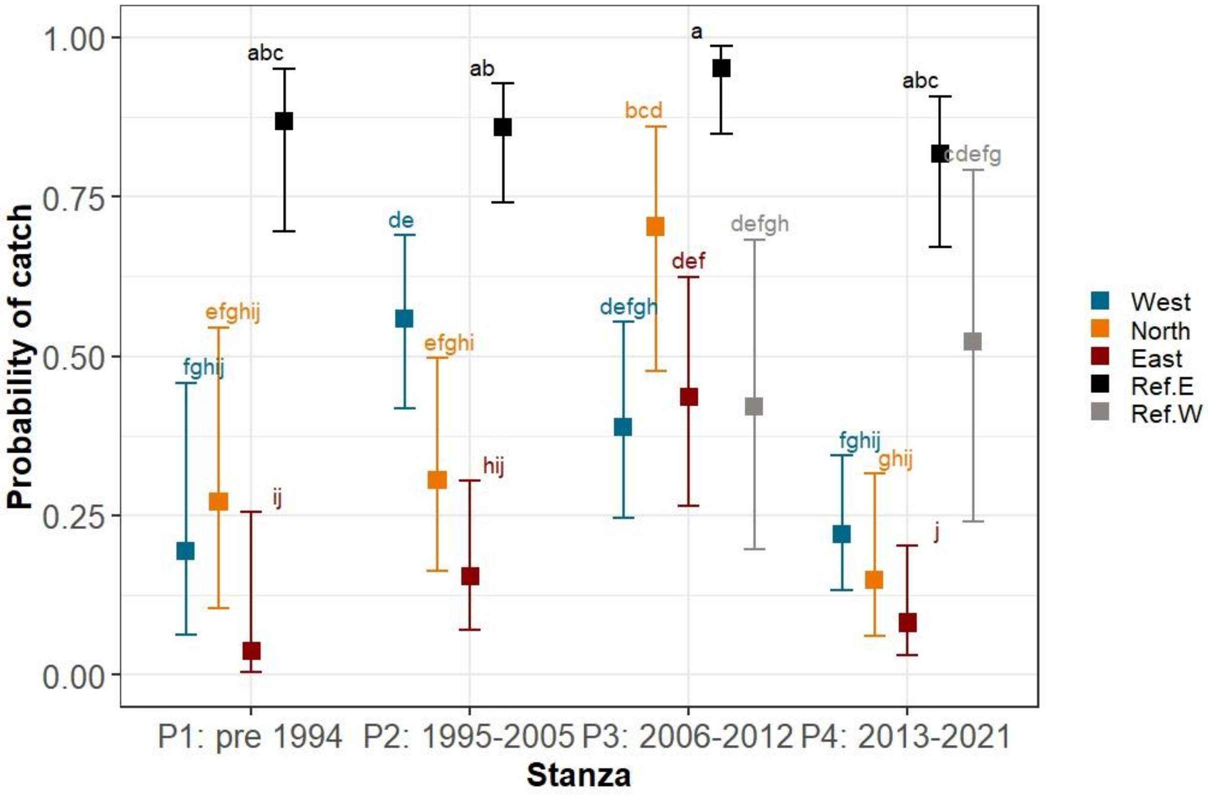

Figure 16. *Temporal changes in modelled Yellow Perch catchability from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

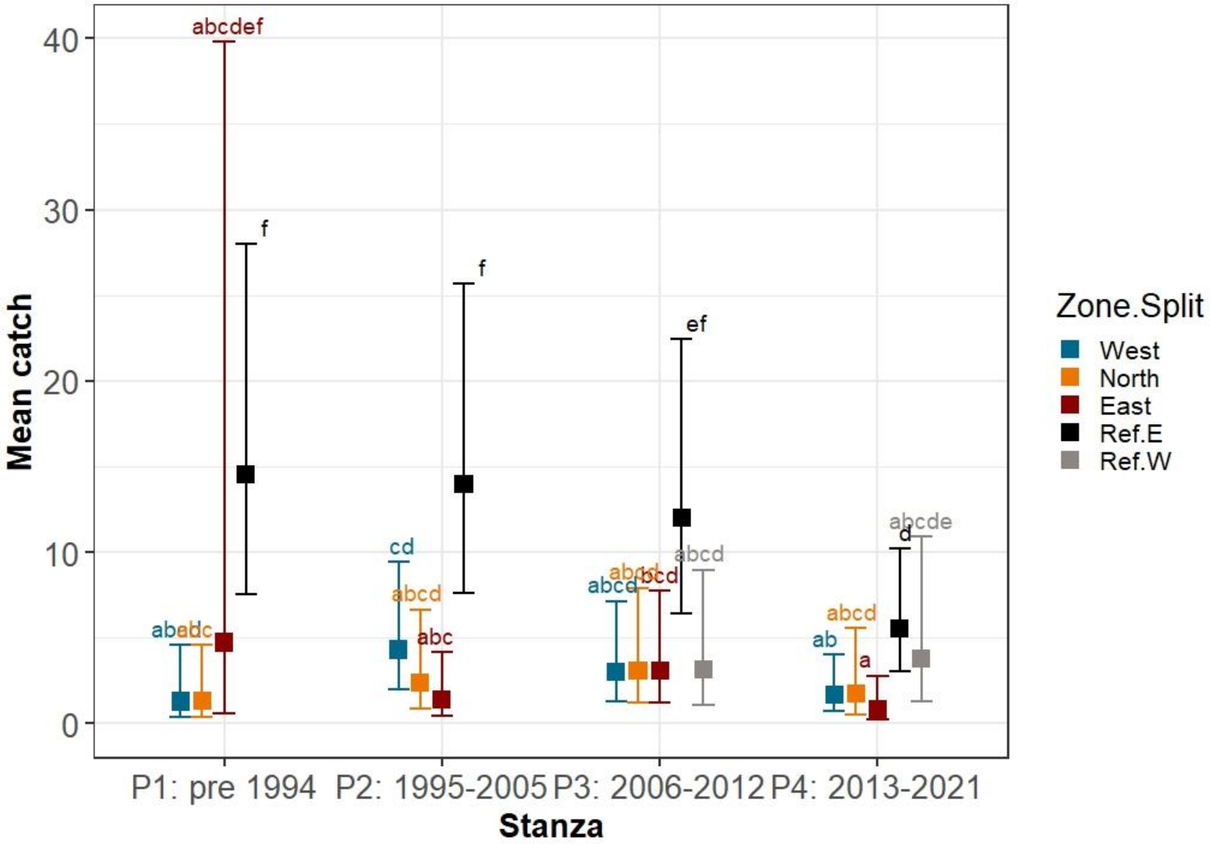

Figure 17. *Temporal changes in modelled Yellow Perch catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional reference (Ref.E), and west regional reference (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY STATUS OF WHITE SUCKER (CATOSTOMIDAE)

Key messages

Catostomidae other than White Sucker were rarely captured in Hamilton Harbour. The mean catch for White Sucker in the harbour overall has declined since the initial listing (P1) but did not vary within harbour zones (Appendix B). The probability of catching White Sucker in the harbour has also declined significantly over time; however, the spawning run of White Sucker at the Cootes Paradise Fishway has not changed and is one of the largest contributors to the catch at the fishway in any given year (1996-2022).

Current catch /regional reference /temporal trends

A significant decline in White Sucker catch from electrofishing data occurred between P1 and P4 across the Hamilton Harbour AOC whereas there was no change at East-Ref embayments (Figure 18). Combined Catostomidae catch from electrofishing surveys was also assessed and trends were found to be the same as White Sucker (both for mean catch and catchability; Appendix B). The probability of capture of White Sucker and other Catostomidae (all harbour zones combined) remained the same from P1 to P3 and declined significantly between P3 and P4 (Figure 19).

In trap nets, Catostomidae other than White Sucker were rarely captured. The catch of White Sucker was on average < 1.0 CPUE in both time stanzas (P3 & P4) despite a slight increase between P3 and P4 (0.27 vs. 0.52), the P4 increase was primarily driven by a mean CPUE of 2.17 in 2014. With the exception of the 2014 catch, the maximum annual CPUE in both of the latter time stanzas was <0.62. In trap net surveys, White Sucker CPUE also declined between P3 and P4 at other sheltered and exposed embayments (including Toronto Harbour AOC; Midwood et al. 2021) as well as at transitional areas sampled in Lake Ontario (see FP-2B section on trap netting IBI).

Adult White Sucker (N=8) were acoustically tagged in Hamilton Harbour and tracked between June 2016 and April 2020 (Larocque at al. 2024). Most of the tagged individuals (88%) left the harbour during the summer and moved into deeper Lake Ontario waters (~10m; max of 32m) but returned to the harbour during the fall and winter (Larocque et al. 2024). Although most of the tagged White Sucker remained close to the harbour (within ~5km), a few individuals made larger movements (~40-50 km) and were detected at other locations near Jordan Harbour, Bronte Creek, Credit River, and Oakville Creek (Larocque et al. 2024). During wintern when the majority of White Sucker resided within the harbour, they were predominantly located in the west zone, slightly offshore using depths of ~3.5 m (Larocque et al. 2024). During the spring spawning window (April 1st – May 31st), White Sucker were found using depths of ~2.0

m in the west end near Bayfront Park, Grindstone Creek, Cootes Paradise, and along the north shore (Larocque et al. 2024).

At the Royal Botanical Gardens Fishway, White Sucker made yearly migrations into Cootes Paradise and its subsequent tributaries (Spencer, Grindstone, and Chedoke creeks) during the spring to spawn. RBG Fishway data noted a slight increase in White Sucker catch between P2 (2391 individuals) and P4 (2974 individuals; Appendix G).

Recommendations

Results indicate that the catch and catchability of White Sucker has declined between P1 and P4 in electrofishing surveys. Preliminary acoustic telemetry results conducted on White Sucker indicated that a greater number of tagged suckers moved out into deeper, cooler waters of Lake Ontario during the summer and autumn, which coincides with the majority of littoral sampling activity (both trap net and electrofishing) in the harbour. Based on the knowledge gained from the telemetry study, examining trends in the White Sucker catch from the spring electrofishing surveys, in addition to the spawning run assessed by the RBG at Cootes Paradise Fishway, would be informative. Also, conducting sampling in Red Hill Creek during the spawning window would provide insight into the relevance of this system for this species as they were historically documented spawning here (Portt and Associates 2003), and existing harbour-wide sampling programs do not access this area. Monitoring of this species should continue as declines in catch of White Sucker have been noted in exposed embayment areas across Lake Ontario (i.e., Toronto and Region AOC; Midwood et al. 2021; FP-2B section).

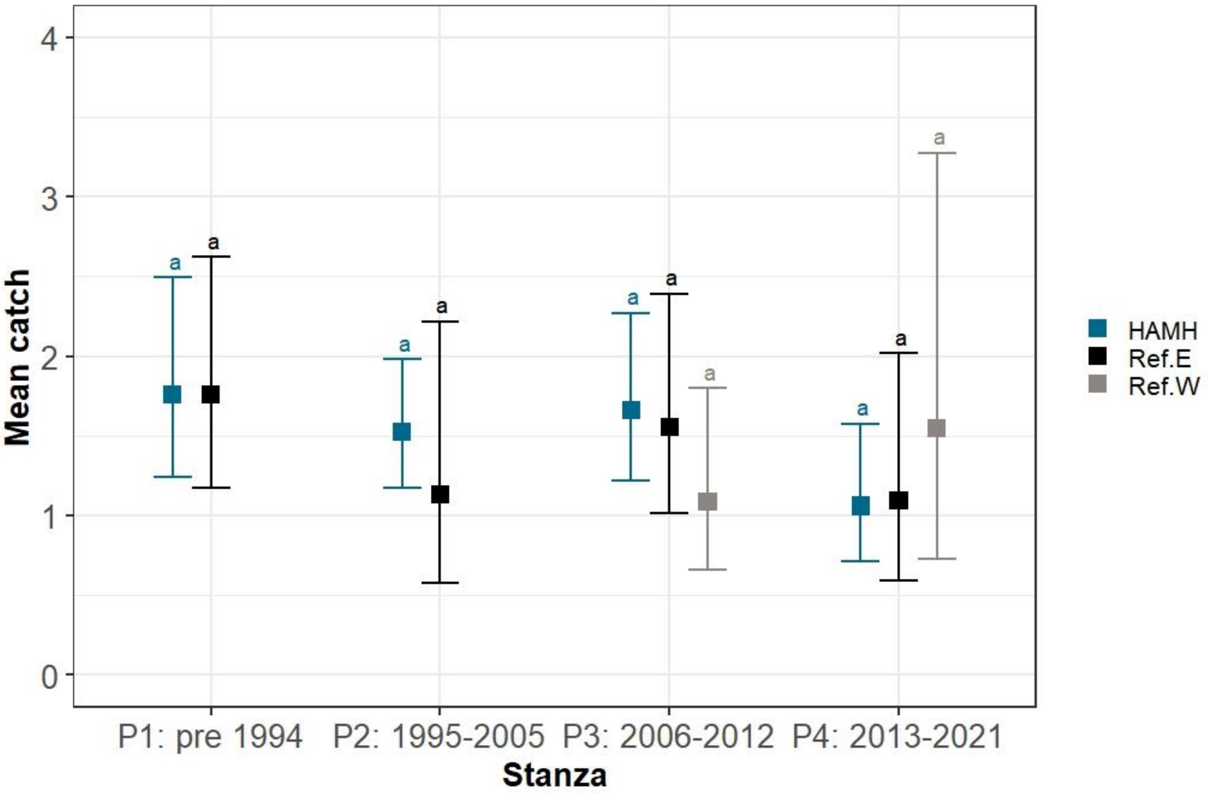

Figure 18. *Temporal changes in modelled overall mean ± SE White Sucker catch from boat electrofishing surveys within Hamilton Harbour, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

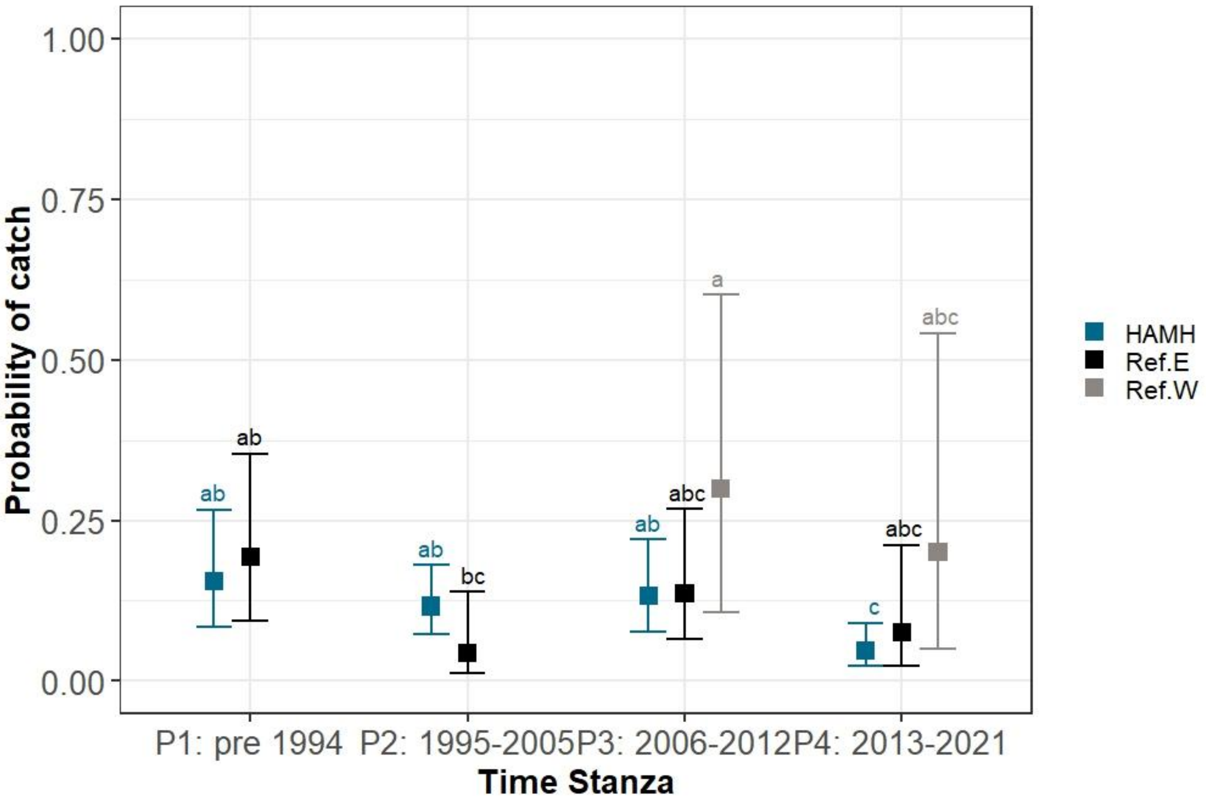

Figure 19. *Temporal changes in modelled mean ± SE White Sucker catchability from boat electrofishing surveys within Hamilton Harbour, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY STATUS OF HAMILTON HARBOUR NATIVE MINNOWS

Key message

The catch of native minnows in Hamilton Harbour AOC electrofishing surveys did not change between P1 and P4.

Current catch /regional reference /temporal trends

The catch of native minnows in the harbour was primarily comprised of Emerald and Spottail Shiner (*Notropis hudsonius*), with only a few records of Bluntnose Minnow (*Pimephales notatus*) (N=2), Common Shiner (*Luxilus cornutus*) (N=1), or Golden Shiner (*Notemigonus crysoleucas*) (N=3) throughout the entire time series. Furthermore, Emerald Shiner (*Notropis atherinoides*) made up 72% of the total catch in the Hamilton Harbour AOC and are therefore, more representative of this group versus that of Spottail Shiners; the results should be interpreted with this in mind. The catch of native minnows did not change significantly between P1 and P4 in electrofishing surveys at the Hamilton Harbour AOC or East-Ref sheltered embayments (Figure 20). Within the time series, native minnow catch peaked in P2 in the north zone of the harbour and were significantly higher than in P4 (Figure 20). In contrast, catch at the west zone of the harbour increased significantly between P3 and P4 and was greater than the East-Ref as well as the east and north zones of the harbour. At the east zone of the harbour, native minnow catch remained unchanged (Figure 20).

Despite elevated catch at the west end during the fourth time stanza, catchability at the west zone was significantly lower than that of the East-Ref, suggesting that only a few transects had elevated catch in the west zone (Figures 20 and 21). Catchabilitydeclined from P3 to P4 in the north and east zones of the harbour and at the East-Ref; it also declined in the west but was not considered significant (Figure 21). Catchability across all three harbour zones was considered similar in P4 and significantly less than East-Ref (Figure 21).

At East-Ref embayments, native minnow group richness was more diverse (see FP-2A), with multiple species contributing to overall abundance. Native minnow catchability was similar between the Hamilton Harbour AOC and East-Ref during P1 but was significantly different during P4. However, the probability of catch was greater during this time period at East-Ref versus the Hamilton Harbour AOC, indicating native minnows were less likely to be encountered across the harbour compared to the East-Ref. Due to their smaller size, Emerald and Spottail Shiners were not captured in trap nets or cages at the RBG fishway.

Recommendations

Continued monitoring of native minnow populations is recommended, particularly as top predator populations increase (i.e., BUI target ~20% top predators and Walleye stocking program).

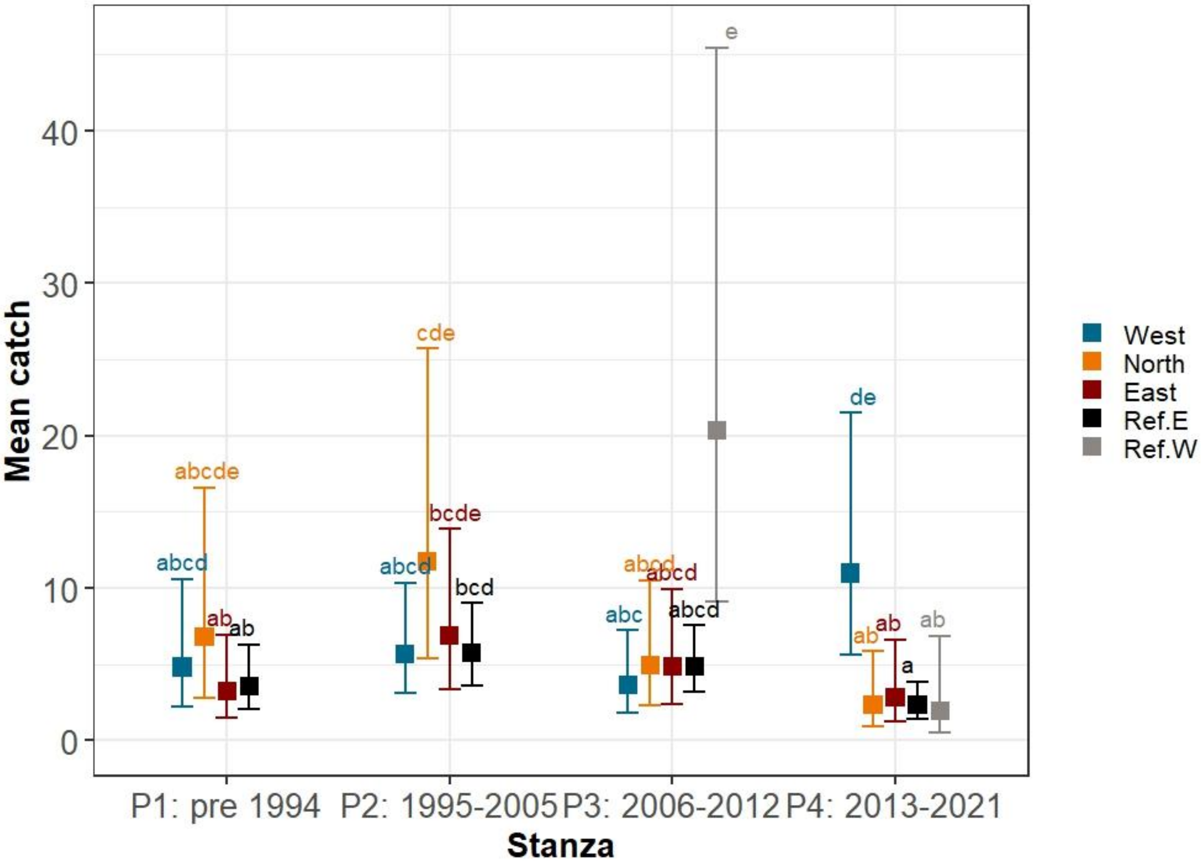

Figure 20. *Temporal changes in modelled mean ± SE of native minnow catch from boat electrofishing surveys within Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

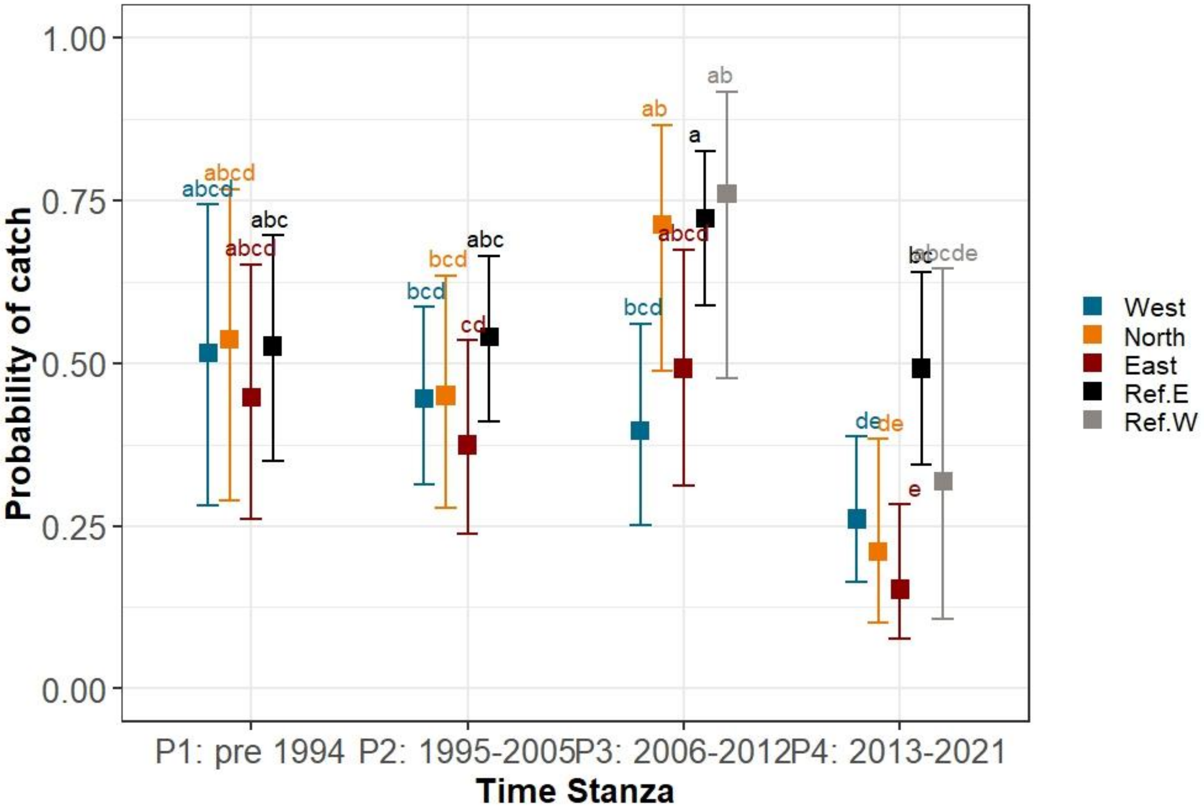

Figure 21. *Temporal changes in modelled mean ± SE native minnow catchability from boat electrofishing surveys within Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY STATUS OF BROWN BULLHEAD

Key messages

The catch of Brown Bullhead declined significantly over time in electrofishing surveys across Hamilton Harbour AOC yet was comparable to catches at East-Ref embayments in the most recent time stanza. At the Cootes Paradise Fishway, Brown Bullhead are the most abundant species in the present-day catch given the decline of Common Carp; however, the total number of individuals captured at the fishway was lower in the most recent time stanza compared to the previous two. Despite this, trap net surveys indicate that Brown Bullhead are hyperabundant in Hamilton Harbour compared to other Lake Ontario embayments. In 2010, Brown Bullhead in the Hamilton Harbour AOC were diagnosed with Epizootic Ulcerative Syndrome (EUS), the first reported cases of the disease in Canada (EFSA Journal 2011). The impact of EUS on the population to date has not been quantified, but it could have a significant impact on age structure and abundance (EFSA Journal 2011).

Current catch /regional reference /temporal trends

Brown Bullhead catches declined significantly in electrofishing surveys between P1 and P4 at all zones across the Hamilton Harbour (Figure 22), whereas catchability remained unchanged over time (Figure 23). Within the harbour, catch declined significantly between P1 and P2 in the east, P2 and P3 in the north, and between P1 and P4 in the west (Figure 22). Harbour-wide, electrofishing models demonstrated significant declines in Brown Bullhead catch between P1 and P2, and again in P3 and P4 (Figure 24). Catch remained unchanged at East-Ref embayments between P1 and P4 and the mean catch of Brown Bullhead in the harbour was considered comparable to that of East-Ref embayments during both P3 and P4 (Figures 22 and 24). There were no significant differences in bullhead catches among areas (Hamilton Harbour AOC, West-Ref, East-Ref) in P3, however during P4, the catch at West-Ref was significantly greater than at both the Hamilton Harbour AOC and East-Ref embayments (Appendix B). At the Cootes Paradise Fishway, the annual catch of Brown Bullhead declined between P2 and P4 (11,069 vs. 10,166); the greatest declines occurred between 2010 and 2014 (Appendix G).

In contrast, the CPUE of Brown Bullhead in trap net surveys were orders of magnitude higher at Hamilton Harbour than at any other sheltered Lake Ontario embayment. Between P3 and P4, the mean CPUE increased at Hamilton (282.26 vs. 379.74) and declined at East-Ref embayments (33.73 vs. 6.59) and transitional areas (11.7 vs. 2.33; FP-2B). These results differed from the electrofishing results that showed a decline in catch between P3 and P4 and no difference in catch among areas (Hamilton Harbour AOC and reference) in the last stanza.

The differences between the trap net and electrofishing surveys can be explained by the gear type used, as well as how catch values are aggregated. Trap nets are set along the east, north, and west shores, and catch is averaged across all nets. As such, harbour-wide mean catch can be influenced by hyperabundant catch rates from just a few nets (e.g., 11,000 bullheads in one net) and consequently not be representative of trends in the overall catch. Both electrofishing and fishway catch indicated a decline in the harbour and in general, bullhead catches are also down at reference locations. Exploring trap net catch by zone would be informative and help determine if there are specific areas in the harbour driving the disparate trends.

Epizootic Ulcerative Syndrome (EUS) was first detected in Hamilton Harbour in 2010 and was primarily observed in bullhead captured in the west zone of the harbour (C. Boston, pers. comm.). The impact on the population has not been quantified but is thought to have been significant, as indicated by reductions in catch following 2010 at the fishway (Appendix G), impacting population age structure as well as abundance. To date, the population continues to suffer from infections annually, but no formal assessment has been undertaken. The occurrence of EUS was the first in Canada and continues to persist in the population. The origin is unknown but may be associated with the ornamental fish industry (EFSA Journal 2011).

Recommendations

The Brown Bullhead population in the harbour should continue to be monitored with the effects of EUS in mind. Further investigation into bullhead biomass may better represent the overall changes to the population age structure post-EUS and further investigation is warranted. Lesion monitoring of fishes should also be documented to monitor for changes in frequency and/or host species.

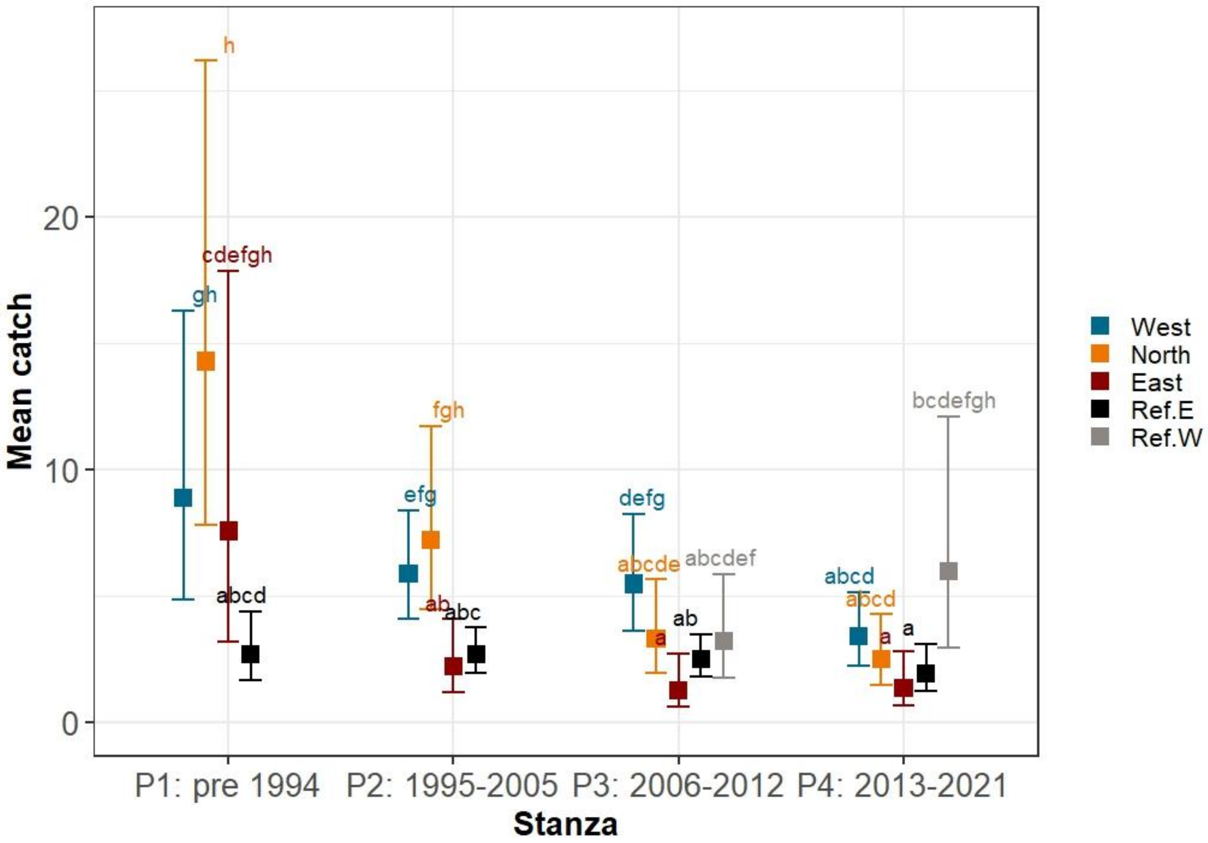

Figure 22. *Temporal changes in modelled mean ± SE Brown Bullhead abundance from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

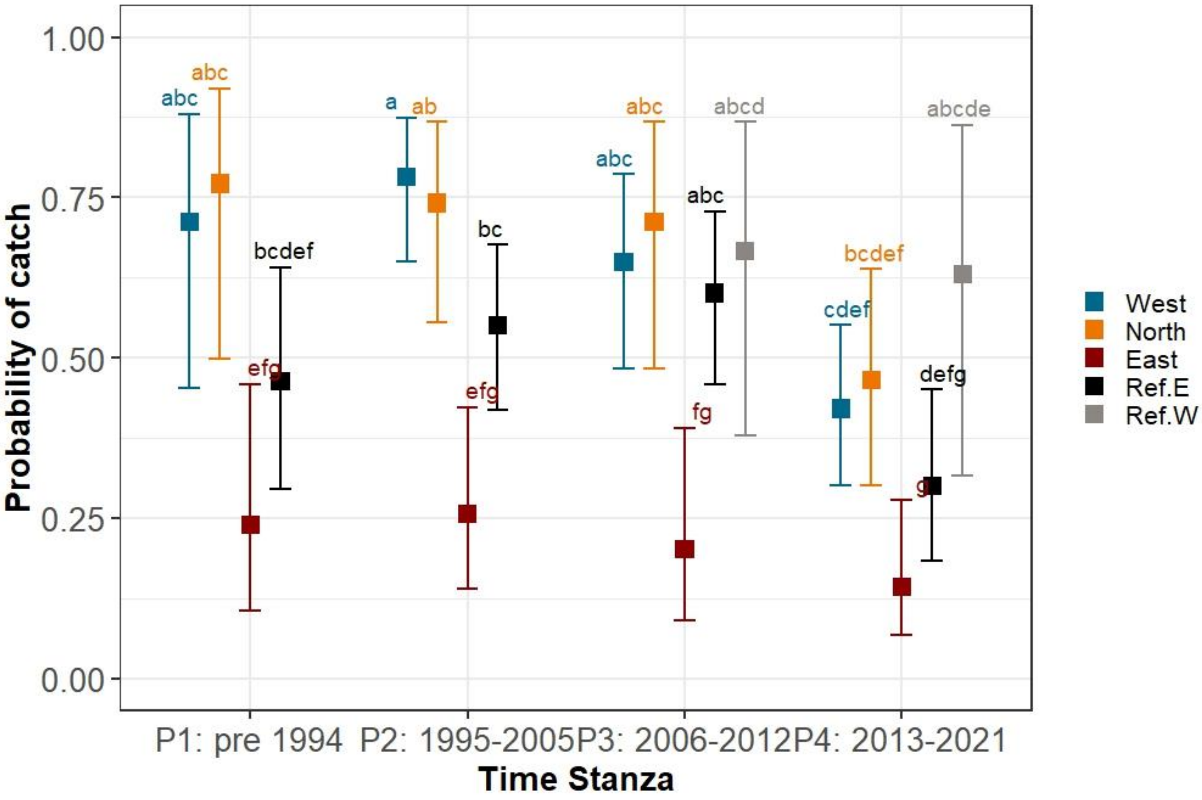

Figure 23. *Temporal changes in modelled mean ± SE Brown Bullhead catchability from boat electrofishing within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

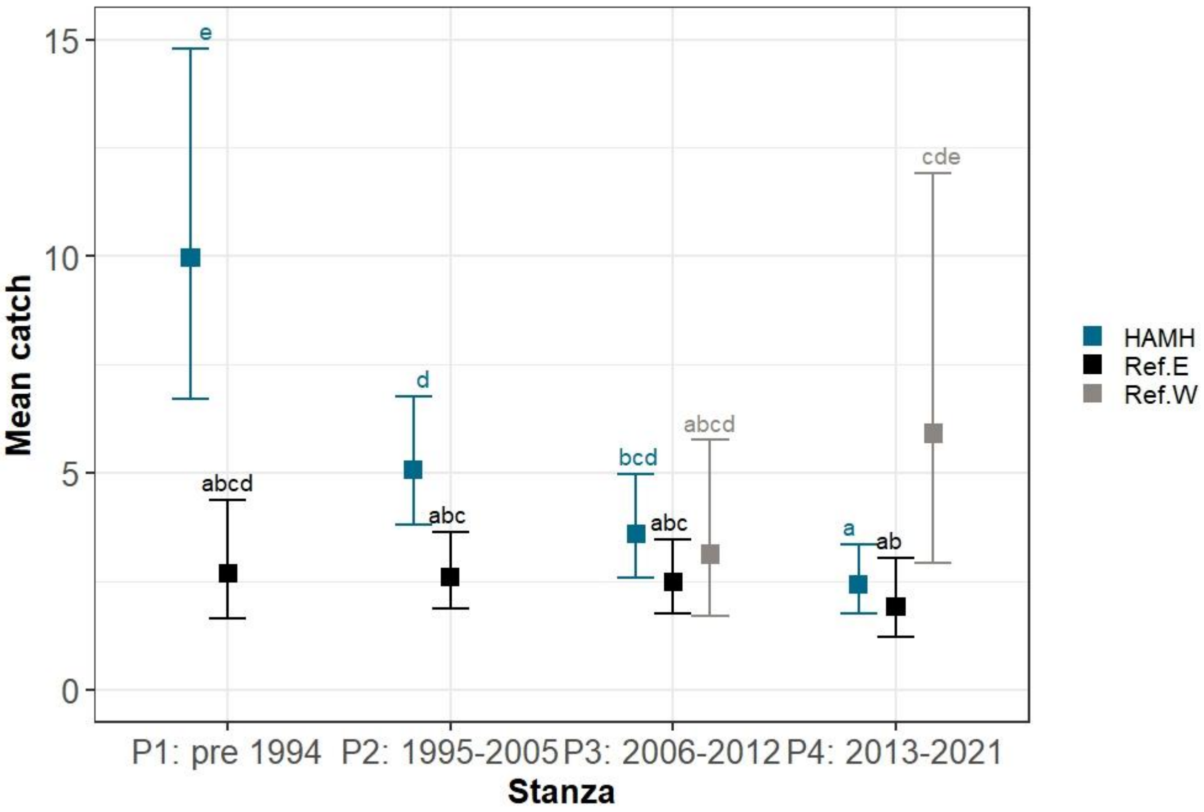

Figure 24. *Temporal changes in modelled mean ± SE Brown Bullhead abundance from boat electrofishing within the Hamilton Harbour AOC, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY OF STATUS OF NON-NATIVE SPECIES – COMMON CARP

Key message

Common Carp declined by >50% in the catch of both electrofishing surveys and at the Cootes Paradise Fishway since the initial listing of the AOC. Significant declines in abundance occurred during the latter two time stanzas (P3 and P4) after exclusion and removal efforts were initiated in P2 (1996-2005). Electrofishing data from the most recent time stanza showed that the mean carp catch in Hamilton Harbour is not different from the mean catch at East-Ref embayments. In contrast, catch data from trap net surveys indicated that Common Carp are more abundant in Hamilton Harbour than at East-Ref embayments.

Current catch /regional reference /temporal trends

In Hamilton Harbour, the catch of Common Carp declined significantly between P3 and P4 in the west zone (Figure 25). The catchability of Common Carp was highest in P1 and P2 at all harbour zones before carp control measures were implemented in P2 at the western zone (Figure 26). The mean catch of carp in the west zone of the harbour declined by >50% (P1: 3.6; P4: 1.4), driving the overall change in Hamilton. There were no significant changes in carp catch at the East-Ref embayments between P1 and P4, and in P4, the mean catch at all harbour zones (P1: 1.4; P4: 1.7) were comparable to East-Ref embayments (1.6; Figure 25). At West-Ref embayments, the mean catch was similar to that of the harbour but was significantly greater than the catch at East-Ref embayments in both P3 and P4 (Appendix B). Catchability in Hamilton Harbour declined after P2 and was comparable to the East-Ref embayments during the fourth time stanza (Figure 26).

At the Cootes Paradise Fishway, there has been a significant decline in the catch of carp attempting to enter the marsh following years of exclusion and active removal. Within the first five operational years of the fishway (1996-2000), over 20,000 Common Carp were seen at the barrier annually. In the last six years (2017-2022), on average, 3,000 carp attempted to enter the marsh at the fishway annually. In the early years of operation at the fishway, Common Carp were so abundant that special modifications were required at the cage entrances to reduce the capture of carp yet allow native fishes to enter, but in later years these modifications were not required for carp exclusion (Appendix G).

In trap nets, the mean CPUE of Common Carp was higher at Hamilton (P3: 2.95; P4: 3.16) than at East-Ref sheltered embayments (P3: 0.25; P4: 0.28) in both P3 and P4. Common Carp CPUE was also elevated at Toronto Harbour embayments in P3 and P4 relative to other exposed Lake Ontario embayments (see section FP-2B).

Common Carp (N=27) were acoustically tagged and tracked across Hamilton Harbour from October 2017 to April 2020 (Larocque et al. 2024). Carp remained almost exclusively resident within the harbour except for one individual that left and did not return (Larocque et al. 2024). In contrast, half of the Common Carp tagged in Toronto Harbour made long-distance movements during the spring and summer while the other half remained resident (Piczak et al. 2023a). Hamilton Harbour carp were primarily located in the west end of the harbour year-round (Larocque et al. 2024). During the winter and fall, carp resided in slightly deeper waters (~4-6m) in the west zone but also along the north shore and central basin of the harbour (Larocque et al. 2024). During spring, Common Carp were detected primarily in the west end near Cootes Paradise and Grindstone Creek and by summer, were more dispersed in the west zone at slightly deeper waters (Larocque et al. 2024). Seven tagged individuals (26%) were detected in Cootes Paradise in the summer and fall of 2018 and 2019; these detections were found during the period when the fishway was left open to allow for other native species to move into the marsh, presumably when carp are thought to remain within the harbour (Larocque et al. 2024).

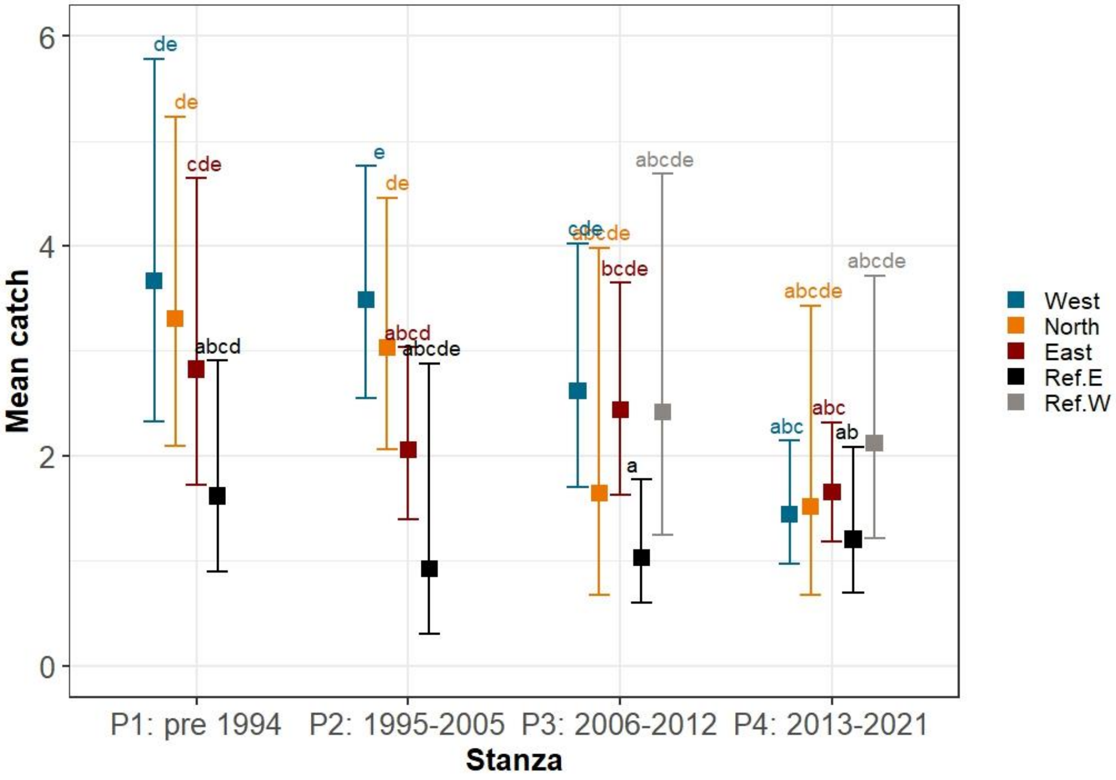

Figure 25. *Temporal changes in modelled mean ± SE Common Carp catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

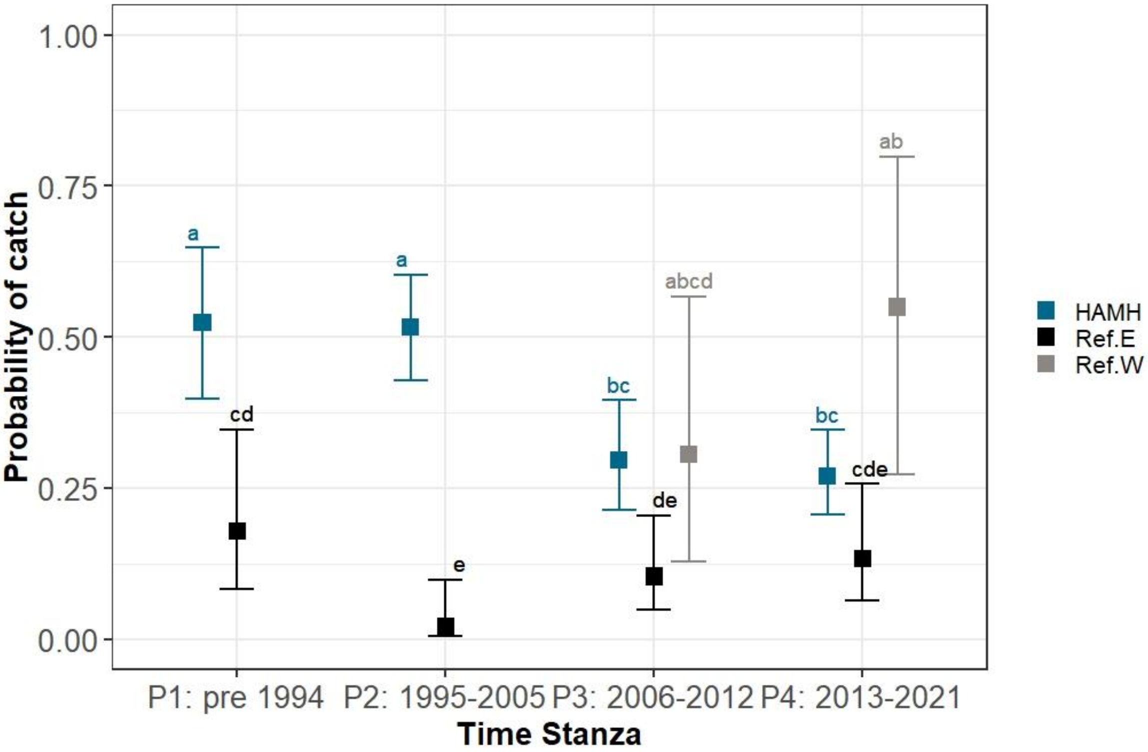

Figure 26. *Temporal changes in modelled mean ± SE Common Carp catchability from boat electrofishing surveys within the Hamilton Harbour AOC, east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

SUMMARY OF STATUS OF NON-NATIVE SPECIES – GOLDFISH

Key message

The catch of Goldfish in Hamilton Harbour increased in P3 concurrent with a significant decline in Common Carp catchability (P3) and catch (P4) in the west zone. Between P3 and P4, Goldfish catch doubled in all three major monitoring programs (boat electrofishing, Cootes Paradise Fishway, and trap nets). Goldfish were largely resident in the west zone of the harbour. Goldfish were rarely captured at East-Ref locations in Lake Ontario but were captured more frequently at West-Ref embayments. West-Ref embayments have higher rates of urbanization and more stormwater management ponds in their watersheds and thus a higher potential for release into natural systems.

Current catch /regional reference /temporal trends

Goldfish catch from electrofishing surveys increased in Hamilton Harbour between P1 and P4; Goldfish catch was higher in P3 and P4 than in P1 and P2 (Figure 27). Goldfish also increased in the catch at West-Ref embayments between P3 and P4, driven by the catch of Goldfish in Jordan Harbour, which is geographically close to Hamilton Harbour. Goldfish catches were higher at Hamilton Harbour AOC than at any other Lake Ontario embayment. Opposite to Common Carp trends in the harbour, Goldfish catches increased between P3 and P4 and were highest in P4. Goldfish were captured more frequently in the west and north zones of the harbour (Figure 27).

Similar to electrofishing surveys, Goldfish were rarely captured in Lake Ontario trap net surveys, with the exception of Hamilton Harbour. The CPUE in Hamilton Harbour trap nets almost doubled between P3 (N=1.2) and P4 (N=2.03). The CPUE of Goldfish at other Lake Ontario embayments was ≤ 0.25 in both time stanzas. The mean annual catch of Goldfish at the Cootes Paradise Fishway was 151.2 fish/year in P2; the mean annual catch increased five-fold in P3 (N=707.7) andmore than doubled in P4 (N=1551.6). The RBG actively removed Goldfish at the fishway in 2020 and 2021, and although the impact of these removals is currently unknown, the total number of Goldfish captured at the fishway in 2022 (N=298 individuals) was the lowest it had been in ten years (Appendix G).

Adult Goldfish (N=12) were acoustically tagged and tracked in the harbour between June 2017 and June 2019. Goldfish spent most of their time in the west end of the harbour except for one tagged individual which left the harbour and was detected about 5 km away within Lake Ontario (Boston et al. 2024). Goldfish began staging at the entrances to spawning locations (e.g., Cootes Paradise Fishway) or at identified spawning locations (Carroll’s Bay/Grindstone Creek ponds) in the late winter/early spring (March – April) before water temperatures were conducive to (Boston et al.

2024). Goldfish used similar spawning habitats as native species including, Northern Pike, White Sucker, and Yellow Perch (Larcocque et al. 2024). During the spawning window (May 1 to June 30), Goldfish were found in shallow (~1.0 m) areas in the west end, at the mouth of Grindstone Creek, Macassa Bay, and to a lesser extent along the north shore (Larocque et al. 2024). Tagged adult Goldfish were large (≥ 300 mm fork length) and were not detected in Cootes Paradise. Adult Goldfish are smaller than Common Carp and become sexually mature at a size that would allow them to pass through exclusion structures at the Cootes Paradise Fishway and Grindstone Creek ponds that are designed to keep out adult carp (Boston et al. 2024). In 2020-2021, smaller individuals were tagged but the resulting analyses were not available for this assessment.

A recent study focusing on the presence of invasive species in stormwater management ponds (SWMP) managed by the City of Hamilton found that Goldfish were present in about 50% of surveyed ponds that outlet to Hamilton Harbour via major tributaries (Red Hill, Spencer, Borers, Chedoke, Ancaster, and Grindstone creeks) as well as Twenty Mile Creek, which flows into Jordan Harbour (West-Ref) where Goldfish were also captured. The majority of SWMP (> 85%) have been built within the City of Hamilton since 2000, which coincides with when Goldfish started to appear in greater numbers in Hamilton Harbour AOC electrofishing and trap net catches, indicating that these ponds may be a point source of Goldfish introduction into Lake Ontario and its embayments. In 2021-2022, DFO removed over 50,000 Goldfish in partnership with the City of Hamilton at SWMP in Hamilton watersheds (Boston, unpublished data).

While Goldfish have been present in the system since at least the 1970s, there were declines in catch noted in the late 1970s that correlated with an outbreak of ulcerative disease (Munkittrick and Leatherland 1984). The more recent recovery of their populations, as shown by increasing catch rates, may reflect modest improvements in water quality in the system since poor water quality was posited as the cause of the disease outbreak. However, increases may still be linked to other persistent water quality issues since they are tolerant of low oxygen levels (Tang et al. 2020) and can forage opportunistically on blue-green algae and promote its growth through a positive feedback loop (Beatty et al. 2017). They have likely also increased in abundance due to decreased competition with Common Carp (Boston et al. 2024).

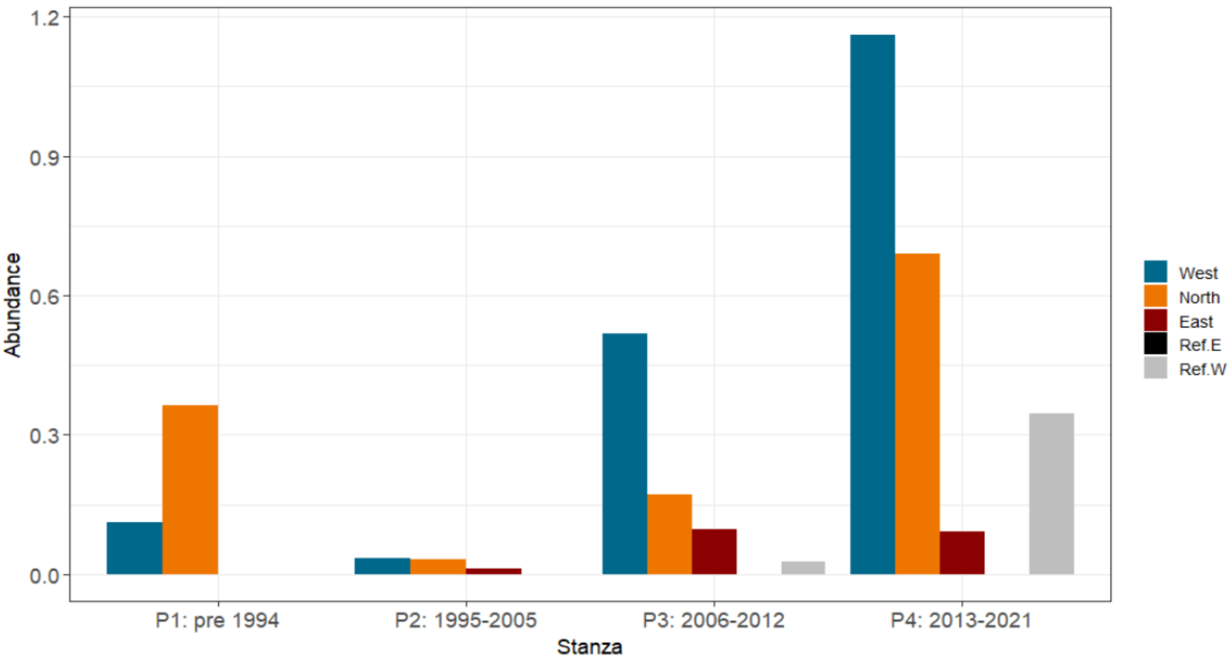

Figure 27. *Temporal changes in mean ± SE Goldfish catch from boat electrofishing surveys within the Hamilton Harbour AOC, east (Ref.E), and west (Ref.W) regional reference areas. There was insufficient capture of Goldfish to support statistical analysis. Therefore, values presented are based on mean catch per transect across electrofishing surveys.*

SUMMARY OF STATUS NON-NATIVE SPECIES – RUDD

Key message

Rudd were first detected in Hamilton Harbour in 2006. A population currently exists and appears to be increasing in the overall catch in the harbour, particularly in the west zone.

Current catch/regional reference/temporal trends

Although Rudd were first detected in Hamilton Harbour in 2006 (P3), they were not captured in electrofishing surveys until P4, indicating that the population has been increasing since initial introduction (Figure 28). Rudd were first detected on the Canadian side of Lake Ontario in Jordan Harbour in P3 following establishment in Buffalo Harbour and the Niagara River during P1 (Kapuscinski et al. 2012). Electrofishing surveys indicated that Rudd were captured in all areas of Hamilton Harbour in P4 (2013-2021) but were most abundant in the west zone followed by the north and east (Figure 28), similar to Common Carp and Goldfish.

Rudd were first detected in trap net surveys in P3 in Hamilton Harbour and the Bay of Quinte. Similar to electrofishing catches, the CPUE of Rudd was highest in P4 (7.83) in Hamilton Harbour. The mean CPUE of Rudd was highest in 2018 (14.75) and lowest in 2012 (0.04), confirming population growth in the harbour in P4. Rudd were also detected at the Cootes Paradise Fishway in greater numbers in P4, but annual catches were low compared to Common Carp and Goldfish. The highest catch at the fishway was 49 in 2022 (Appendix G); however, Rudd are laterally compressed and at smaller lengths, may readily pass through the fishway into the marsh undetected.

Data collected from acoustically tagged adult Rudd (N=14) has not yet been fully analyzed as Rudd were only recently tagged in October 2021 (Midwood, unpublished data). However, preliminary results revealed that Rudd moved throughout the entire harbour as well as into Cootes Paradise, Grindstone Creek (including the ponds during the spring spawning window), and Red Hill Creek. It appeared that Rudd remained resident to the harbour year-round, although four tagged fish were detected at the receiver in the canal to Lake Ontario. Rudd depth use varied seasonally, in which tagged Rudd moved deeper in the autumn (mean ± SE; 3.1 ± 0.3 m), deepest in the winter (4.6 ± 0.3 m), moved shallower in the spring (2.3 ± 0.3 m), and were shallowest during summer months (1.8 ± 0.3 m; Midwood, unpublished data).

Rudd are known to be omnivorous with juveniles consuming benthic invertebrates and zooplankton with adults occasionally consuming fish but generally relying on a macrophyte diet in the summer when submerged aquatic vegetation becomes more readily available (Guinan et al. 2015). Rudd have been shown to hybridize with the native Golden Shiner (Burkhead and Williams 1991), which could have negative impacts on local populations of this species in the watershed; however, Golden Shiner were rarely captured in Hamilton Harbour electrofishing surveys at the time when Rudd were first detected in the harbour (2006). The effects of an increasing Rudd population across the harbour are currently unclear and further work will be required to better understand the impacts on native fishes and habitat.

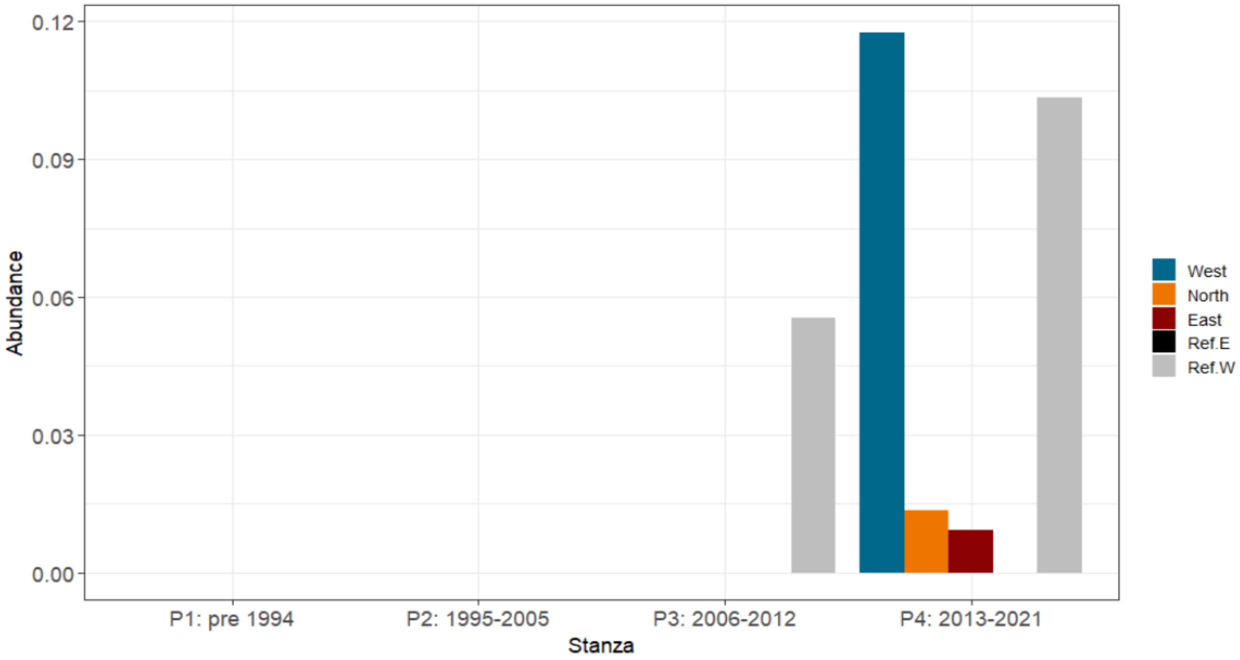

Figure 28. *Temporal changes in Rudd abundance from boat electrofishing surveys within the Hamilton Harbour AOC, east (Ref.E) and west (Ref.W) regional reference areas. There was insufficient capture of Rudd to support statistical analysis. Therefore, values presented are based on mean catch per transect across electrofishing surveys.*

RECOMMENDATIONS FOR FUTURE MANAGEMENT ACTIONS FOR INVASIVE CYPRINIDS

Exclusion and removal efforts have clearly proven to be effective for Common Carp with marked declines in catch over time during routine monitoring surveys in Hamilton Harbour and at the Cootes Paradise Fishway (Appendix G; Johnston et al. 2001; Crawford and Theysmeyer 2004). However, the Goldfish is a smaller cyprinid species that can likely by-pass these barriers, and concurrent with the decline in the population of Common Carp, Goldfish increased. This suggests that the decline in Common Carp may have created an opportunity for the Goldfish population in the harbour to expand. The more recent introduction of the Eurasian Rudd could negatively impact efforts to restore aquatic vegetation within the Hamilton Harbour AOC; however, the extent of their impacts in the system have not yet been documented.

It is recommended that exclusion and removal efforts apply to all three species of invasive cyprinids where and when possible as removal efforts have been effective with carp. One opportunity to increase removal efforts is at the Cootes Paradise Fishway where these species are often released back into Hamilton Harbour. Alternatively, angling incentives (e.g., invasive species derbies) may provide a method for both public outreach/awareness and invasive species removal. Telemetry studies involving all three species have indicated that they are largely resident within the harbour; however, some movements outside of the harbour have also been observed in all three species (Boston et al. 2024; Midwood, unpublished data), with Common Carp more than capable of large-scale movements (Piczak et al. 2023b). However, during the spawning window, almost all tagged individuals were found within the harbour and targeted specific habitats for spawning which is important for native species. Both Common Carp and Goldfish have been shown to aggregate in the winter/early spring prior to spawning (Boston et al. 2024), making the “Judas fish technique” a potentially viable option for removal. Indeed, its application via telemetry to identify and remove winter/early spring aggregations of Common Carp in North American lakes has been successful (Bajer et al. 2011). Resource managers should further discuss the continued use of barriers (Cootes, Grindstone, Windermere) for invasive cyprinid control, and the development of a harbour and/or lake-wide management program for these species may be necessary.

SUMMARY STATUS OF ROUND GOBY

Key message

Round Goby became established in Hamilton Harbour in the 1990s. Minnow trap surveys indicate that the catch of gobies has declined in the most recent time stanza. Round Goby are not well sampled via electrofishing and are too small to be captured in trap nets; therefore, alternate sampling approaches like those employed by McMaster University are required to target this species.

Current catch/regional reference/ temporal trends

Round Goby were sampled by McMaster University between 2002 and 2022 (April to October) throughout the Hamilton Harbour AOC (Appendix E). Gobies were first reported in the harbour in 1999 but did not appear in electrofishing catches (low densities) until around 2002 (Balshine et al. 2005; Boston et al. 2016). Minnow trap sampling documented an overall decline in catch from a peak of 6-8 individuals per trap in the early 2000s to current levels of 2-4 individuals (Appendix E). Total Round Goby catch, as well as body size and mass (g), steadily declined over time across the harbour following initial sampling (2002) and eventually stabilized around 2014 (Appendix E). Declines in catch noted around 2014 may be related to the population reaching a stable carrying capacity, increased predation through the addition of Walleye to the system, changing environmental conditions, or other factors.

Round Goby were captured as incidentals during juvenile Northern Pike surveys completed by DFO in the Hamilton Harbour watershed (Budgell et al. 2024). Spatial differences in catch were apparent with the most gobies captured in the harbour (N=1638) followed by the Red Hill (N=405) and Grindstone Creek (N=50) during seine net surveys in 2021. Incidental observations of Round Goby have occurred from an underwater Remotely Operated Vehicle (ROV) survey in 2022, which showed numerous gobies amongst rocky substrates by the docks at CCIW (Larocque, unpublished data).

Recommendations

It is recommended that Round Goby monitoring continues in the harbour (by McMaster University) but could be supplemented with video observations or other gear types to further assess the harbour population size.

PRIMARILY OFFSHORE FISHES

The percentage of primarily pelagic offshore species (defined based on Minns et al. 1994) contributing to the numbers and biomass of fishes at littoral sampling locations in Hamilton Harbour is higher than at East-Ref embayments (FP2A-IBI), indicating littoral fish habitat impairment. In general, the proportion of offshore species contributing to total abundance at non-impaired embayments is low (< 10%), but at the Hamilton Harbour AOC and West-Ref embayments, it ranges from about 25%-60% of the total catch. High catch of these offshore species can artificially inflate the IBI score (delisting target) because these species are also classified as specialists. Gizzard Shad is a native species and specialist, so it can positively influence the IBI score. In areas with large populations of pelagic/offshore species like the Hamilton Harbour AOC, it is important to examine the adjusted IBI score (IBI*) to understand the magnitude of the effect of these individual species.

PRIMARILY OFFSHORE FISHES – GIZZARD SHAD

Key message

Gizzard Shad have increased in Hamilton Harbour catches over time and were more abundant at West-Ref (i.e. more degraded areas) than East-Ref embayments. This species is tolerant of degraded, eutrophic conditions and an increase in catch over time indicates that water quality and habitat conditions have declined for native, littoral species.

Current catch/ regional reference/ temporal trends

Gizzard Shad increased significantly in the catch at Hamilton Harbour between P1 and P4 driven by an increase at the west zone (Figure 29). Within the time series, catch increased between P3 and P4 at sites in the west and east zones (Figure 29). A similar pattern was seen in catchability; the probability of catching Gizzard Shad significantly increased from P3 to P4 in the west zone of the harbour (Figure 30). At East-Ref embayments, catch declined significantly between P1 and P4 and catchability remained low and unchanged among time stanzas (Figures 29 and 30). In P4, catches at Hamilton Harbour and West-Ref embayments were significantly higher than the catch of Gizzard Shad at East-Ref embayments (Appendix B).

In trap net catches, the mean CPUE of Gizzard Shad was similar between time stanzas in Hamilton Harbour; P3 (2.11) and P4 (1.61). At East-Ref embayments, there was a decline in abundance between P3 (2.15) and P4 (0.49). Gizzard Shad increased in numbers captured at the Cootes Paradise Fishway from P2 to P3 and again in P4 (Appendix G).

Different trends were noted between the two gear types. Gizzard Shad increased significantly in Hamilton Harbour AOC electrofishing catches between P3 and P4, specifically at the west zone of the harbour but CPUE decreased slightly between the two time periods in trap net surveys. In contrast, there were no changes in electrofishing catches at East-Ref embayments between P3 and P4 but Gizzard Shad CPUE decreased in trap net catches between the two time periods. Goretzke and Connerton (2020) found that Gizzard Shad increased in gillnet catches at warmwater sampling locations in the eastern basin of Lake Ontario within the P4 time stanza; in 2013, Gizzard Shad CPUE increased to its highest level since 1981 and was higher in P4 than earlier time stanzas.

Recommendations

It is recommended that Hamilton Harbour AOC Gizzard Shad populations be monitored moving forward as they are an indicator of hypereutrophic and degraded systems (Dicenzo et al. 1996; Bremigan and Stein 2001). Further work may be done to better understand the trophic structure impacts an increasing population may have on the Hamilton Harbour AOC fish community. Gizzard shad have been previously documented in other systems to have a ‘middle-out’ effect on community composition as they are not controlled by zooplankton abundance (ability to switch to detritus and phytoplankton), or predators (size out midway through age 2) and are hyper-fecund (Devries and Stein 1992). Additionally, they can outcompete Bluegill due to their shared feeding guilds and in turn, may reduce forage opportunities for piscivores such as Largemouth Bass (VanDeHey et al. 2014).

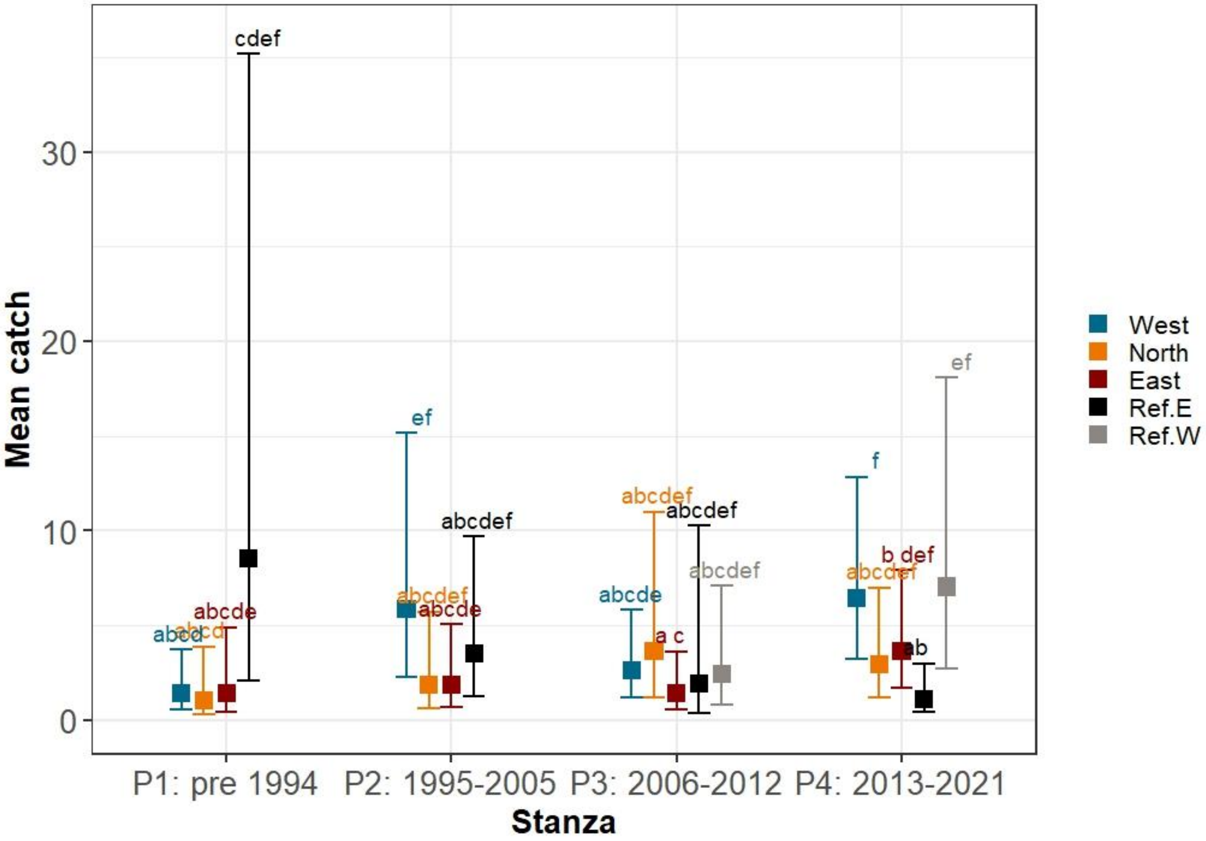

Figure 29. *Temporal changes in modelled mean ± SE Gizzard Shad catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

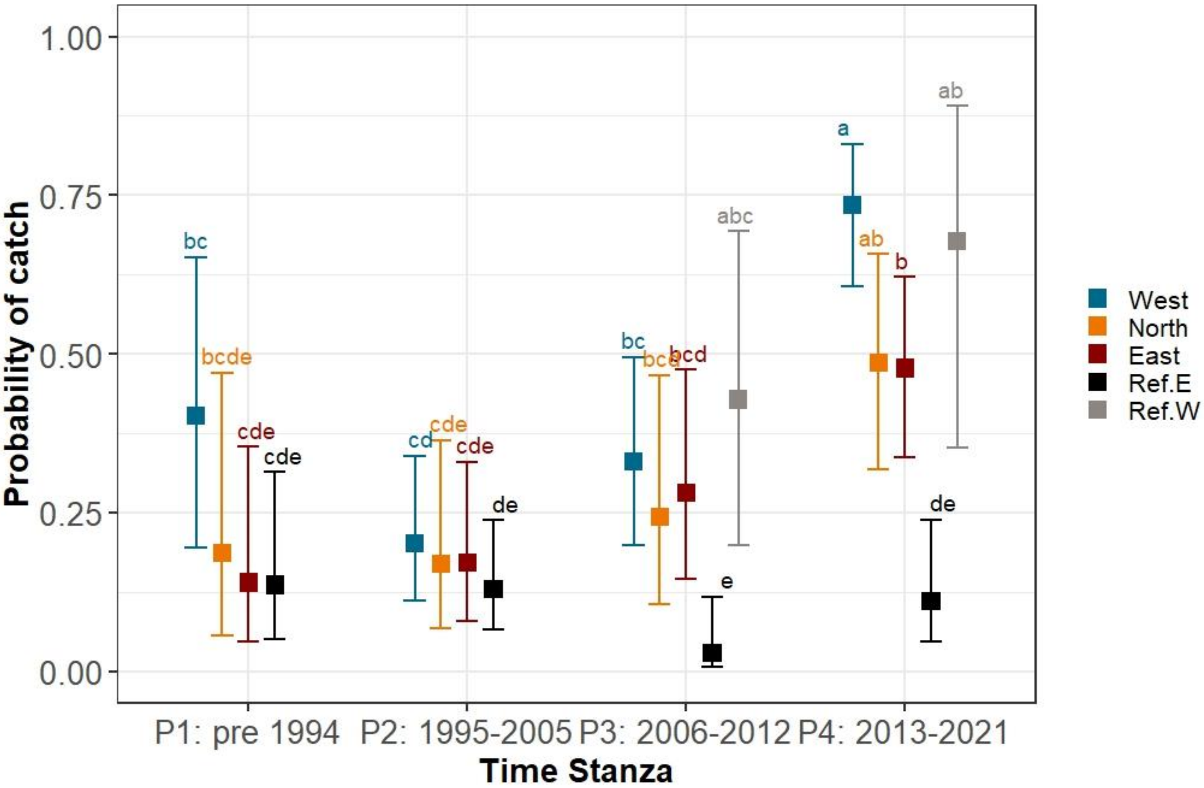

Figure 30. *Temporal changes in modelled mean ± SE Gizzard Shad catchability from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

PRIMARILY OFFSHORE FISHES – ALEWIFE

Key message

Alewife (*Alosa pseudoharengus*) declined significantly over time in Hamilton Harbour but not at East-Ref embayments.

Current catch/regional reference/temporal trends

Electrofishing-based catches of Alewife in Hamilton Harbour declined significantly between P1 and P4 in all three spatial zones but remained unchanged at East-Ref embayments (Figure 31). Declines in the harbour were driven by reduced catches at the west and north zones between P2 and P3 (Figure 31). There were no changes in Alewife catch between P3 and P4 at any Hamilton Harbour zones or East-Ref and West-Ref embayments (Appendix B). Similarly, the probability of catching an Alewife in Hamilton Harbour electrofishing surveys has declined significantly at all harbour zones and East-Ref embayments between P1 and P4 (Appendix B).

Alewife were rarely captured in summer trap net surveys, likely due to a combination of gear bias (i.e. large trap mesh size) and summer water temperatures in embayments at the time of the surveys, which are not suitable for this coldwater species. Alewife CPUE increased between P3 (0.04) and P4 (7.23) in the harbour, however, with the exception of 2015 (CPUE=13.75), CPUE in other years was < 1.0 (zero in most years). It is unclear why Alewife catch was elevated in 2015 compared to other years; however, if 2015 were removed, Alewife CPUE in trap nets between P3 and P4 would have been similar in Hamilton Harbour to East-Ref embayments.

Recommendations

Further analysis on trends in Alewife catch in the spring and/or autumn (cooler water temperatures) should be completed in a manner that is more comparable to other lake-wide assessments to determine population trends (e.g., hydro-acoustics or trawling). In general, trap net CPUE of Alewife were lower at sheltered embayments than at exposed embayments, likely as a result of warmer water temperatures during the survey period (Appendix D). Alewife are considered a preferred prey item for Walleye and piscivorous birds, so any potential recovery of the species in P4 could be dampened by predation. In MNRF trawling surveys, Alewife catch at several locations in the upper Bay of Quinte have recovered from low catches since P2 (Ontario Ministry of Natural Resources and Forestry 2022); however, while density indices remain stable in Lake Ontario, biomass indices have been lower since 2015 based on lake-wide spring bottom trawl surveys (Weidel et al. 2019, 2021).

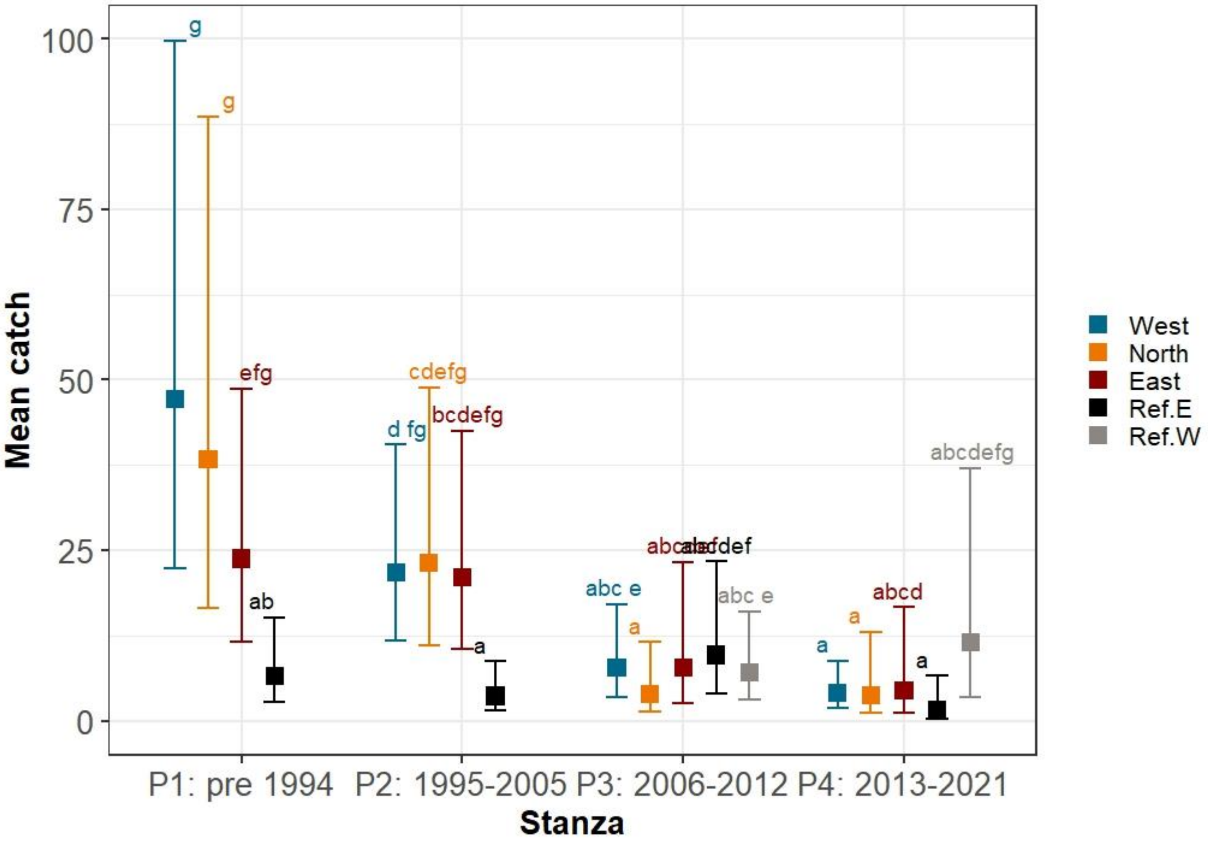

Figure 31. *Temporal changes in modelled mean ± SE Alewife catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

PRIMARILY OFFSHORE FISHES – WHITE PERCH

Key Message

The catch of White Perch in the Hamilton Harbour AOC did not change in electrofishing surveys between P1 and P4 or on a zonal basis. In contrast, the CPUE in trap net surveys more than doubled between P3 and P4 within the harbour. At East-Ref embayments, catch increased significantly between P1 and P4 in electrofishing surveys but the CPUE in trap net surveys did not change between P3 and P4. White Perch are a non-native species known to target eggs of desirable fish species (including Walleye; Roseman et al. 2006) and are tolerant of eutrophic and degraded conditions; therefore, increases in trap net CPUE in the Hamilton Harbour AOC are concerning and the differences in trap net catches between the East-Ref embayments and Hamilton Harbour indicate an increasing, hyperabundant species.

Current Catch/Regional Reference/Temporal Trends

From electrofishing surveys, there was no change in the White Perch catch between P1 and P4 in Hamilton Harbour or at East-Ref embayments; however, catch increased significantly at East-Ref embayments between P3 and P4 and was higher in P4 than at any harbour location (Figure 32). The probability of catching White Perch between P1 and P4 at East-Ref embayments did not change. However, catchability declined at the west zone of Hamilton Harbour but remained unchanged at the north and east zones (Appendix B). Increased catch at East-Ref embayments was due to a single sampling year in P4 when White Perch were captured in high abundance at a few locations; this is reflected in the catchability model where no change occurred.

In trap net catches, the mean CPUE of White Perch more than doubled in the harbour between P3 (59.4) and P4 (130.82) and were hyperabundant in Hamilton Harbour compared to East-Ref embayments in P3 and P4 (4.33 vs. 3.73). The catch at East-Ref embayments was similar between the two time periods but increased in transitional areas by more than six-fold (FP-2B). Trap net CPUE at the Bay of Quinte increased between P3 and P4 but declined at Weller's Bay and West Lake (FP-2B). In gillnet assessment surveys in the eastern basin of Lake Ontario, White Perch abundance was markedly higher in P4 than in earlier time stanzas (Goretzke and Connerton 2020).

Trap net and electrofishing demonstrated different trends; the CPUE more than doubled in the harbour for trap nets between P3 and P4 and was orders of magnitude higher than at East-Ref embayments, compared to relatively no change in abundance from electrofishing surveys. Differences are likely related to gear selectivity for this species and differences in trap net set locations versus that of electrofishing transects.

In recent years, RBG electrofishing survey data has indicated significant recruitment of White Perch, which does not seem to overlap with the strong recruitment years for other native species, such as Bluegill, a typically dominant YOY species in Cootes Paradise (Appendix G).

White Perch are opportunistic foragers and consequently have multiple competitive interactions between littoral and pelagic piscivores (e.g., Largemouth Bass and Walleye), invertivores (Bluegill), and zooplanktivores which can have a large impact on the overall food web structure of native species (Roseman et al. 2006; Couture and Watzin 2008; Feiner et al. 2013). Furthermore, White Perch have been documented on Walleye spawning reefs in Lake Erie predating on eggs and were found to be the largest egg predators across spawning reef areas (~253 Walleye eggs per stomach; Roseman et al. 2006). As White Perch continue to increase in abundance across the harbour (FP-2B), their broad coverage of the resident food web and opportunistic egg predation may pose a large threat to the overall recovery efforts and health of the system and should be closely monitored.

Recommendations

Given the large increase in abundance documented across trap net surveys between P3 and P4, and their generalist status, further investigation into White Perch populations throughout the harbour is warranted. Future studies may look to assess diet (stable isotopes) due to their overlapping trophic range (invertivores, benthivores, piscivores), which may have an impact on multiple different native species particularly if abundance continues to increase, and if forage availability is limited. The creation of an action plan to reduce or limit the population of White Perch across the Hamilton Harbour area may be warranted.

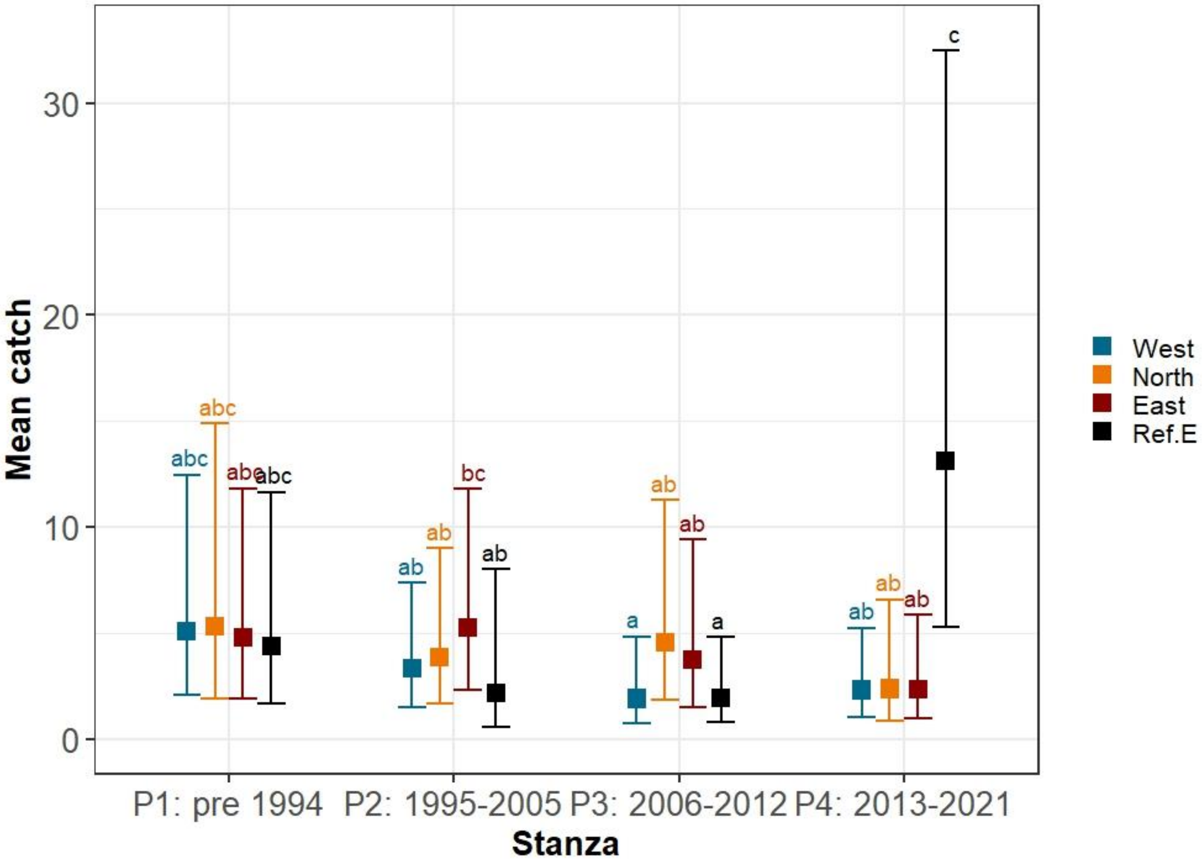

Figure 32. *Temporal changes in modelled mean ± SE White Perch catch from boat electrofishing surveys within the Hamilton Harbour AOC (west, north, east), east regional baseline (Ref.E), and west regional baseline (Ref.W). Values not connected by the same letter(s) are interpreted as being significantly different (p<0.05).*

GENERAL DISCUSSION

To aid in the assessment of the status of fish populations in the Hamilton Harbour AOC, specific species were identified as key contributors to a more desirable, mesotrophic fish community. In this section, trends in the catches of these species and others that are more indicative of a eutrophic ecosystem (and as such would ideally show declining catch) were explored, with the core comparison between when the Hamilton Harbour AOC was first listed (P1) and the most recent sampling period (P4). For most key species, observed trends derived from electrofishing catch information counter what is desirable (Table 2). For top predators, which can help reinforce the trophic structure of the system by providing top-down control, three of the four species in the delisting criteria showed either a declining trend in catch (Smallmouth Bass) or no change (Largemouth Bass and Northern Pike). The sole predator species that showed a positive trend in catch was Walleye, which has been stocked into the system and thus, the increased catch of this species does not necessarily indicate an improvement in conditions within the AOC. Evidence of natural Walleye recruitment in the Hamilton Harbour AOC is limited, but necessary to show that conditions have improved sufficiently to support Walleye. Declines or a lack of change were also observed over the same time period for all four of these top predators in electrofishing surveys in eastern Lake Ontario. While declines in this region are concerning, past modeling work predicted that as total phosphorus levels declined, there could also be declines in some top predators (Hossain et al. 2019). Similar patterns for top predators have also been observed recently (i.e., P3 to P4; Table 3) based on both electrofishing and trap net data, reinforcing the longer-term electrofishing trends. While such declines are evident in both the eastern reference areas (East-Ref) and the Hamilton Harbour AOC, it is important to stress that absolute catch or catchability values for most of the top predators (exception being Northern Pike) are still lower in the Hamilton Harbour AOC compared to the East-Ref areas and the proportion of biomass comprised of top predators (an indication of trophic structure) remains persistently lower (see FP-2A and FP-2B) and more comparable to west reference embayments.

Like top predators, more littoral-oriented native fishes also did not demonstrate increasing catch rates and instead are either declining (e.g., White Sucker and Pumpkinseed), showing no changes in catch (e.g., native minnows), or increased and then declined within the time series (e.g., Bluegill and Yellow Perch). In contrast, in East-Ref areas, catches of native species were largely stable with the exception of Yellow Perch, which declined since P1. More recently (i.e., P3-P4), Yellow Perch have also demonstrated declining trends in multiple data sets within the Hamilton Harbour AOC, and while electrofishing catch at East-Ref areas has also declined, trap net CPUE remains stable as well as electrofishing catchability. Increases in catch and richness of native fishes are critical indicators of recovery for fish populations in the Hamilton Harbour AOC, and at present, the trends are instead indicative of continuing and potentially increasing impairment.

Potentially positive trends include a declining catch of Common Carp and Brown Bullhead; however, both species remain proportionally hyperabundant in the system compared to East-Ref areas. Gizzard Shad, in contrast, have seen marked increases in encounter and catch rates, particularly in the west zone of the harbour during P4. Such increases may be linked to shifts in productivity in the system, which are discussed briefly in the general discussion section. Gizzard Shad can also forage in more pelagic waters, and as noted, more offshore-oriented species have long dominated the catch in the Hamilton Harbour AOC. While some of these species have declined (e.g., Alewife), others, like White Perch and Gizzard Shad, remain in high abundance.

In addition to the limited recovery of native fishes, existing and novel invasive fishes are hampering the recovery of the native fish community in Hamilton Harbour through competition for prey and habitat, as well as habitat degradation. Common Carp were first detected in Hamilton Harbour in the late 1880s, and by the mid-1950s, they had become one of the most abundant species following the collapse of the native fishery (Holmes and Whillans 1984). As noted above, Common Carp have declined in the catch significantly since the initial listing of the Harbour AOC due to management efforts; however, they are still one of the top contributors to overall biomass in the system. Removal efforts to keep populations low and manageable should continue, which may lead to improvements in habitat conditions in areas where they are restricted (e.g., Cootes Paradise).

The arrival of two novel invasive fishes during the study period (Round Goby and Rudd) and recent increases in the catch of Goldfish and White Perch present new challenges concerning the recovery of the native fish community in Hamilton Harbour. Goldfish were first detected in the harbour during surveys conducted between 1960 and 1961 (Whillans 1979). In the 1970s, there was an established population of Goldfish at the west zone of the harbour but they had died off by the end of the decade and the cause was attributed to reproductive failure associated with industrial contamination (Munkittrick and Leatherland 1984). Goldfish were rarely captured (i.e., ≤0.02) during routine fish community surveys (1992-2002) until recently (mid-2000s), when an increase in numbers was observed alongside a decline in Common Carp (Boston et al. 2016, 2024; Ontario Ministry of Natural Resources and Forestry 2020). In addition, the Eurasian Rudd was first detected in the harbour in 2006 and an established population currently exists based on electrofishing and trap net data. Furthermore, an increase in the abundance of White Perch, as noted through trap net surveys, is concerning, and further assessment of the Hamilton Harbour population may be warranted to better understand the impacts that this species may have on native fish recovery.

Multiple lines of evidence were used to assess species-specific catch trends (electrofishing, trap nets, fishway counts), population size (mark-recapture PIT study), and fish movement (acoustic telemetry) in the Hamilton Harbour AOC and at Lake Ontario reference embayments. Using multiple gear types (e.g., active vs. passive) provides a more holistic assessment of fish assemblages in an area due to different gear restrictions related to sampling locations (e.g., depth, physical habitat conditions, area sampled) and differences in species mobility (i.e., different capture rates for sedentary vs. mobile fishes). Furthermore, we noted seasonal differences in fish catches and made recommendations for species that are largely (e.g., Alewife and White Sucker) or partially (Walleye) absent from the harbour during the summer when the majority of sampling occurs. If the sampling programs came to different conclusions about the status of a species, those differences were discussed within each species section.

Generally, the timing of declines in catch for most fish species typically occurred from either P2 to P3 or from P3 to P4. Overall increases in abundance for species typically peaked in P2, while some increases were delayed and not noted until P3. Following these increases, we noted declines in P4 in multiple species back to similar levels documented during the initial listing of the harbour. Overall, the fish community and species analyzed in this section do not appear to be in a stable state and are still changing due to various interactions. Additions of Walleye to the system, one of the main changes in P4, may have affected the native forage base and consequently, other native piscivores while also reducing resource competition for some non-native fishes (e.g., White Perch). Further work such as characterizing the available native and non-native forage prey base throughout Hamilton Harbour and gaining a better understanding of the food web structure through bioenergetics modelling and diet analysis of stocked Walleye, will be required to fully understand the effects of Walleye additions on the system. While there has been a significant reduction in the invasive Common Carp population, there have been increases in other existing (Goldfish and White Perch) and novel (Round Goby and Rudd) invasive species populations, which should be monitored in the future. Water quality issues driven by increased urbanization, densification, and watershed hardening persist and are expected to continue. The availability of food sources for fish species at all trophic levels remains largely unknown in the Hamilton Harbour AOC. Lake-wide trends in fish catches suggest that factors outside of the AOC may also affect local fish populations, particularly for fishes that are not exclusively resident to the harbour. These and other stressors are discussed in more detail in the “General Discussion” section of this report.

Future species-specific recommendations include reducing adult mortality of important sport fishery species (i.e., piscivores). To address adult mortality of these species we recommend: 1) conducting creel surveys in the Hamilton Harbour AOC to better understand recreational fishing pressures, specifically in the west zone, where fish residency and angling pressure appear to be high, and 2) limiting lethal sampling in monitoring programs. Continued monitoring of fish populations is recommended for future comparisons, including population estimates for marginal species (e.g., Northern Pike). These population estimates can be linked to estimates of habitat supply, information that was not available for this assessment but could provide more informed BUI targets (e.g., predicted trophic proportions based on available habitat). It would also be helpful to explore the trap net data on a zonal basis to see if there are similar patterns in catch and richness within the harbour as observed in the electrofishing sampling. This spatial breakdown would also support a more formal statistical comparison of trap net-based catch. Finally, additional reference areas comparable to Hamilton Harbour in terms of habitat and bathymetry (e.g., Wellers Bay) and routine monitoring will help discern the effects of lake-wide and local stressors on the fish community in the Hamilton Harbour AOC.

CRITERION FP-1B: OVERALL FISH COMMUNITY

SUMMARY

Fish species presence data (see Table 4 for data sources and gear types) were compiled from 1985-2022 from Fisheries and Oceans Canada, Ontario Ministry of Natural Resources and Forestry, Royal Botanical Gardens, Hamilton Conservation Authority, and Conservation Halton. A total of 92 fish species were found in eight sectors (Hamilton Harbour, Cootes Paradise, Cootes Paradise Fishway, Grindstone Creek, Indian Creek, North Shore Tributaries, Red Hill Creek and Spencer Creek). Within Hamilton Harbour specifically, 55 species were detected between 1985 and 2012, and 43 species from 2013 to 2022. Since 2013 there have been declines in species richness in Hamilton Harbour, Cootes Paradise, Cootes Paradise Fishway, as well as four out of the five watersheds in the Hamilton Harbour AOC. These declines occurred across multiple guilds, even among fishes tolerant to low dissolved oxygen and other measures of ecosystem degradation. Reinforcing these declines in fish community diversity, the species most abundant in Hamilton Harbour are primarily tolerant to low dissolved oxygen and feed on invertebrates or plants/algae (e.g., Gizzard Shad, Common Carp, and Goldfish), and there are fewer dissolved oxygen meso-tolerant piscivores like Largemouth Bass and Northern Pike. The presence of hypoxic conditions in the harbour prevents species sensitive to low dissolved oxygen from thriving, and likely limits the recovery potential of coldwater fishes in particular. The loss of several benthic species [Johnny Darter (*Etheostoma nigrum*) and Tadpole Madtom (*Noturus gyrinus*)] within Hamilton Harbour can likely be attributed to exploitative competition with the invasive benthic Round Goby. Although these benthic species are no longer found in the Hamilton Harbour proper, they are found elsewhere in the watershed draining into the harbour. The overall decrease in species richness cannot be attributed to a single factor, but instead is likely driven by a combination of factors including: poor water quality, thermal intolerance, competition, impaired benthic conditions, prey-availability, lake-wide trends in fish community, and urbanization in the watershed.

KEY MESSAGES

- Electrofishing-based surveys in the harbour indicate significant temporal changes in the overall fish community; zonal (east, north, and west) differences in fish assemblages were identified.
- As of 2013, the Hamilton Harbour fish community was distinct and not significantly correlated to any other Lake Ontario embayments.
- A large proportion of the fish biomass in the harbour is linked to tolerant invertivores and herbivores (e.g., Gizzard Shad, Common Carp, Brown Bullhead, and Goldfish); there were low incidences of many of the desirable species

identified in the delisting criteria as meso-tolerant carnivores (e.g., Largemouth Bass).
- A total of 92 different fish species have been observed in the Hamilton Harbour watershed since 1985. In the harbour proper, 55 were detected between 1985 and 2012, but only 43 species have been observed since 2013.
- There have been declines in species richness since 2013 in Hamilton Harbour, Cootes Paradise, and the Cootes Paradise Fishway, as well as the watersheds draining into Hamilton Harbour with the exception of the Red Hill Creek watershed, which had low species richness prior to 1996 followed by extensive restoration works.
- Competition with Round Goby is a potential driver of declines and losses to benthic fish species [e.g., Logperch (*Percina caprodes*) and Johnny Darter] and other native species (e.g., Pumpkinseed) that compete for invertebrate resources in the harbour.
- Presence of summer hypoxic conditions is likely to limit the recovery of coldwater fishes for the foreseeable future.
- The data suggests a combination of environmental factors (e.g., biotic competition, impaired benthic environment, poor water quality) are contributing to declines in species richness.

REMAINING CONCERNS AND UNCERTAINTY

- The species-presence dataset was compiled from multiple datasets that used different sampling gears with variable effort, both factors that can influence species detection. As such, absences within the dataset should be interpreted with caution.
- Seasonal sampling bias is also present in the data. Seasonally transient fishes may be underrepresented but would likely contribute little to the resident fish community structure.
- Recent (post-2012) declines in the presence of some fish species are likely driven by multiple different stressors, but the magnitude of the effect from various stressors, and the influence of ongoing ecosystem degradation or shifting trophic structure, remains unclear.

FUTURE MONITORING

- Maintaining standardized trap netting and boat electrofishing surveys in Hamilton Harbour and regional reference locations is important to help contextualize changes in the AOC.
- A comprehensive benthic invertebrate community survey should be conducted across the harbour to assess the status of prey resources for native fishes; benthic invertebrate surveys have not been conducted since the early 2000s and, to our knowledge, the most recent data (2014) indicate declines in some species.

RECOMMENDED ACTIONS

- Fisheries and Oceans Canada should complete an assessment of fish community changes (Community Trajectory Analysis; De Cáceres et al., 2019) among Hamilton Harbour AOC, Toronto and Region AOC, and the Bay of Quinte using the long-term electrofishing dataset.
- The extent of connectivity among distinct habitat ecotypes within the Hamilton Harbour AOC and its watershed should be quantified since movement corridors within suitable habitats will be important to support the dispersal and recolonization of species currently with low abundance.

BACKGROUND

In a large, sheltered embayment such as Hamilton Harbour, a healthy fish community should include a diverse species assemblage that is able to use the available habitat to forage during all life stages and reproduce. Ideally there would be a mix of cold, cool and warmwater species that can utilize the resources of different thermal habitats and forage across trophic levels. The community should exhibit varied habitat preferences, such as riverine or lacustrine (lake), as well as a mix of species that are benthic (bottom feeders) and pelagic (open water feeders). In general, a more diverse fish community reflects a more resilient aquatic environment that is better equipped to deal with environmental changes.

Historically, the mix of deep, cold water in Hamilton Harbour, warm, vegetated shallow waters in Cootes Paradise, and riverine habitat in the watersheds draining into the harbour, sustained a diverse and productive fish community (Whillans 1979). The fish community has changed substantially since the 1800s when European settlements began to expand which eventually led to the listing of Hamilton Harbour as an Area of Concern (AOC) in 1985 (HHRAP 1992a, b). Fish community shifts can be linked to habitat and water quality changes (e.g., decreased access to coldwater habitat due to hypoxia, loss of warmwater vegetated habitat, and degradation of stream habitat), as well as overfishing, both commercially and recreationally (Holmes and Whillans 1984). Hamilton Harbour historically supported a diverse coldwater fish community including Lake Trout (*Salvelinus namaycush*), Lake Herring (*Coregonus artedii*), and Deepwater Ciscos (*Coregonus sp.*), with numbers high enough to support a commercial fishery (Holmes and Whillans 1984). Overexploitation of the fishery and declining water quality conditions (i.e., contaminants, hypoxic zones) in the harbour led to the decline and extirpation of coldwater species. Spawning runs of Atlantic Salmon (*Salmo salar*) and Lake Sturgeon (*Acipenser fulvescens*) were known to have occurred in Red Hill Creek and Spencer Creek, but they were extirpated from the harbour by the late 1800s, largely due to the degradation of stream habitat and overexploitation. Warmwater fishes such as Northern Pike, Smallmouth Bass, Largemouth Bass, and suckers (*Catostomidae*) were historically abundant in both Cootes Paradise and Hamilton Harbour; however, a loss of 74% of the total marsh area in the Hamilton Harbour watershed, combined with overfishing, led to continued population declines (Holmes and Whillans 1984). Species tolerant to poor water quality conditions such as Common Carp were able to take advantage of the changes in the harbour and occupy the niche left by other declining populations. A total of 59 species were found in Hamilton Harbour in the early 1980s with an additional 14 species considered extirpated at that time. Overall, by 1985 the fish community in Hamilton Harbour was less diverse, had a lower abundance and proportion of top predators and coldwater species, and a higher proportion of generalist species (Holmes and Whillans 1984; Holmes 1988).

Since the designation as a Great Lakes Area of Concern (AOC) in 1985 and the subsequent implementation of a Remedial Action Plan (RAP), there have been several factors that have continued to impact the fish community in Hamilton Harbour. Stressors have included invasive dreissenid mussels (*Dreissena polymorpha/ Dreissena bugensis*), predatory zooplankton and fishes (e.g., Round Goby, Goldfish), climate change, water quality issues, urban expansion, industrial pollution, and water level fluctuations (IJC 2009; Boston et al. 2016; Collingsworth et al. 2017). Conversely, there have also been a number of restoration projects that have sought to improve fish habitat and water quality (Boston et al. 2016). Collectively these factors continue to affect the present-day fish community and have been the focus of multiple research and monitoring studies in the harbour (see Bowlby et al. 2009; Brousseau et al. 2011; Hiriart-Baer et al. 2016; Bowlby and Hoyle 2017; Visha et al. 2021).

As part of the Hamilton Harbour RAP, delisting targets were established to help guide and assess fish community impairment (see History of Fish Populations Section). The first delisting target for the Hamilton Harbour AOC is fish community focused; its stated goal is to: *“Shift from a fish community indicative of eutrophic environments (e.g. White Perch, Alewife, bullheads, and carp) to a self-sustaining community more representative of a mesotrophic environment with a balanced trophic composition that includes top predators (e.g. Northern Pike, Largemouth Bass and Walleye) and other native species (e.g. Suckers, Yellow Perch and sunfishes)”* (HHRAP 2019). While section FP-1A documents species-specific trends through time and relative rates of capture compared to areas outside the Hamilton Harbour AOC, the focus of this section is on the fish community more generally and changes in community composition through time. First, we briefly reviewed works that explored changes in fish community composition or contrasted the Hamilton Harbour AOC with fish communities in other parts of Lake Ontario. We then provided an overview of species presence and richness both within the harbour proper itself and its adjacent watersheds. The objectives of this second component were to: identify species that have not been recently (i.e., since 2012) observed within the harbour, assess whether these species were present in harbour watersheds, and explore patterns of occurrence across different fish guilds within the harbour and surrounding watersheds.

SUMMARY OF PAST FISH COMMUNITY WORK

Due to the morphology of Lake Ontario, there are few sheltered embayments comparable to Hamilton Harbour that have a similar bathymetric profile and a mix of warm, cool, and cold water. As such, finding suitable reference locations or a baseline for conditions in Lake Ontario is challenging. The most comparable sites are in eastern Lake Ontario in the Bay of Quinte and Prince Edward County, as well as Jordan Harbour and Frenchman's Bay in western Lake Ontario. Hamilton Harbour is also often compared to Toronto Harbour since they share similar stressors, although Hamilton Harbour is less influenced by intrusions of cool/cold waters from Lake Ontario (Hlevca et al. 2015). Bowlby and Hoyle (2017) evaluated fish catch data from trap netting (2006-2013) in impaired embayments (Hamilton Harbour and Toronto Harbour) and compared it to unimpaired embayments, finding that the Hamilton Harbour fish community was distinct and not significantly correlated to any other Lake Ontario embayments. The main driver for this difference was relatively higher abundances of Brown Bullhead, Channel Catfish (*Ictalurus punctatus*), and White Perch, and lower abundances of Smallmouth Bass and White Sucker in Hamilton Harbour (Bowlby and Hoyle 2017). Similarly, Boston et al. (2016) found a dominance of generalist species in Hamilton Harbour such as Brown Bullhead, Channel Catfish, and Common Carp, and offshore species like White Perch and Gizzard Shad. A low abundance of many of the delisting target species (e.g., Rock Bass, Pumpkinseed, Bluegill, Smallmouth Bass, Largemouth Bass, Black Crappie, and Walleye) in the Hamilton Harbour AOC further differentiated it from other sites (Bowlby and Hoyle 2017). Only Northern Pike and Yellow Perch catches were comparable in the harbour relative to unimpaired embayments (i.e., not significantly different) (Bowlby and Hoyle 2017). Overall, between 2006 and 2012, there were 28 fish species identified using both electrofishing and trap netting, which is less than half of the historical species richness (Holmes and Whillans 1984; Boston et al. 2016).

A key interest of this assessment is temporal change within the harbour, and to truly understand how the fish community has changed over time, a holistic look at the fish community assemblage is required; community ordination techniques (e.g., non-metric multidimensional scaling; McCune and Grace 2002) can support this type of assessment. A recent study assessing the influence of island creation within the Hamilton Harbour AOC documented large-scale temporal shifts in fish community composition at both island and non-island locations between 1988 and 2019 (Maynard et al. 2022). While the presence of islands was found to have a small but positive impact on some components of the fish community (e.g., higher Index of Biotic Integrity scores, more sensitive species and Centrarchids, and fewer generalist species and individuals), in the 30-year time series, the addition of an island explained far less variance in community composition than the random effect of year (Maynard et al. 2022). This suggests that systemic changes in fish community composition driven by interannual variation in factors other than those explored in Maynard et al. (2022) were a more important driver of fish community change. Put simply, the fish communities at harbour locations included in Maynard et al. (2022) as of 2019 were markedly different from those at the same locations in 1988.

Specific species were identified as driving the temporal shifts in the fish community, with six species showing increases in catch [e.g., Gizzard Shad, Brook Silverside (*Labidesthes sicculus*), and Rock Bass] while 12 others declined (e.g., Alewife, White Perch, and Pumpkinseed; Maynard et al. 2022). However, given that this study was focused solely on the Hamilton Harbour AOC, it was unable to tease out whether the changes in the fish community were influenced by lake-wide or Hamilton Harbour specific factors. As suggested in sections FP-1A and FP-2A, declines in specific species and fish community metrics do appear to be largely Hamilton Harbour specific; however, some changes were also evident in other areas in Lake Ontario, such as declines in non-native species richness from electrofishing surveys. From the perspective of the RAP delisting targets, declines in White Perch, Alewife, Brown Bullhead, and Common Carp are all positive indicators if associated with concurrent increases in desired target species (e.g., Northern Pike, bass, sunfish, and Yellow Perch). However, results from Maynard et al. (2022) did not detect an increase in the desired species and instead present data that is consistent with an overall decline in fish abundance (see section FP-2A) and not a positive change in the fish community structure.

HARBOUR AND WATERSHED FISH COMMUNITY PRESENCE

As the Hamilton Harbour fish community is not meeting delisting criteria and clear evidence exists that some native fishes have declined (see sections FP-1A and FP-2A), we undertook a preliminary evaluation of fish species’ presence in the harbour and surrounding watersheds. There were two primary objectives for this preliminary exploration. First, to identify species that have historically been observed in the harbour but are absent in sampling records since 2013, and second, to identify potential source populations for recovery of species in low abundance or those that have been largely extirpated from the harbour itself. Species were also grouped based on trophic, thermal, habitat, and diet guilds to help identify/interpret patterns in species presence among watersheds.

METHODS AND DATA SOURCES

Littoral (< 5 m depth; Goforth and Carman 2009) fish assemblage data were compiled from multiple sources (Table 4). Although this is an extensive list of sources and datasets, it is likely missing some data, particularly site-specific studies not included in long-term datasets. Fish species were assigned to thermal (cold, cool or warm), habitat (lacustrine, riverine/lacustrine, riverine), feeding (pelagic, benthic, benthopelagic), and diet (invertivore, carnivore, herbivore, detritivore and planktivore) guilds based on the Ontario Freshwater Fishes Life History Database (OFFLHD; www.ontariofishes.ca). Tolerance to dissolved oxygen was based on findings from Tang et al. (2020). Similar to DiBattista et al. (2022), we focused more on documenting species presence or occurrence, and thus, distinct gear types were combined into a single presence dataset despite known differences in catchability (see Portt et al. 2006). While no-catch information is not definitive of absence, the capture of a single individual suggests some level of persistence. It is understood that a single individual may be suggestive of lower abundances, particularly when sampling effort is high, and may also be associated with sampling bias due to gear, season, and time of day, which highlights the importance of the associated trend data.

The study area for this analysis consisted of the littoral zone of the harbour proper and the watersheds draining into the harbour, which together are herein called the Hamilton Harbour watershed. Location data was used to group sites into sectors, including those that were more lake-influenced (i.e., Hamilton Harbour, Cootes Paradise, Cootes Paradise Fishway [herein called Fishway]) and those that were watershed-influenced (Grindstone Creek, Spencer Creek, Indian Creek, Red Hill Creek, North shore tributaries) (Figure 33).

To facilitate analyses of temporal trends, the same four time stanzas used in FP-1A and FP-2A were defined as: P1 – 1985-1994 (initial Dreissena invasion), P2 – 1995-2004 (Shift in dominance to Quagga mussels and completion of major habitat projects in Hamilton Harbour), P3 – 2005-2012 (Round Goby are fully established), and P4 – 2013-2021 (cold winter of 2012/2013 and Walleye stocking). For this section, we have combined P1, P2, and P3, to compare against the most recent stanza, P4. As noted in other sections throughout this report, time stanzas roughly aligned with a variety of ecosystem and community changes in the system. Rarity was calculated as the cumulative total of a fish species' presence in each of the eight sectors during each time stanza (P1, P2, P3, P4); the maximum possible number of "presences" was thus 32. Species that were detected in at least 20/32 (>63%) time stanzas and watersheds combinations were considered "prolific", those with 15 to 19 occurrences (47 – 59%) were "very common", 6 to 14 (19 – 43%) were "common", 3 to 5 (9 – 16%) were "rare", and species detected in two or fewer (<6%) watersheds/time stanzas combinations were considered "very rare". The species distribution data were examined, and specific breakpoints were assigned based on natural breaks in the data and a pre-established goal of having more species in the “common” group and fewer in the “very rare” or “prolific” groups. This categorical assignment of rarity should not be interpreted as indicative of the abundance of an individual species within any time stanza or sector. Percent change within a guild between P1-P3 (1985 to 2012) and P4 (2013 to 2021) was calculated as the mean of the percent change within sectors.

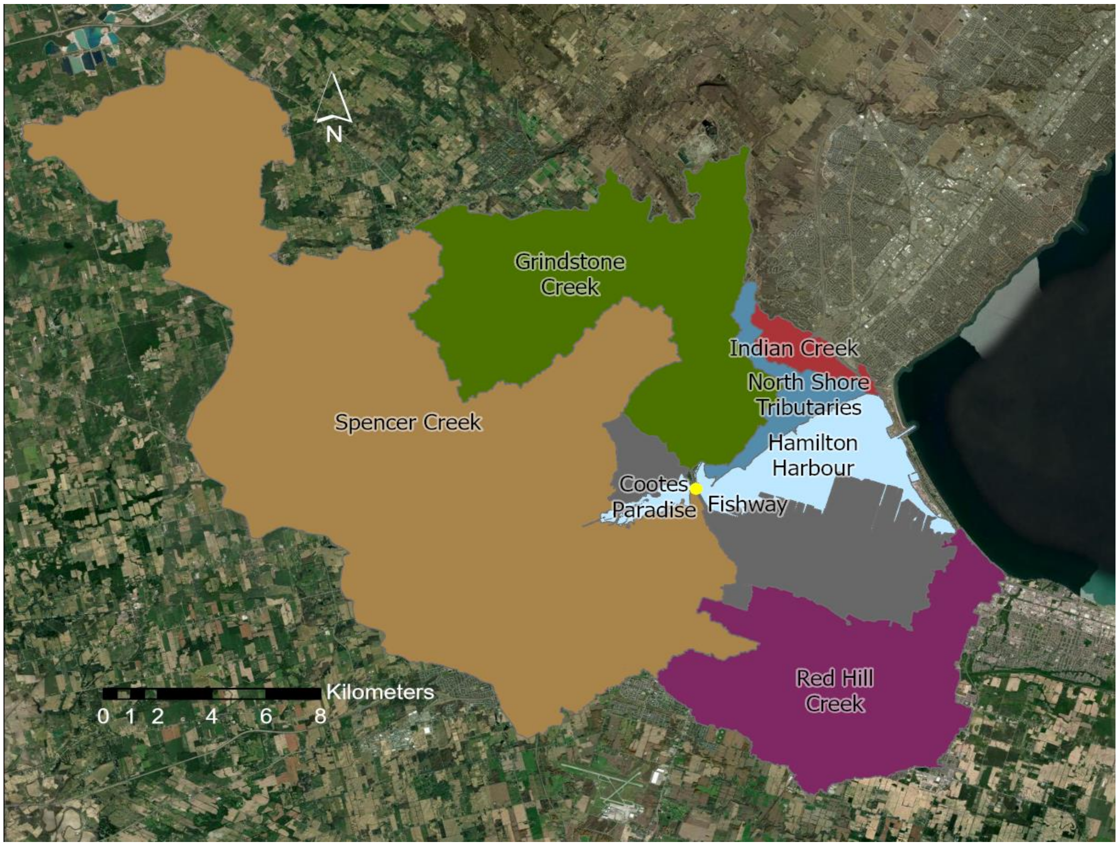

Figure 33. *Location of the eights sectors (Hamilton Harbour, Fishway, Cootes Paradise, Red Hill Creek, Spencer Creek, Grindstone Creek, Indian Creek and North Shore Tributaries) where fish presence data were collected and evaluated.*

Table 4. *Data sources used for fish community presence analysis. The number of years when each data source collected information per time stanza is also shown. P1 = 1985-1994; P2 = 1995-2004; P3 = 2005-2012; and P4 = 2013-2021.*

Organization	Sampling program	Gear	Years	Years Sampled Per Time Stanza
Fisheries and Oceans Canada	Long-term monitoring	Boat electrofishing	1988-2021	P1 = 4; P2 = 5; P3 = 4; P4 = 6
Fisheries and Oceans Canada	Northern Pike sampling	Fyke nets	2020-2021	P4 = 2
Halton Conservation Authority	Long-term monitoring and projects	Mixed – electrofishing, seining, dip nets, minnow traps	1985-2022	P1 = 7; P2 = 11; P3 = 7; P4 = 8
Hamilton Conservation Authority	Long-term monitoring and projects	Backpack electrofishing	1985-2022	P1 = 8; P2 = 11; P3 = 7; P4 = 10
McMaster University (Appendix F)	Fish community near Sewage Treatment Plant Outfalls	Mixed – Backpack electrofishing, fyke nets, minnow traps, Windemere traps	2016-2019	P4 = 4
McMaster University (Appendix E)	Long-term goby monitoring	Minnow traps	2002-2022	P2 = 4; P3 = 7; P4 = 10
Ontario Ministry of Natural Resources and Forestry	Long-term Trap netting program	Trap nets	2006-2021	P3 = 4; P4 = 6
Royal Botanical Gardens (Appendix G)	Long-term monitoring	Boat electrofishing	1994-2022	P1 = 1; P2 = 11; P3 = 7; P4 = 10
Royal Botanical Gardens	Fish passage through Fishway	Fishway	1996-2022	P2 = 10; P3 = 7; P4 = 10
Royal Botanical Gardens	Long-term monitoring	Small trap nets	1989-2022	P1 = 1; P2 = 4; P3 = 5; P4 = 5

RESULTS AND DISCUSSION

A comparison of species presence between P1-P3 and P4 across the eight sectors of the Hamilton Harbour AOC found a decline in species richness. It is important to note that species that may have only been encountered a limited number of times could be the result of misidentification in the field, and the fact that a species was not found during a time period or in a sector does not indicate that it was not there, since timing, sampling effort, gear bias, or species behaviour/phenology may have been factors in their absence. It should also be noted that a significant seasonal bias occurs within the data, with the majority of sampling occurring the late spring, summer, and early autumn.

In the Hamilton Harbour sector, specifically, 14 species were encountered in P1-P3 but not in P4 (Table 5), yet nine of these were present in at least one other sector in the system and five [Cisco (*Coregonus artedi*), Golden Redhorse (*Moxostoma erythrurum*), Muskellunge (*Esox masquinongy*), Silver Redhorse (*Moxostoma anisurum*), and Trout-Perch (*Percopsis omiscomaycus*)] were not found in any other sectors in P4. Of the nine species present in sectors other than the Hamilton Harbour sector, five species [Rainbow Smelt (*Osmerus mordax*), Tadpole Madtom, Threespine Stickleback (*Gasterosteus aculeatus*), Sea Lamprey (*Petromyzon marinus*), and White Crappie (*Pomoxis annularis*)] were only found in one sector in P4. In general, these species were not frequently observed in the data record (1985-2021; 5/14 were listed as “rare” or “very rare”). Muskellunge, in particular, are very rare in the system, and while there was interest in re-introducing this species in the early 2000s due to water quality and habitat improvements in the littoral zone (Theijsmeijer et al. 2003), changes in habitat productivity detailed in section FP-2A likely make this less feasible at this time, and reintroduction could be further challenging due to competition with Northern Pike and Walleye. Twelve of the 14 species not found in P4 included invertebrates in their diet, which points to potential limitations in food availability. A lack of recent benthic invertebrate sampling makes it difficult to draw conclusions about the invertebrate community in P4. Milani and Grapentine (2017) found declines in the invertebrate Pionidae (mites) in benthic samples collected from the harbour between 2000 and 2014 and severely toxic sediments at the west end, north shore, and east end of the harbour. Milani and Grapentine (2017) also looked at the survival of the worm *Tubifex tubifex* and found improvements in the percentage of hatched cocoons and number of young per adult between 1990 and 2000, followed by declines back to pre-1990 levels by 2014. Paired with past assessments of impaired benthic invertebrates (Dermott et al. 2007), limited benthic foraging opportunities may affect some species of benthivorous fishes.

Coldwater species in Hamilton Harbour have declined the most in richness (proportionally) since 2013 compared to coolwater or warmwater species, including the loss of Cisco, Sea Lamprey, and Trout-Perch. Cisco are considered very rare now in the study area, so it is not surprising that they were not found in P4; however, it is important to note that none of the datasets compiled here are designed to explicitly sample for Cisco (i.e., limited sampling in the late fall and early winter), which may limit their detection potential for all time stanzas. During the 2016 Hamilton Harbour Walleye surveys, two Cisco were captured in the Farr Island shoal while electrofishing (the dataset was not included as the protocol is not a community assessment; D. Reddick pers. comm.). Mid-water trawling, which is better suited to detect pelagic species, did not find Cisco in Hamilton Harbour (J. Midwood unpublished data). Cisco are largely limited by water temperature (< 20°C) and dissolved oxygen (> 6 mg/L) preferences, and consequently, they can only occupy a narrow band of water in Hamilton Harbour during typical sampling windows (e.g., during summer). Bowlby et al. (2016) looked at thermal and dissolved oxygen limitations to Cisco habitat in Hamilton Harbour using data from 1987 to 2012. From 1987-2002, optimal habitat was estimated to be absent for 1-7 weeks per year. From 2002 to 2012, Cisco habitat was found to have improved markedly, where both the number of weeks of impaired habitat and the number of weeks of absent optimal habitat declined (Bowlby et al. 2016). Improvements have been noted in dissolved oxygen at the center of the harbour over time (D. Depew; unpublished data), but high variability and frequent upwellings of anoxic hypolimnetic waters (Flood et al. 2021) likely make the harbour uninhabitable for Cisco across all seasons. Similarly, the loss of historic spawning beds and ongoing challenges with sedimentation of remaining spawning habitats likely limit Cisco population recovery as well.

Sea Lamprey, a non-native coldwater species, were rarely encountered during the study period. They are actively controlled in the Great Lakes, so their absence from the Hamilton Harbour AOC is not surprising. They are, however, occasionally captured at the Cootes Paradise Fishway, suggesting that they are still present at low levels throughout the system. Finally, Trout-Perch were common among sectors in P1-P3 and preferred deeper waters during the day, moving to shallow water at night (Scott and Crossman 1998). Their decline in P4 may be due to reasons similar to Cisco in terms of dissolved oxygen limitations at depth during the summer months. However, given the timing of their extirpation (between P2 and P3), Round Goby invasion is likely an important factor in their decline given some evidence for dietary overlap between these two species (Burkett and Jude 2015). Both of the native coldwater species were not found elsewhere in the harbour in P4, so the possibility for recolonization from within the harbour and watersheds for Cisco and Trout-Perch is not thought to be possible and would require immigration from other Lake Ontario populations.

The compiled dataset focused exclusively on survey techniques that sample littoral areas. Two of the species captured in P1-P3 (Rainbow Smelt and Threespine Stickleback) were observed in only one sector in the compiled dataset in P4, but were observed in pelagic waters of the harbour during recent mid-water trawling surveys (Midwood et al. 2019). Rainbow Smelt are not native to Lake Ontario and were introduced in Lake Michigan in the early 1900s and spread throughout the Great Lakes (Evans and Loftus 1987). Rainbow Smelt were considered common during the study period but in P4 only one individual was captured at the Cootes Paradise Fishway. During mid-water trawl surveys, adult Rainbow Smelt were primarily captured in a similar location (west end of the harbour) in the spring, which coincides with their spawning window (Scott and Crossman 1998). Declining offshore productivity in the Great Lakes since the early 2000s, related to offshore reduced phosphorus and the introduction of invasive Zebra/Quagga mussels (*Dreissena spp*), Spiny Waterflea (*Bythotrephes longimanus*), and Round Goby, has contributed to the significant basin-wide decline of Rainbow Smelt (Dai et al. 2019), which is likely reflected in the decline in Hamilton Harbour occurrences. The second species, Threespine Stickleback, was also common during the study period and found in six of the eight sectors in P1-P3, but only in the North Shore tributaries during P4. While previously captured in the harbour itself during P2, Threespine Stickleback have not been observed in its littoral waters since; however, a small number (N=3) were captured in mid-water trawls in 2016 (Midwood et al. 2019), but none during similar surveys in 2018 (J. Midwood, unpublished data). In Lake Ontario, Threespine Stickleback have declined in abundance since the early 2000s and have remained low since 2005 (Weidel et al. 2021). However, they are frequently captured in north-central Lake Ontario and in mid-water trawls in Toronto Harbour (Midwood et al. 2018), suggesting local habitat conditions in the Hamilton Harbour AOC may be partially limiting for the species. Identification of the limiting environmental factors for Rainbow Smelt and Threespine Stickleback in the harbour, as well as in Lake Ontario, is an important next step as both are important prey fishes for other pelagic species (Weidel et al. 2021).

Two benthic species, Tadpole Madtom (commonly found across time stanzas and sectors) and Johnny Darter (very common), were both missing from surveys in Hamilton Harbour proper in P4 but were found in other sectors (Table 5). Both species are coolwater benthivores, tolerant of low dissolved oxygen, and share similar diet and habitat preferences with the invasive Round Goby. A number of studies have looked at Round Goby and native benthivorous fishes and have found mixed results in terms of direct competition (Burkett and Jude 2015; Leino and Mensinger 2016); however, Firth et al. (2021) found significant diet overlap between Johnny Darter and Round Goby in the Sydenham River, Ontario. In the harbour proper, Johnny Darter have not been recorded since P2, so their absence in the system does coincide with the arrival of

Round Goby. Tadpole Madtom were more common in Grindstone Creek and Spencer Creek than in Hamilton Harbour in P1-P3, but by P4, were only found in Grindstone Creek, although less frequently, which points to greater declines in Tadpole Madtom in the watersheds than in the harbour proper. Although these species were not present in P4, there is potential for their re-establishment since they are found elsewhere in the system.

Five of the species that were detected in P1-P3 in Hamilton Harbour but not in P4 are predominantly riverine fishes. Occurrences of these species were infrequent in the harbour itself, suggesting that the few that were caught in P1-P3 in Hamilton Harbour are likely individuals that moved down from one of the tributaries. Western Blacknose Dace (*Rhinichthys obtusus*), Central Mudminnow (*Umbra limi*), and Creek Chub (*Semotilus atromaculatus*) continue to be present in at least one watershed (Table 5). In contrast, Golden Redhorse and Silver Redhorse are both considered very rare and while found in Hamilton Harbour, the Fishway, and Spencer Creek in P1-P3, they were not found in P4. Both these species prefer riverine habitat, particularly low-flow main channels with little siltation and pollution and they are also rare within the Great Lakes (Scott and Crossman 1998). The degraded condition of the Hamilton Harbour AOC and its tributaries is likely a limiting factor for these species; however, species identification of redhorse suckers (Moxostomidae) can also be challenging, and vouchers of these specimens may be required. Another riverine species, Brook Stickleback (*Culaea inconstans*), were only detected in the harbour during P4 but were consistently observed from P1-P3 to P4 in the watersheds (Table 5). In general, the presence of predominantly riverine species in the harbour is likely incidental and their presence or absence in Hamilton Harbour specifically is thus likely not explicitly linked to conditions in the harbour.

Thermal and Habitat Guilds

Fish species were categorized based on thermal (warm, cool, or cold), habitat (lacustrine, riverine/lacustrine or riverine), and trophic (pelagic, benthopelagic, or benthic) guilds, all of which experienced declines (Table 5). In general, there was a decline in fish species richness across all sectors of the harbour but the largest mean proportional decline occurred in coldwater species followed by coolwater, and warmwater species (57.0%, 17.1%, and 14.3%, respectively; Figure 34). Patterns in changes in richness by thermal guilds within the harbour reinforce the species-specific changes discussed previously, with coldwater species showing the largest proportional decline. Outside of the harbour proper and the Fishway, Spencer Creek watershed supports the greatest diversity of coldwater fish species (five), including Brook Trout (*Salvelinus fontinalis*), a sensitive coldwater species that has not been documented in any other sector. While coldwater species have not been found during sampling in Cootes Paradise during P4, with the exception of Trout-Perch, they are still encountered at the Cootes Paradise Fishway and in Spencer Creek. The guild that had the greatest species richness in Hamilton Harbour was the warm-riverine/lacustrine-benthopelagic grouping (16 species; declined by 12.5%), which includes Goldfish and Common Carp, that may be able to utilize the more available shallow, silty, and sparsely vegetated habitat than Smallmouth Bass, Largemouth Bass, and Pumpkinseed, that share the same guild yet require different microhabitat features. The cool-riverine/lacustrine-benthic guild (9 species; declined by 33.3%) includes invasive Round Goby, which as mentioned previously, may have contributed to the decline of Johnny Darter and Tadpole Madtom. Not surprisingly, the riverine-benthic habitat guild (regardless of the thermal guild) was absent from the harbour in P4; however, as noted previously, species in this guild were rare to begin with in the harbour and it is likely that their detections therein were incidental.

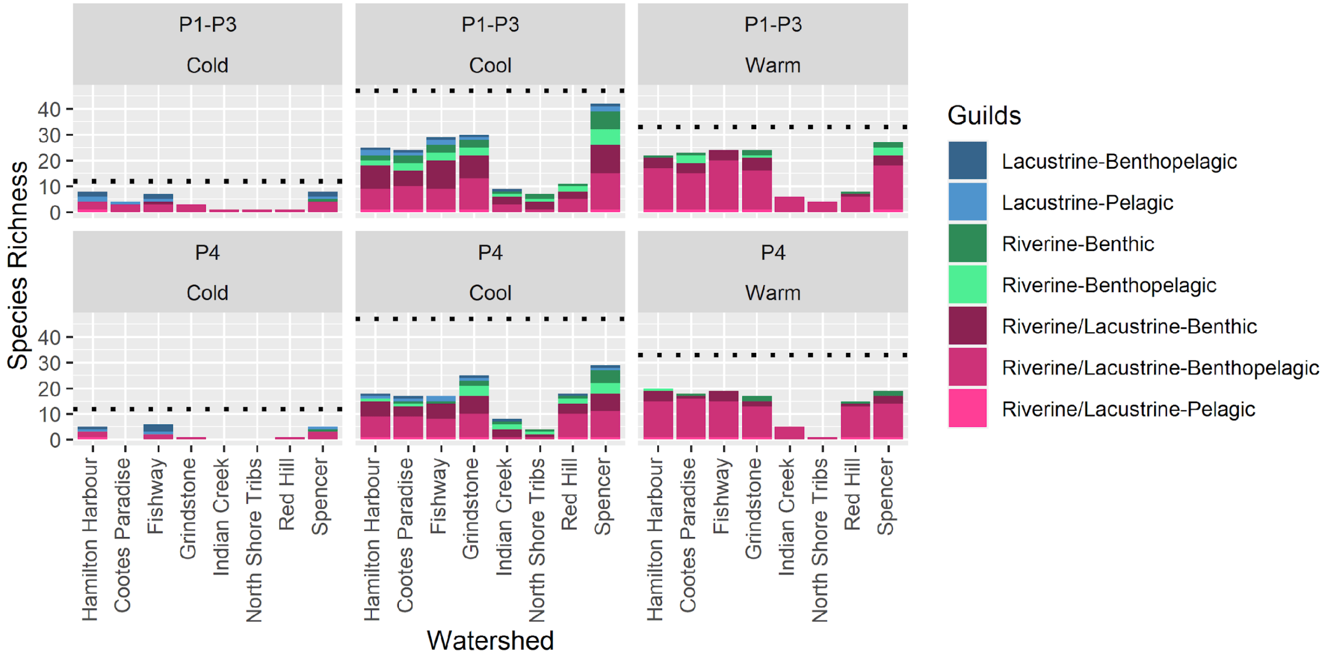

Figure 34. *Species richness by watershed for P1-P3 (top panels) and P4 (bottom panels). Coldwater species are on the left, coolwater species in the middle, and warmwater species on the right. Dotted horizonal line represents the maximum number of species in all sectors for a thermal guild and time period.*

Diet and Dissolved Oxygen Tolerance

Fish species presence was compared between P1-P3 and P4 based on their diets and were classified as carnivores, invertivores, detritivores, herbivores, and planktivores (and in some instances assigned to more than one of these groups; Appendix A). Seventy species included invertebrates in their diet and of those, 14 were sensitive to low dissolved oxygen, 43 were meso-tolerant to low dissolved oxygen, and 13 were tolerant to low dissolved oxygen. Sensitive invertivore species including Brook Trout, Redside Dace (*Clinostomus elongatus*), Cisco, and Northern Hog Sucker (*Hypentelium nigricans*) were not detected in the harbour or watersheds, with Logperch as the sole sensitive species present. Invertivores tolerant to low dissolved oxygen included some of the more abundant species, like Brown Bullhead and White Sucker, and invasive species, like Common Carp and Goldfish (see FP-1A, FP-2A). Declines in invertivores were seen across all three levels of dissolved oxygen tolerances, but the greatest declines were seen in the meso-tolerant group, with some watersheds (Cootes Paradise and Spencer Creek) seeing a drop of more than 10 species between P1-P3 and P4 (Figure 35). Within the sensitive species grouping, Cootes Paradise and Grindstone Creek also had a larger proportion of decline (67% and 50% decline respectively). The smallest change in species richness was in the species groups that were tolerant to low dissolved oxygen, with declines of only one or two species between P1-P3 and P4 (Figure 35).

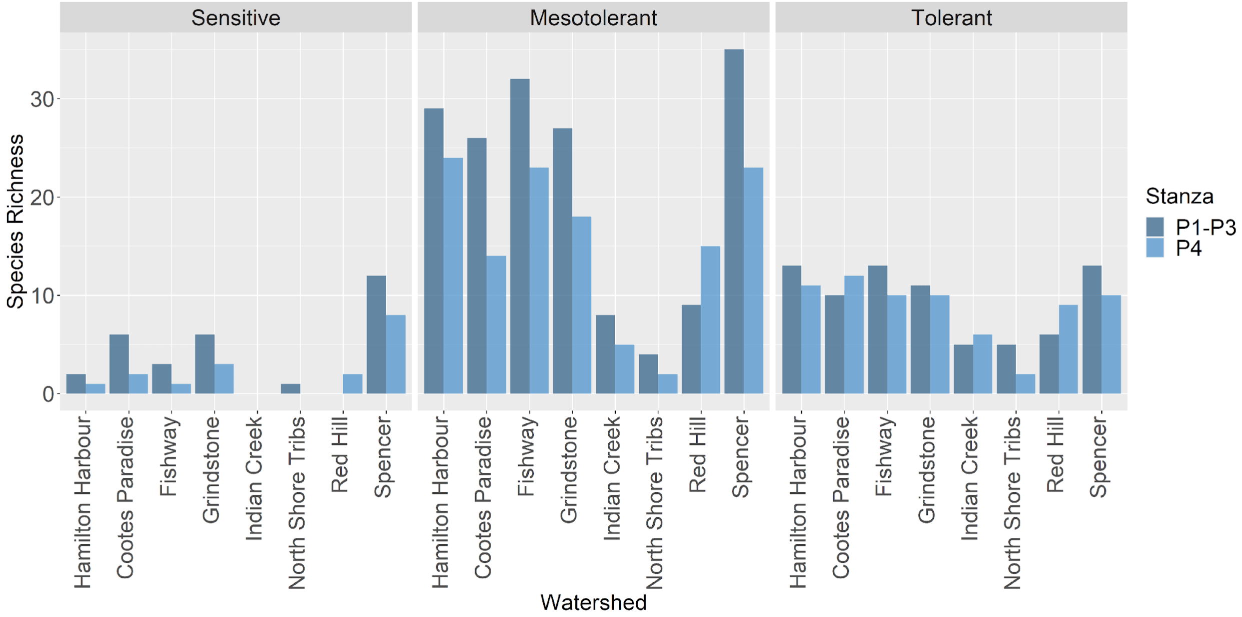

Figure 35. *Species Richness of Invertivores for P1-P3 (light blue) and P4 (dark blue), including sensitivity to low dissolved oxygen levels. Invertivores feed on invertebrates including insects, molluscs and crustaceans (based on OFFLHD; www.ontariofishes.ca).*

A total of 34 carnivorous species were found in Hamilton Harbour and surrounding watersheds, including one sensitive (Brook Trout), 25 meso-tolerant, and six tolerant species. Brook Trout have only been found in the Spencer Creek watershed but they were present in P1-P3 and P4 (Figure 36). Species richness declines were greatest in the meso-tolerant group, followed by the tolerant group (18% and 14%, respectively; Figure 36). Many desirable sport fish species for Hamilton Harbour are meso-tolerant carnivores, including Northern Pike, Largemouth Bass, Smallmouth Bass, and Yellow Perch. Tolerant carnivores included Brown Bullhead, Green Sunfish (*Lepomis cyanellus*), and Longnose Gar.

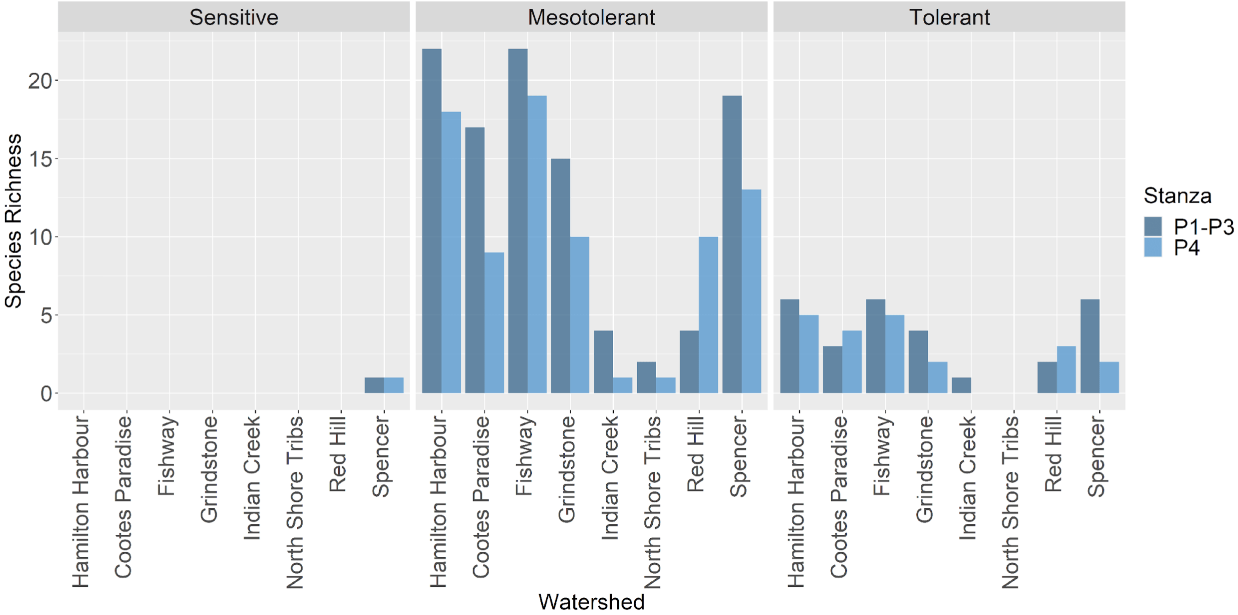

Figure 36. *Species Richness of carnivores for P1-P3 (light blue) and P4 (dark blue), including sensitivity to low dissolved oxygen levels. Carnivores are fish species that feed on other fish (piscivore) and/or other vertebrates and include parasitic feeders (based on OFFLHD; www.ontariofishes.ca).*

Detritivores only make a small contribution to the overall number of species (92), with a total of eight species. The Rosyface Shiner (*Notropis rubellus*) was the only sensitive detritivore, and it was only found in Cootes Paradise, Grindstone Creek, and Spencer Creek in P1-P3 (Figure 37). Declines in meso-tolerant detritivores were seen in Hamilton Harbour (Sea Lamprey; detritivore as juveniles), the Fishway [Sand Shiner [*Notropis stramineus*)], Grindstone Creek [Brassy Minnow (*Hybognathus hankinsoni*)], and Spencer Creek (Brassy Minnow, Sand Shiner, and Sea Lamprey; Figure 37). These uncommon *Leucisidae* can be easily mis-identified in the field, so these trends should be interpreted with caution. The three tolerant detritivores [e.g., Common Carp, Fathead Minnow (*Pimephales promelas*), and White Sucker] were present in all watersheds and both time periods except in the North Shore tributaries where only one species was detected in P4 (loss of invasive Common Carp and Fathead Minnow).

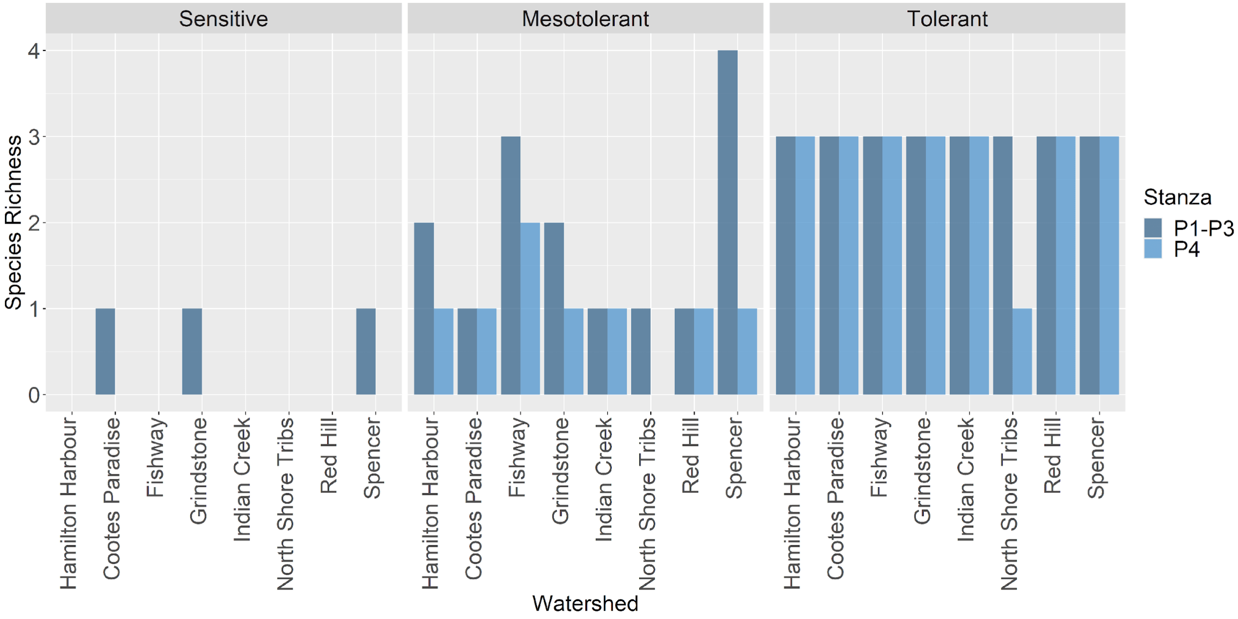

Figure 37. *Species Richness of detritivores for P1-P3 (light blue) and P4 (dark blue), including sensitivity to low dissolved oxygen levels. Detritivores feed on non-living organic matter in various states of decomposition (based on OFFLHD; www.ontariofishes.ca).*

There were 15 herbivorous species detected in all eight sectors over time including five sensitive, five meso-tolerant, and five tolerant species. There were no sensitive herbivorous species found in the Hamilton Harbour sector. Sensitive herbivores were found in Cootes Paradise, the Fishway, Grindstone Creek, and Spencer Creek in P1-P3, but by P4, they were only found in Red Hill Creek [Blacknose Shiner (*Notropis heterolepis*)] and Spencer Creek [American Brook Lamprey (*Lethenteron appendix*), Blacknose Shiner and Northern Hog Sucker](Figure 38). There was no change in the number of meso-tolerant herbivores in Hamilton Harbour and Grindstone Creek, but declines were seen in Cootes Paradise, the Fishway, and Spencer Creek; in P4, one additional species, Mimic Shiner (*Notropis volucellus*), was found in Red Hill Creek (Figure 38). Five tolerant herbivorous species increased in abundance between P1-P3 and P4 at multiple harbour sectors (Figure 38) and included two invasive species (Goldfish and Rudd), and three native species (Gizzard Shad, Brown Bullhead, and Golden Shiner). For this section, Gizzard Shad have been classified as herbivorous (based on OFFLHD; www.ontariofishes.ca), meaning they feed on phytoplankton, epilithic algae, epiphytic algae, and macrophytes. They do, however, have a varied diet and are also facultative detritivores. Together, tolerant herbivores (Gizzard Shad, Goldfish, Rudd, and Brown Bullhead) contribute significantly to fish abundance and biomass in the harbour (FP-1A and FP-2A; Boston unpublished data; Boston et al. 2016).

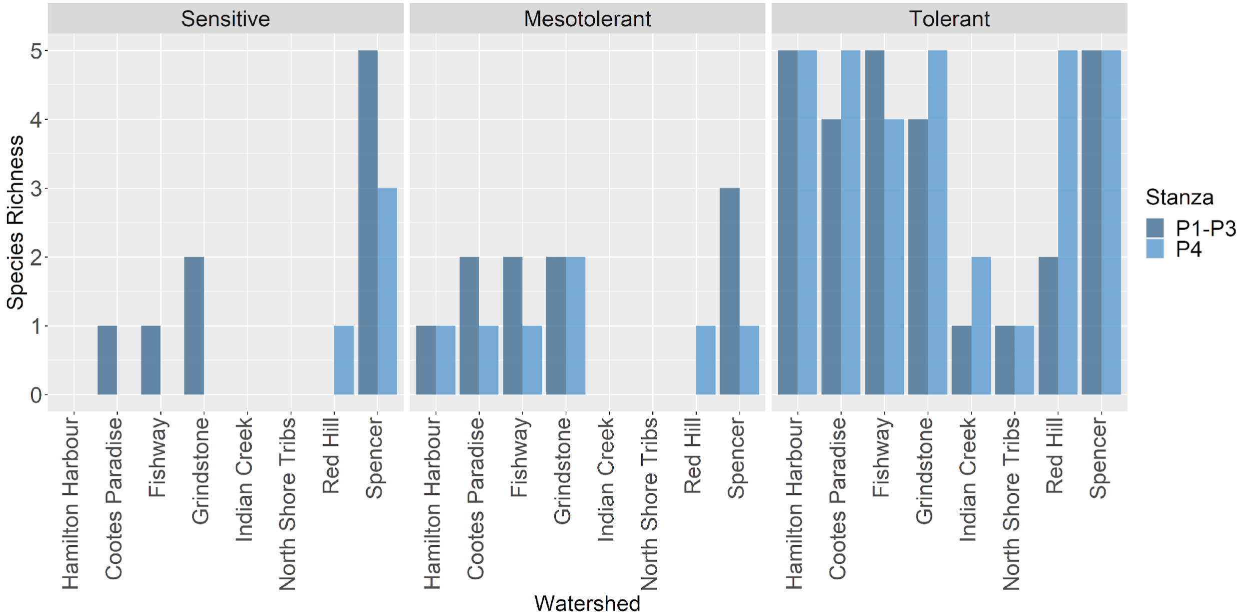

Figure 38. *Species Richness of herbivores for P1-P3 (light blue) and P4 (dark blue), including sensitivity to low dissolved oxygen levels. Herbivores are fish that feed on phytoplankton, epilithic algae, epiphytic algae and macrophytes (based on OFFLHD; www.ontariofishes.ca).*

Twelve planktivorous fish species were present in the Hamilton Harbour watershed during the study period, including three sensitive and nine meso-tolerant species. Sensitive species had greater declines in P4 than meso-tolerant species (50% and 28%, respectively; Figure 39). Cisco were found in Hamilton Harbour in P1-P3 but were not found again in P4. Although Cisco were not found during routine monitoring or during targeted larval surveys in the spring of 2018 (Brown et al. 2022), there is evidence of Cisco in Hamilton Harbour as two were caught in 2016 spring Walleye sampling surveys (D. Reddick pers. comm.). None of the sensitive planktivores [Cisco, Silver Shiner (*Notropis photogenis*), and River Chub (*Nocomis micropogon*)] were found in Hamilton Harbour, Cootes Paradise, or the Fishway in P4. Only the River Chub was found in the Grindstone and Spencer Creek sectors during P4 (Figure 39). For meso-tolerant planktivores, Hamilton Harbour and Cootes Paradise had five and six species, respectively, with no change from P1-P3 to P4 (Figure 39). The largest declines were in Grindstone Creek [loss of Brassy Minnow and Finescale Dace (*Chrosomus neogaeus*)] and Spencer Creek (loss of Brassy Minnow, Emerald Shiner, and Tadpole Madtom; Figure 39). There was no change in Emerald Shiner presence between P1-P3 and P4, except in Spencer Creek where it was not found during P4.

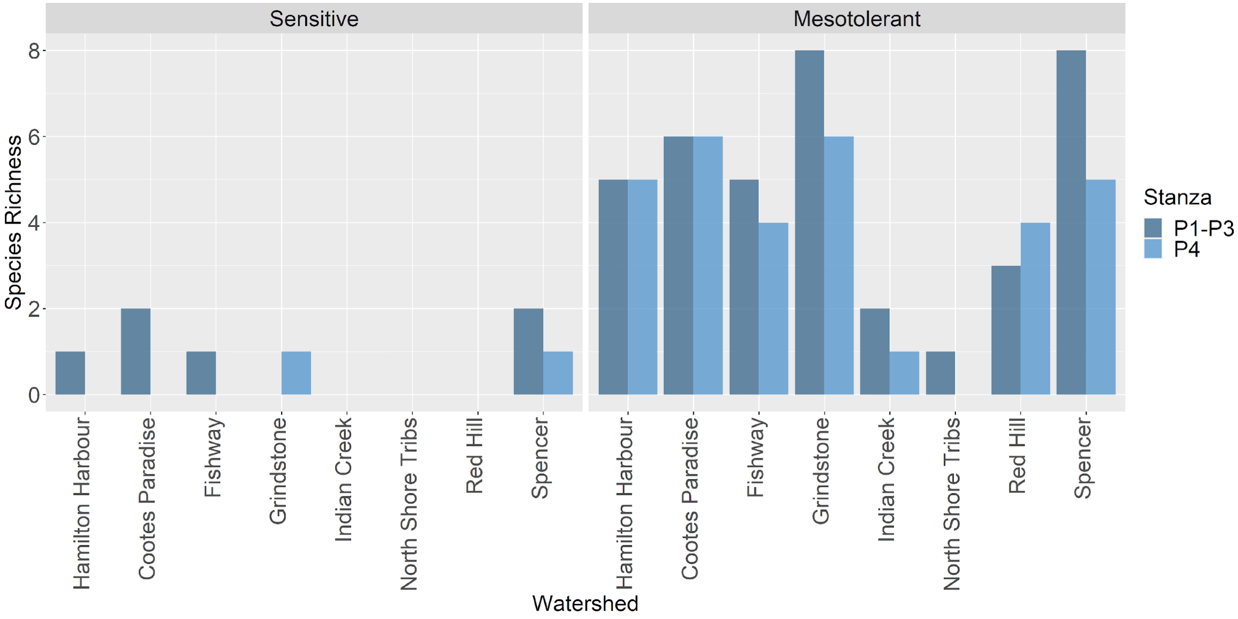

Figure 39. *Species Richness of planktivores for P1-P3 (light blue) and P4 (dark blue), including sensitivity to low dissolved oxygen levels. Planktivores feed by filtering plankton from the water column (based on OFFLHD; www.ontariofishes.ca).*

Species presence findings have an important caveat related to sampling effort since effort is tightly linked to estimates of species richness in any system. For example, the Spencer Creek watershed did show a drop in species richness between P1-P3 and P4, which may partially be attributed to less sampling effort in P4. Extensive surveys were done in Spencer Creek in the late 1990s, after which sampling effort diminished. Biases in gear types may also influence which species are captured within a sector, and our focus on sampling efforts in only the littoral zone clearly contributed to the apparent absence of more pelagic fishes (e.g., Rainbow Smelt). Despite these challenges, simple plots of species rarefaction (Figure 40) suggest that Hamilton Harbour, Cootes Paradise, Spencer's Creek, and Grindstone Creek all had sufficient sampling effort to yield an adequate representation of the fish community. If a more fulsome assessment of fish species richness among sectors is desirable, additional sampling efforts in Red Hill Creek, Indian Creek, and the North Shore Tributaries may be required.

While sections FP-1A and FP-2A have used the Fisheries and Oceans Canada (DFO) long-term electrofishing dataset to explore temporal changes in species-specific and fish community metrics relative to other areas in Lake Ontario, a relatively novel approach, community trajectory analysis (De Cáceres et al. 2019) holds promise as a means of comparing fish communities among different areas. Community trajectory analysis quantifies species community changes to determine if communities are becoming more similar (converging) or different (diverging). This would allow for a more holistic regional assessment of changes in fish community composition and indicate whether fish assemblages in the Hamilton Harbour AOC are converging or diverging from other parts of Lake Ontario. Additionally, it may be beneficial to split up species foraging guilds based on life stages in future assessments. Such an approach could help identify specific guilds that have resource bottlenecks that may have downstream effects on overall species presence.

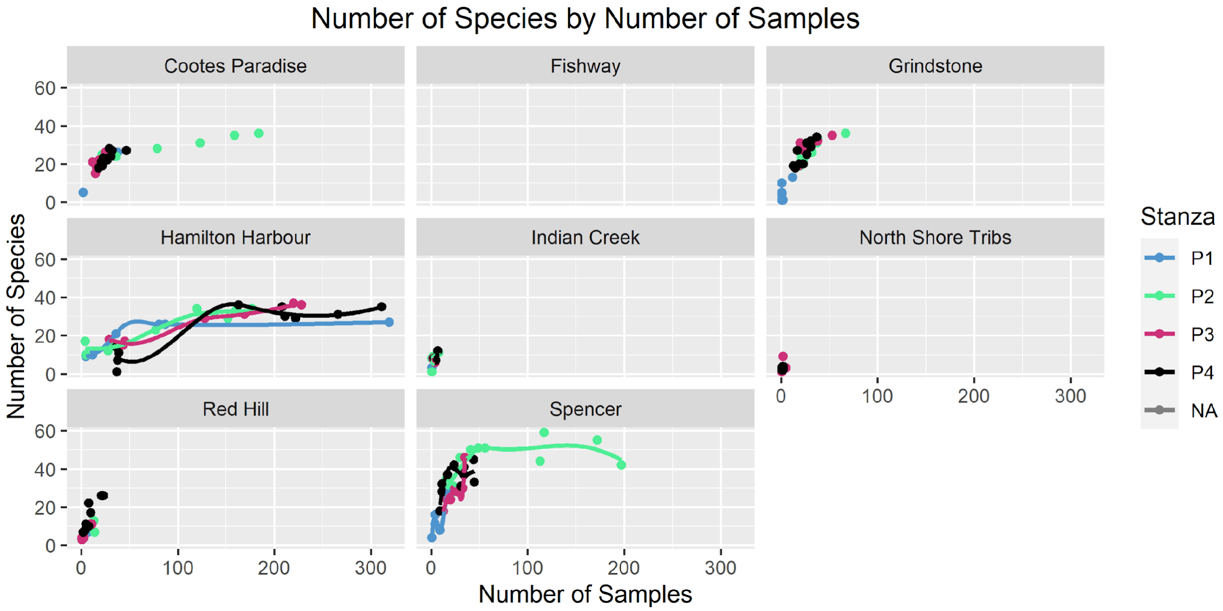

Figure 40. *Species rarefaction curves were calculated for each watershed. Samples were summarized by date and unique transect or trap number where available and were totalled by year. Species richness was the total count of species in a year.*

CONCLUSIONS

Past characterizations of the fish community in the Hamilton Harbour AOC have noted how distinct it is from other similar areas in Lake Ontario (Bowlby and Hoyle 2017). More recent temporal assessments have noted a marked change in fish community assemblages over the past 30 years (Maynard et al. 2022); however, these changes have largely not been in line with AOC targets, with declines in species richness (P3-P4) and catch (P2-P3; section FP-2A). Using fish presence information from multiple datasets, we identified specific species that have shown declines in the most recent assessment period (P4; 2013-2022). Some of these species were encountered only rarely throughout the sector (e.g., Muskellunge and White Crappie), while others, now absent from the harbour, are primarily riverine species that are still common within watersheds draining into Hamilton Harbour (e.g., Western Blacknose Dace). The absence of some benthic species in the harbour (e.g., Johnny Darter and Tadpole

Madtom) may be partially related to competition with the invasive Round Goby. Benthic species may also be affected by systemic anoxia, which also serves as a limiting factor for species that are sensitive to low dissolved oxygen since only Logperch (among the 15 dissolved oxygen sensitive species that have been observed within the system) are found in the harbour. While most species-specific changes can be linked to conditions or limitations within the harbour, the absence of Rainbow Smelt and Threespine Stickleback in recent nearshore sampling records tracks with declines in these species in Lake Ontario.

By exploring thermal, habitat, and foraging guilds among species, patterns in the dominant species guilds in the harbour are evident with warmwater fishes that are tolerant of hypoxia and feed on invertebrates, plants and algae, or multiple trophic levels (i.e., generalists) among the most common. In contrast, the majority of species listed in the RAP targets fall within the meso-tolerant (to hypoxia) carnivore guilds. Declines in coldwater fishes in the harbour are not surprising given noted issues with hypoxia in the deeper, pelagic areas of harbour, and these chronic conditions that resulted in the extirpation of these fishes from the harbour itself will not be resolved in the near future. Few coldwater fishes remain in the system, which saw the largest decline in species since 2013. Amongst sectors, species richness only increased in Red Hill Creek, with increases in both cool- and warmwater fishes. Many of these species are associated with wetland habitats (e.g., Bluegill and Bowfin), so these increases may be related to increased sampling and more targeted sampling in the wetlands (e.g., Budgell et al. In Review), which were created as part of habitat offsetting works within the Red Hill Creek watershed. It should also be noted some reaches in Red Hill only had one species detected during some sampling events, which suggests some of the observed increases in richness may be associated with the recolonization of areas that have experienced significant anthropogenic stress (Portt and Associates 2003). Despite seeing a drop in species sensitive to low dissolved oxygen, there was not a subsequent increase in tolerant species, which also showed declines. This tracks with overall declining patterns in species richness in the harbour that was also evident when split into native and non-native species (see FP-2A). Without a single major stressor correlating across all sampling locations, such declines in richness across guilds are suggestive that there is not a dominant factor driving declines, rather it is likely that multiple stressors are contributing to changes in the fish community in the system (see General Discussion).

Table 5. *Fish species found in Hamilton Harbour and sectors. Species categorized based on rarity as prolific (P), very common (VC), common (C), rare (R) or very rare (VR).*

	Common Name	**Rarity**	**Hamilton Harbour**		**Fishway**		**Cootes Paradise**		**Grind-stone Cr.**		**North Shore Tribs**		**Indian Cr.**		**Red Hill Cr.**		**Spencer Cr.**	
			P1-P3	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**
Cold	**Lacustrine-Benthopelagic**		**2**	**1**	**2**	**3**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**0**
	Atlantic Salmon	R	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
	Lake Trout (r)	R	1	1	1	1	0	0	0	0	0	0	0	0	0	0	1	0
	Sea Lamprey (r)	R	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0
	Lacustrine-Pelagic		**2**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**
	Chinook Salmon (c)	C	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1
	Cisco (vr)	VR	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Riverine/Lacustrine-Benthic		**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	Longnose Sucker	R	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Riverine/Lacustrine-Benthopelagic		**3**	**2**	**3**	**2**	**3**	**0**	**3**	**1**	**1**	**0**	**1**	**0**	**1**	**1**	**4**	**3**
	Brook Trout (r)	R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	Brown Trout (c)	C	1	1	1	1	1	0	1	0	0	0	0	0	1	0	1	1
	Rainbow Trout (p)	P	1	1	1	1	1	0	1	1	1	0	1	0	0	1	1	1
	Trout-Perch (c)	C	1	0	1	0	1	0	1	0	0	0	0	0	0	0	1	0
	Riverine/Lacustrine-Pelagic		**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
	Coho Salmon (vr)	VR	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Riverine-Benthic		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**
	American Brook Lamprey (vr)	VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
Coldwater total (n=10)			**8**	**5**	**7**	**6**	**4**	**0**	**3**	**1**	**1**	**0**	**1**	**0**	**1**	**1**	**8**	**5**
Cool	**Lacustrine-Benthopelagic**		**1**	**1**	**1**	**0**	**1**	**1**	**1**	**1**	**0**	**0**	**1**	**1**	**0**	**1**	**1**	**1**
	Golden Shiner	VC	1	1	1	0	1	1	1	1	0	0	1	1	0	1	1	1
	Lacustrine-Pelagic		**2**	**1**	**2**	**2**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**2**	**1**
	Alewife	C	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1
	Rainbow Smelt	C	1	0	1	1	0	0	0	0	0	0	0	0	0	0	1	0
	Riverine/Lacustrine-Benthic		**9**	**6**	**11**	**6**	**6**	**4**	**9**	**7**	**3**	**1**	**3**	**3**	**3**	**4**	**11**	**7**
	American Eel	R	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0

	Common Name	**Rarity**	**Hamilton Harbour**		**Fishway**		**Cootes Paradise**		**Grind-stone Cr.**		**North Shore Tribs**		**Indian Cr.**		**Red Hill Cr.**		**Spencer Cr.**	
			P1-P3	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**
🟩	Bigmouth Buffalo	C	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0
	Brassy Minnow	R	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
	Greater Redhorse	R	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Johnny Darter	VC	1	0	1	0	1	1	1	1	1	0	0	0	0	0	1	1
	Logperch	VC	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	Longnose Dace	VC	0	0	1	0	0	0	1	1	1	0	1	1	1	1	1	1
	Mottled Sculpin	R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	Round Goby	VC	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1
	Shorthead Redhorse	C	1	1	1	1	0	0	1	0	0	0	0	0	0	0	1	1
	Silver Redhorse	VR	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
	Tadpole Madtom	C	1	0	1	0	1	0	1	1	0	0	0	0	0	0	1	0
	Tubenose Goby	VR	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
	White Sucker	P	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	Riverine/Lacustrine-Benthopelagic		**8**	**8**	**8**	**7**	**9**	**8**	**12**	**9**	**1**	**1**	**3**	**1**	**6**	**9**	**16**	**10**
	Blackchin Shiner	R	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	1
	Blacknose Shiner	C	0	0	0	0	0	0	1	0	0	0	0	0	0	1	1	1
	Brook Stickleback	VC	0	1	0	0	1	1	1	1	0	0	1	1	1	1	1	1
	Emerald Shiner	P	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	0
	Finescale Dace	R	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1	1
	Lake Chub	VR	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
	Longnose Gar	C	1	1	1	1	0	0	0	0	0	0	0	0	0	1	1	0
	Mimic Shiner	C	0	0	0	0	1	1	1	1	0	0	0	0	0	1	0	0
	Northern Pearl Dace	C	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1
	Northern ike	VC	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1
	Northern Redbelly Dace	C	0	0	0	0	0	0	1	1	0	0	1	0	0	0	1	1
	Rudd	C	1	1	1	1	0	1	0	1	0	0	0	0	0	1	1	1
	Spottail Shiner	P	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1
	Threespine Stickleback	C	1	0	1	0	1	0	1	0	0	1	0	0	1	0	1	0

	Common Name	**Rarity**	**Hamilton Harbour**		**Fishway**		**Cootes Paradise**		**Grind-stone Cr.**		**North Shore Tribs**		**Indian Cr.**		**Red Hill Cr.**		**Spencer Cr.**	
			P1-P3	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**
	Walleye	C	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	0
	Yellow Perch	VC	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	Riverine/Lacustrine-Pelagic		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**
	Brook Silverside	VC	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	Riverine-Benthic		**2**	**0**	**3**	**1**	**3**	**1**	**3**	**2**	**2**	**1**	**1**	**1**	**1**	**1**	**7**	**5**
	Blackside Darter	C	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1
	Fantail Darter	C	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1	1
	Golden Redhorse	VR	1	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
	Northern Brook Lamprey	R	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
	Northern Hog Sucker	R	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
	Rainbow Darter	C	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	1
	Western Blacknose Dace	P	1	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1
	Riverine-Benthopelagic		**2**	**1**	**3**	**0**	**3**	**1**	**3**	**4**	**1**	**1**	**1**	**2**	**2**	**2**	**6**	**4**
	Common Shiner	VC	1	1	1	0	1	1	1	1	0	0	0	1	1	1	1	1
	Creek Chub	P	1	0	1	0	1	0	1	1	1	1	1	1	1	1	1	1
	Hornyhead Chub	R	0	0	0	0	0	0	1	1	0	0	0	0	0	0	1	1
	Redside Dace	VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	River Chub	C	0	0	1	0	1	0	0	1	0	0	0	0	0	0	1	1
	Striped Shiner	VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Coolwater total (n=46)			**25**	**18**	**29**	**17**	**24**	**17**	**30**	**25**	**7**	**4**	**9**	**8**	**11**	**18**	**42**	**29**
Warm	**Riverine/Lacustrine-Benthic**		**4**	**4**	**4**	**4**	**4**	**1**	**5**	**2**	**0**	**0**	**0**	**0**	**1**	**1**	**4**	**3**
	Black Bullhead	C	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0
	Brown Bullhead	P	1	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1
	Channel Catfish	C	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0
	Freshwater Drum	C	1	1	1	1	1	0	1	0	0	0	0	0	0	0	1	0
	Iowa Darter	R	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1
	River Darter	VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
	Riverine/Lacustrine-Benthopelagic		**16**	**14**	**18**	**13**	**14**	**15**	**15**	**12**	**4**	**1**	**6**	**5**	**6**	**12**	**17**	**13**

	Common Name	**Rarity**	**Hamilton Harbour**		**Fishway**		**Cootes Paradise**		**Grind-stone Cr.**		**North Shore Tribs**		**Indian Cr.**		**Red Hill Cr.**		**Spencer Cr.**	
			P1-P3	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**
	Black Crappie	VC	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	Bluegill	VC	1	1	1	1	1	1	1	1	0	0	0	1	0	1	1	1
	Bluntnose Minnow	P	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
	Bowfin	C	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	Common Carp	P	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
	Fathead Minnow	P	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
	Goldfish	P	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1
	Green Sunfish	P	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	1
	Largemouth Bass	P	1	1	1	1	1	1	1	1	0	0	1	0	0	1	1	1
	Longear Sunfish	R	0	0	1	0	1	0	1	0	0	0	0	0	0	0	1	0
	Muskellunge	VR	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Pumpkinseed	P	1	1	1	1	1	1	1	1	0	0	1	0	1	1	1	1
	Rock Bass	VC	1	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1
	Sand Shiner	VR	0	0	1	0	0	0	0	0	0	0	0	0	0	0	1	0
	Silver Lamprey	VR	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	Smallmouth Bass	VC	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1
	Spotted Gar	VR	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
	White Bass	C	1	1	1	1	0	1	0	0	0	0	0	0	0	0	1	0
	White Crappie	C	1	0	1	0	0	1	1	0	0	0	0	0	0	0	1	0
	White Perch	VC	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	Riverine/Lacustrine-Pelagic		**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**0**	**0**	**0**	**0**	**0**	**1**	**1**	**1**
	Gizzard Shad	VC	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1
	Riverine-Benthic		**1**	**0**	**0**	**0**	**1**	**1**	**2**	**2**	**0**	**0**	**0**	**0**	**1**	**1**	**2**	**2**
	Black Redhorse	VR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
	Central Mudminnow	C	1	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
	Stonecat	R	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	1
	Riverine-Benthopelagic		**1**	**1**	**0**	**0**	**3**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**3**	**0**
	Rosyface Shiner	R	0	0	0	0	1	0	1	0	0	0	0	0	0	0	1	0
	Silver Shiner	VR	0	0	0	0	1	0	0	0	0	0	0	0	0	0	1	0

	Common Name	**Rarity**	**Hamilton Harbour**		**Fishway**		**Cootes Paradise**		**Grind-stone Cr.**		**North Shore Tribs**		**Indian Cr.**		**Red Hill Cr.**		**Spencer Cr.**	
			P1-P3	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**	**P1-P3**	**P4**
🟧	Spotfin Shiner	R	0	1	0	0	1	0	0	0	0	0	0	0	0	0	1	0
Warmwater total (n=32)			**22**	**20**	**24**	**19**	**23**	**18**	**24**	**17**	**4**	**1**	**6**	**5**	**8**	**15**	**26**	**19**
Over all total (n=88)			**55**	**43**	**60**	**42**	**51**	**35**	**57**	**43**	**12**	**5**	**16**	**13**	**20**	**34**	**77**	**53**

CRITERION FP-1C: PELAGIC PREY FISH

SUMMARY

Three hydroacoustic and trawling prey fish surveys were completed in the Hamilton Harbour Area of Concern (AOC) in 2006, 2016, and 2018. Mid-water trawls in 2016 and 2018 dominated by young of year Alewife and Gizzard Shad are consistent with the higher proportions of small and medium-bodied fishes estimated in the hydroacoustic surveys for all years. Given the age estimated from their size, it suggests that the Hamilton Harbour AOC provides nursery habitat for these species.

Recent surveys and telemetry studies highlight the importance of the western sector of the Hamilton Harbour AOC and this sector also tended to have higher densities of prey fishes (Larocque et al. 2024). In the 2016 survey, we observed seasonal differences in the distribution of fish in the water column. In the summer and fall, most observed fish density occurred above the thermocline, below which hypoxia is prevalent during those seasons. This suggests that a large volume of habitat in the Hamilton Harbour AOC is unavailable to fishes due to low oxygen levels in key foraging seasons. Low dissolved oxygen conditions make portions of the water column unavailable to the fish community and likely negatively impact trophic transfer and community dynamics (Bowen and Currie 2017).

Differences in design among surveys limited comparisons among surveys and an assessment of trends through time. Similarly, a lack of appropriate regional reference sites for the Hamilton Harbour AOC made it difficult to assess the status of prey fishes. The Hamilton Harbour AOC did generally have higher prey fish density and biomass compared to the Toronto and Region AOC (herein Toronto AOC) and Lake Ontario. However, we would expect a highly productive and protected system like the Hamilton Harbour AOC to have more fish than areas like the exposed embayments and open coast areas of the Toronto AOC and Lake Ontario. Given the observed effect of hypolimnetic hypoxia on fish distributions in the summer and fall of the 2016 survey, fish populations are likely still impaired, although there is insufficient evidence to confirm this assessment since suitable reference information from Lake Ontario is unavailable.

While we cannot directly assess BUI#3 based on this evidence alone, we recommend that the hydroacoustic and trawling data be used to provide context related to the condition of the ecosystem and forage base for the fish assessments using other gear types, as seen in FP-1A and FP-1B. Future analyses should combine the 2018 hydroacoustic data with concurrently collected lower trophic data and diets to explore the relationship between fish and plankton density in the AOC and include deployment of continuously measured bottom-mounted hydroacoustics. Future work could be undertaken concurrently with Coordinated Science Monitoring Initiatives for Lake Ontario, where binational partners complete more intensive lake-wide hydroacoustic surveys. Such a survey would help contextualize our results with patterns in the whole lake and could be tailored to include appropriate reference sites for the Hamilton Harbour AOC.

KEY MESSAGES

- Hydroacoustics show that fish are largely absent in the hypoxic zones established below the thermocline (Flood et al. 2021) in the Hamilton Harbour AOC. This limits available habitat, may artificially inflate estimates of catch and biomass, and is consistent with findings of avoidance by Walleye (an important top predator; Brooks et al. 2019). The full consequence of hypoxia on pelagic fish populations is unknown but it likely contributes to habitat impairment and reduced habitat availability.
- Despite hypolimnetic hypoxia reducing the volume of available suitable habitat, trawling catches of Alewife and Gizzard Shad in every survey suggest the Hamilton Harbour AOC provides nursery habitat for these species.
- 2016 and 2018 hydroacoustic and trawling surveys show the west sector of the Hamilton Harbour AOC is an important aggregation site for fish. Fisheries and Oceans Canada (DFO) telemetry studies support this (see section FP-1A, Larocque et al. 2024).
- Hydroacoustic and trawling surveys suggest the density of pelagic forage fishes in the Hamilton Harbour AOC is dominated by small-bodied fishes, most likely young of year Alewife and Gizzard Shad.
- The results from FP-1C support the interpretation of core community sampling metrics (electrofishing and trap netting; see sections FP-2A and FP-2B).

REMAINING CONCERNS AND UNCERTAINTY

- Currently, there is a lack of appropriate hydroacoustic reference sites for the Hamilton Harbour AOC. Hoyle et al. (2018) defined the Hamilton Harbour AOC as a sheltered embayment and the Toronto and Region AOC as an exposed embayment, making them not directly comparable. Similarly, the Hamilton Harbour AOC is a highly productive system relative to Lake Ontario; the observed higher fish density and biomass is to be expected. It is thus difficult to determine whether the greater density and biomass of fish observed in the Hamilton Harbour AOC relative to both Lake Ontario and the Toronto AOC (in general) is an indication of reduced impairment, a function of habitat compression (i.e., fish concentrated in the epilimnion), or is to be expected given the more protected and therefore potentially more productive nature of the

Hamilton Harbour AOC. The Bay of Quinte (also a sheltered embayment) was proposed as a suitable reference site, but logistical issues in the 2018 hydroacoustics survey prevented sampling.
- Due to different sampling designs (different sectors, day vs. night sampling), comparisons among sampling events prior to 2016 were not possible. Additionally, even similar sampling designs can yield highly variable results over the years due to local habitat conditions and fish movement. For example, samples collected in the same location using the same method in 2009 and 2010 in the Toronto AOC show they were considerably different, emphasizing the potential challenge of comparing among years. Generally, in all years, the Hamilton Harbour AOC had higher density and biomass than the Toronto AOC, while the open coast (including Bronte Harbour) had the lowest values.
- One of the core challenges of analyzing hydroacoustic data is that the replicates used in analyses are artificially derived and subset from the overall transect. As a result, these sampling units tend to be spatially autocorrelated (see action #1).

FUTURE MONITORING

1. Currently, we do not recommend future surveys. Given the lack of reference sites and differences in design among previous studies, another survey is unlikely to provide insight into temporal trends of forage fish in the Hamilton Harbour AOC.
2. If sampling is to occur, future studies should replicate the 2018 survey to allow for multi-year comparisons, with additional sampling in appropriate regional reference sites (likely Presqu’ile Bay, Wellers Bay, and the Bay of Quinte). There should also be a discussion to consider seasonal sampling, given the differences observed among seasons in Midwood et al. (2019). Future hydroacoustic surveys should be coordinated through lake-wide Coordinated Science and Monitoring Initiative works (Lake Ontario is slated for sampling in 2028) to leverage multi-jurisdictional sampling and put observed forage fish density and biomass of the Hamilton Harbour AOC within the context of the whole lake.

RECOMMENDED ACTIONS

1. Future analyses should explore alternative statistical approaches that can incorporate spatial autocorrelation (e.g., Dormann et al. 2007), and/or adjustments to the sampling design (e.g., shorter transects with more replicates); this will ensure these types of data are being analyzed in the most appropriate manner. Details for analysis-specific actions are recommended in the conclusion of Gutowsky (2022).
2. Future analyses should combine the 2018 hydroacoustic dataset with phytoplankton and zooplankton information (Laser Optical Plankton Counter and

430 kHz or greater hydroacoustic data) collected in the same survey to look for relationships between fish and zooplankton density in the Hamilton and Toronto AOCs. This may provide additional insight into fish community dynamics around the seasonal thermocline and hypoxic zones in the harbour.

BACKGROUND

Split-beam hydroacoustics paired with trawling is a standardized assessment tool for pelagic fishes used by fisheries management agencies in Lake Ontario and other Great Lakes (OMNRF 2020). Three hydroacoustic and benthic or mid-water trawling surveys were completed in the Hamilton Harbour AOC in 2006, 2016, and 2018, each with unique study questions and objectives (K. Leisti unpublished data; Midwood et al. 2019, 2022). Generally, the goal of these surveys was to compare the density and biomass of prey fish among sectors within the Hamilton Harbour AOC in 2006 and 2016 (K. Leisti unpublished data; Midwood et al. 2019), and among sites in Lake Ontario and the Toronto AOC in 2018 (Midwood et al. 2022). The focus of the 2006 survey was to estimate day and night density and biomass of pelagic fishes in the spring and summer. The 2016 survey had a specific focus on the depth distribution of fish in relation to seasonal thermocline depth. The 2018 survey was focused on the spatial distribution of prey fish with methods similar to those used during open-lake hydroacoustic surveys (e.g., OMNRF 2020). The 2018 survey included lower-trophic composition (i.e., microbes, phytoplankton, and zooplankton) sampling to explore the connection between primary productivity, food-web composition, and prey fish density (i.e., vertical distributions in the water column).

These surveys provide supporting data to assess the delisting criteria for the Hamilton Harbour AOC, specifically Beneficial Use Impairment (BUI) #3 (Degradation of fish and wildlife populations), to support "…*a self-sustaining community more representative of a mesotrophic environment with a balanced trophic composition that includes top predators … and other native species*" (HHRAP 2019). Top predator species may occupy, and forage in, both littoral and pelagic habitats, and so assessing prey fish density and biomass in the pelagic zones of Hamilton Harbour AOC and Lake Ontario indicates the forage base available to these fishes. This is an important contextual component in support of the overall BUI assessment of fish populations in Hamilton Harbour AOC.

METHODS

Several surveys of fishes in open waters within the Hamilton Harbour AOC have been completed by Fisheries and Oceans Canada (DFO). These surveys used split-beam hydroacoustics to develop estimates of fish density (based on area [#/ha] or volume [#/m^3]) and biomass (similarly by area [kg/ha] or volume [g/m^3]) in areas of interest.

Hydroacoustics were paired with bottom (2006 survey) or mid-water (2016 and 2018 surveys) trawling to validate the presence of fish, determine species composition, and estimate the length of fish to convert hydroacoustic data into estimated biomass. Surveys were switched from bottom to mid-water trawls due to safety and logistical concerns.

For all DFO hydroacoustic surveys, data were binned along 50-m transects to yield Elementary Distance Sampling Units (EDSU) that were later treated as a sample (after Simmonds and MacLennan 2005). Detailed reports on the methods used to filter the hydroacoustics data and derive estimates of density and biomass are available in currently unpublished reports (Milne 2009, 2011, 2012a, 2012b, 2017, for report examples). For the 2006 survey, only daytime data are presented; therefore, prey fish were primarily detected in schools. In contrast, the local (2016) and regional (2018) surveys were undertaken at night when prey fish were more dispersed and more likely to be detected as single targets. These single targets yield more accurate estimates of density and biomass since there is no “shadow” effect from a school (Guillard and Vergès 2007). Temperature and dissolved oxygen profiles using an EXO sonde were typically collected for each survey transect to aid in the post-processing of the hydroacoustics data and to provide some information on local environmental conditions.

2006, 2009, and 2010 Surveys, Leisti et al. (unpublished report)

Three locations were sampled over multiple years during daylight hours: Hamilton Harbour AOC (spring, summer, and fall in 2006), Toronto AOC (fall in 2009 and 2010), and Bronte Harbour (fall 2010) (Figure 41). All surveys used a 200 kHz split beam echosounder, running ~1 km transects in different sectors of each sampling location (Table 6; Figure 41). During Hamilton Harbour AOC and Toronto AOC surveys, bottom trawls were concurrently used to validate the presence of fish, inform species composition, and estimate lengths of the targets to convert hydroacoustic data into estimates of biomass; while primarily benthic, these trawls would also sample fish from the water column during deployment/retrieval. Gillnets were used for the same purpose in Bronte Harbour. Biomass and density estimates for these surveys were summarized as g/ha and #fish/ha, making them distinct from later surveys.

Table 6. *This is Table 12 reproduced from Midwood et al. (2022), with the addition of Hamilton Harbour AOC 2006 and 2016 sector codes. Sector codes are for each year of hydroacoustics. Blank fields indicate samples were not taken in those sectors for that year. Sectors that are underlined are located in the Toronto and Region Area of Concern.*

Analysis Sector Name	2006 Sector Code	2009 Sector Code	2010 Sector Code	2016 Sector Code	2018 Sector Code
Bluffers Park				BLUF	
Bronte North Harbour			BRNH		
Etobicoke				ETOB	
Hamilton Harbour AOC North	N			N	HH_N
Hamilton Harbour AOC North East	NE			NE	HH_NE
Hamilton Harbour AOC South					HH_S
Hamilton Harbour AOC South East					HH_SE
Hamilton Harbour AOC South Central	SC			SC	
Hamilton Harbour AOC West	W			W	HH_W
Humber Bay Offshore		HBOF	HBOF		
Lake Ontario Credit River					LK_CR
Lake Ontario Open Coast					LK_OC
Rouge River				ROGE	
Tommy Thompson Park		TTPK	TTPK	TTPK	
Toronto Eastern Headlands OR Ashbridges' Bay		TO_EHDL	TO_EHDL	TO_EHDL	TO_AB
Toronto Humber Bay Nearshore		TO_HBNR	TO_HBNR	TO_HBNR	TO_HB
Toronto Inner Harbour		TO_INNH	TO_INNH	TO_INNH	TO_IH
Toronto Outer Harbour		TO_OUTH	TO_OUTH	TO_OUTH	TO_OH
Toronto Outer Harbour (excludes an outlier in 2016)				OUTH.B	
Toronto Outer Islands		OUTI	OUTI	OUTI	

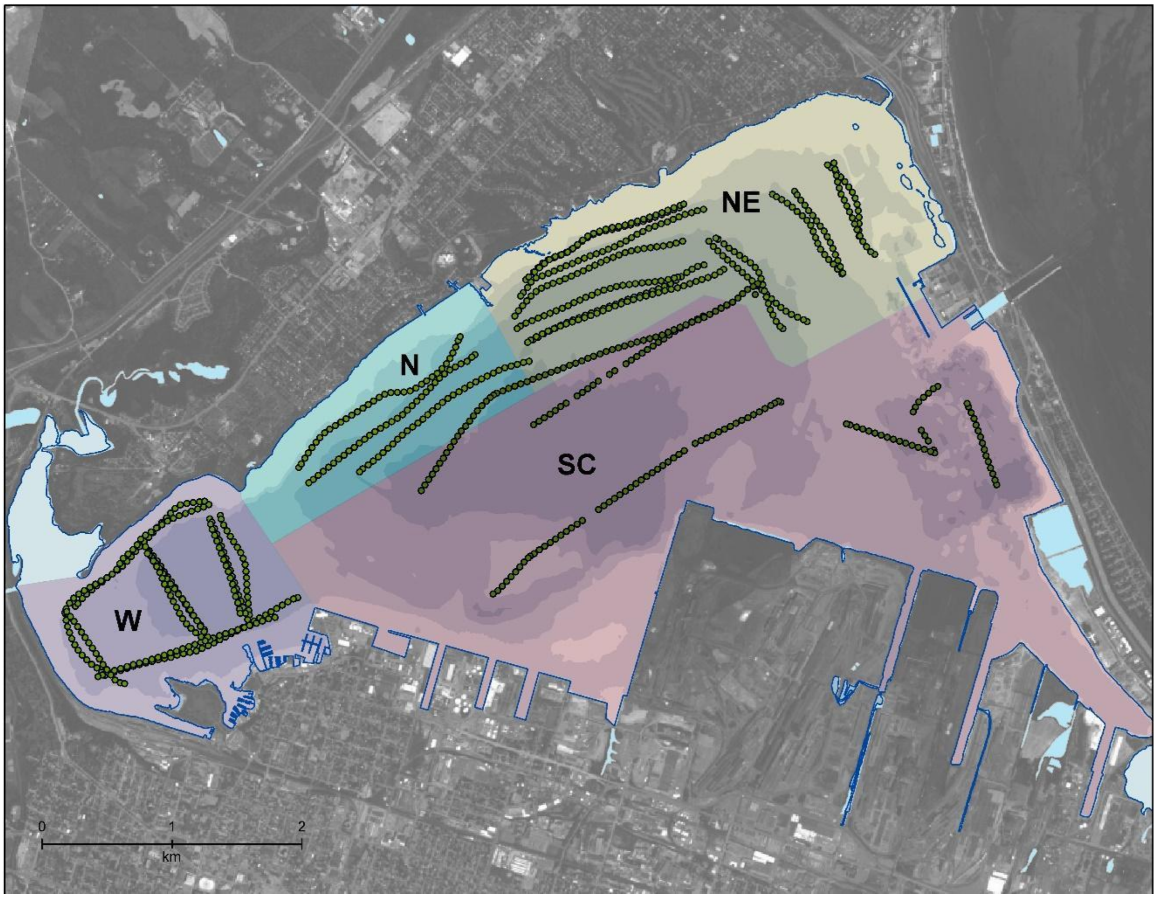

Figure 41. *Figure 1 reproduced from Leisti et al. (unpublished report). Map of the Hamilton Harbour AOC 2006 analysis sectors, including all fall daytime hydroacoustic transects. Sector names as follows: north (N), north-east (NE), south central (SC), west (W).*

2016 Survey, Midwood et al. (2019)

Hamilton Harbour AOC was sampled at night over three seasons (spring, summer, and fall) in 2016. Toronto and Region AOC was also sampled in 2016 and reported in Midwood et al. (2018); locations are noted in Table 6 for posterity. All surveys used a 200 kHz split beam echosounder, running ~1 km transects in different sectors of the Hamilton Harbour AOC, with the same sectors used as in the 2006 study (Table 6, Figure 42). As in previous surveys, water temperature (°C) and dissolved oxygen (mg/L) were recorded but with the specific purpose of verifying the presence and depth of the thermocline and thus, the depth of the hypoxic zone that forms below the thermocline in Hamilton Harbour AOC (Bowlby et al. 2016). A two-way analysis of variance (ANOVA) was used to compare the distribution of fish biomass (g/m^3) and density (#fish/m^3) among analysis sectors and seasons for the water column stratum (sum of 1 m depth bins).

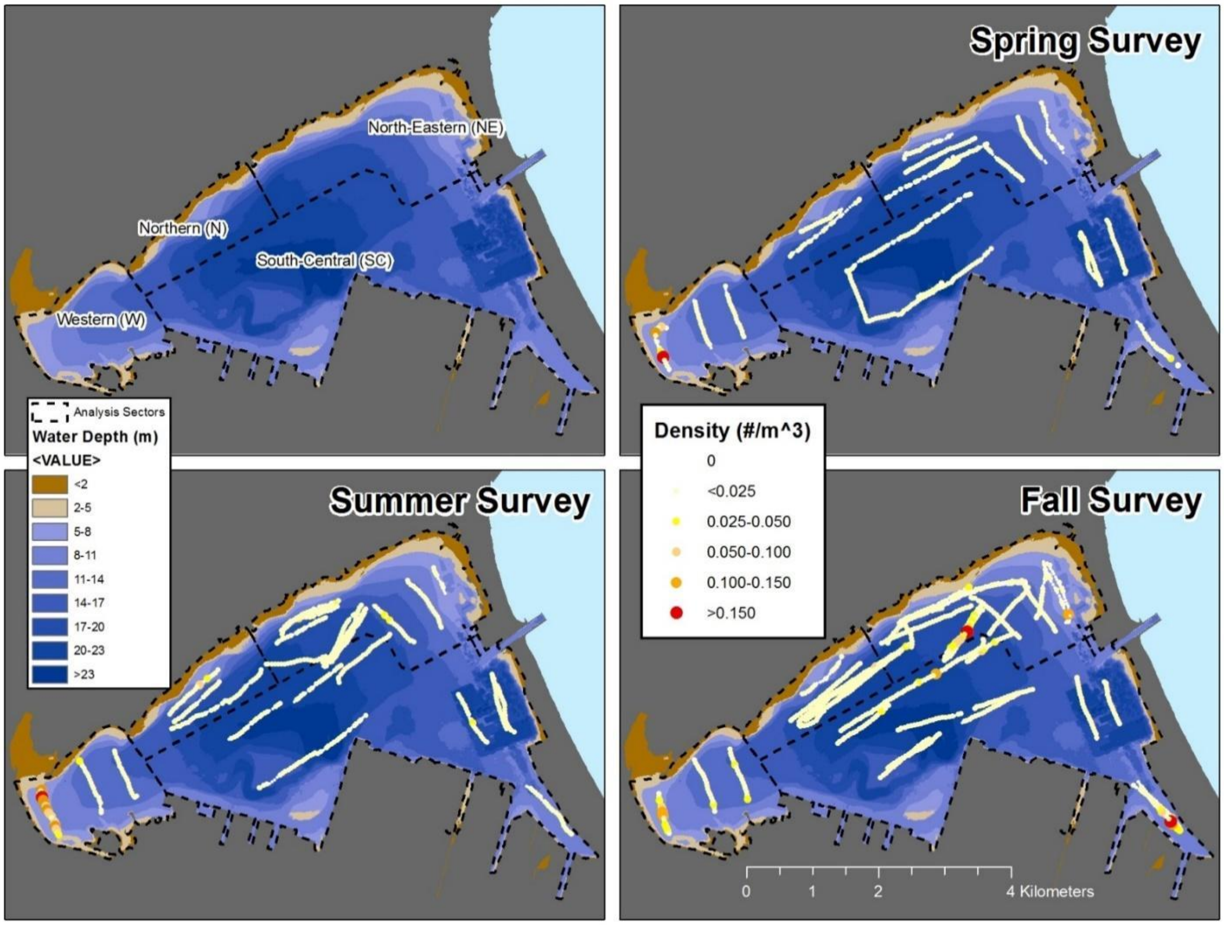

Figure 42. *Figure 11 reproduced from Midwood et al. (2019). 2016 echo integration estimates of night-time fish density within Hamilton Harbour AOC sectors across seasons. Shown is the spatial distribution of the estimated fish density (numbers/m^3, with total length > 2.9 cm) through the water column (sum of 1m bins) for each 50 m Elementary Distance Sampling Units (EDSU).*

2018 Survey, Midwood et al. (2022)

Surveys were completed at night in the fall in the Hamilton Harbour AOC, Toronto AOC, and the open coast of Lake Ontario. A 120 kHz split-beam hydroacoustic transducer was used (BioSonics DTX 120 kHz [7.7˚ X 7.7˚]) to make these surveys comparable to the Lake Ontario prey fish assessments completed yearly by the Ontario Ministry of Natural Resources and Forestry (OMNRF 2020). Sampling sectors in the Hamilton and Toronto AOCs were defined from past surveys (Table 6, see Midwood et al. 2018, 2019) with additional sectors added proximate to the mouth of the Credit River (Figure 43). Within sampling sectors, transects were directed along depth contours (6, 8, 10, 12, 16, and 20-m). Mid-water trawling was completed only for the 8-m contour since it was the only depth contour common across all sampling sectors. Alongside the hydroacoustic surveys, a depth-targeted Schindler-Patalas zooplankton trap was used to sample every two metres at all locations, and a Laser-Optical Plankton Counter was towed for the Toronto AOC locations only to capture zooplankton biomass and density. The objective of these concurrent surveys was to explore correlations between the zooplankton and prey fishes; however, these data have not been processed at the time of writing this report. Only the fish hydroacoustic data were summarized in Midwood et al. (2022) as part of the Toronto AOC fish populations assessment.

Given the variability in sampling approach among years, temporal comparisons are not possible. Instead, we briefly review the findings of each survey.

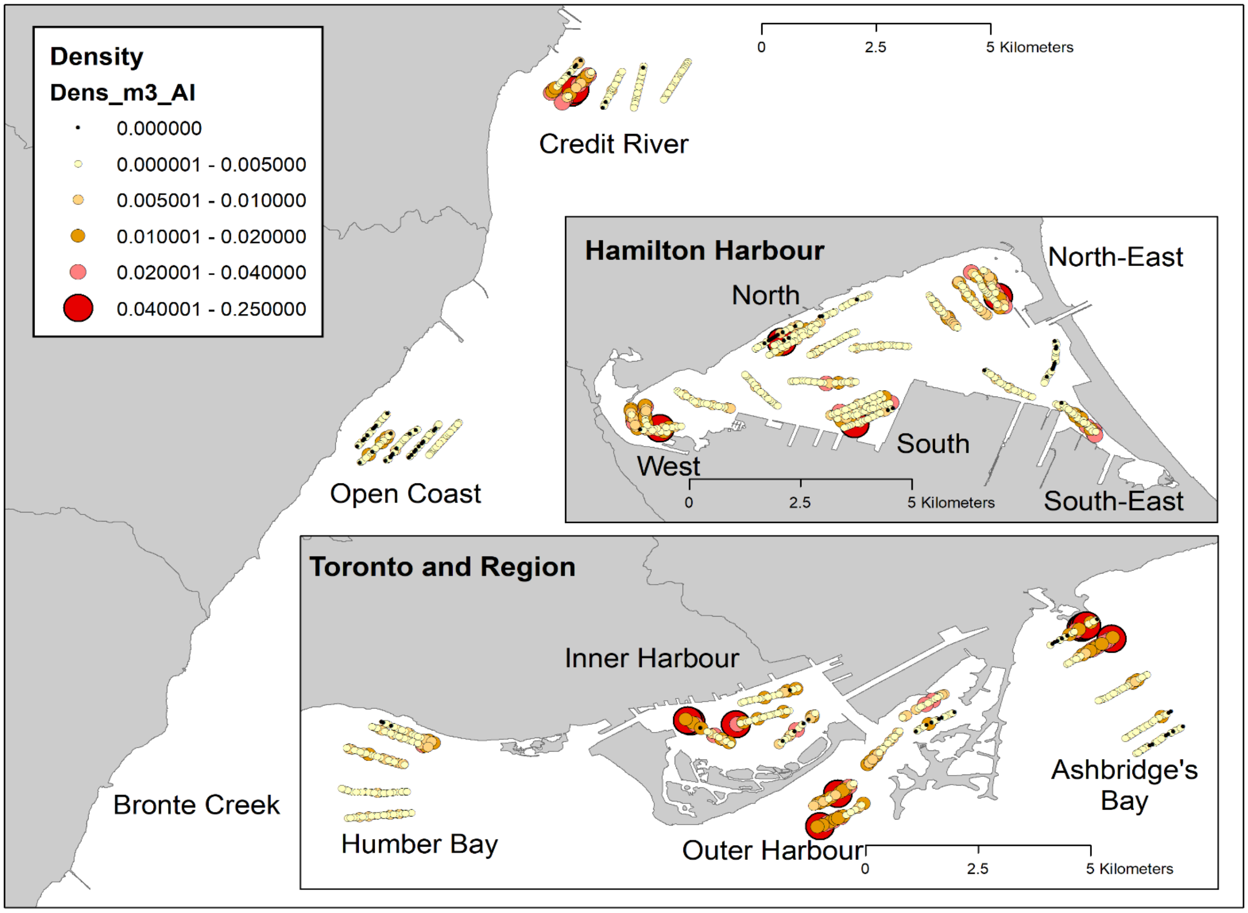

Figure 43. *Figure 42 reproduced from Midwood et al. (2022). Estimates of fish density (density/m^3) for the 2018 Fisheries and Oceans Canada's hydroacoustic survey. Larger, darker circles denote greater density in a transect. The regions are presented in other figures and tables using alternate codes including: Hamilton Harbour AOC (North = HH_N; North-East = HH_NE; West = HH_W; South = HH_S; and South-East = HH_SE), Toronto AOC (Humber Bay = TH_HB or HBNR; Inner Harbour = TH_IH or INNH; Outer Harbour = TH_OH or OUTH; and Ashbridge's Bay = TH_AB or EHDL); and Lake Ontario (Open Coast = LK_OC; and Credit River = LK_CR).*

RESULTS AND DISCUSSION

2006, 2009, and 2010 surveys, K. Leisti (unpublished data)

Thirteen species were captured in bottom trawls in Hamilton Harbour AOC; the top three species were Emerald Shiner (n=13963 fish, 86%), Alewife (n=1367 fish, 8%), and Gizzard Shad (n=413 fish, 2%). Alewife dominated Toronto AOC in 2009 (n=20467 fish, 56%), followed by Round Goby (n=8867 fish, 24%), and Rainbow Smelt (n=4508 fish, 12%). In Toronto for 2010, Threespine Stickleback was most abundant (n=9517 fish, 65%), followed by Round Goby (n=2984 fish, 20%) and Rainbow Smelt (n=1484 fish, 10%). For Bronte Harbour, Yellow Perch (n=26 fish, 51%) was dominant followed by White Sucker (n=14 fish, 27%) and Alewife (n=8 fish, 16%).

Based on biomass estimated from hydroacoustics, all four sectors in Hamilton Harbour AOC had greater than twice the estimated mean biomass than any of the sectors from the other survey locations; only the Tommy Thompson Park (TTPK) sector in the Toronto AOC came close in 2010. Fish densities estimated from hydroacoustics were also generally greater in Hamilton Harbour AOC compared to Toronto (2009) and Bronte Harbour (Figure 44). Two sectors (TTPK and the Eastern Headlands) within the 2010 Toronto AOC dataset had densities five times greater than anywhere else. One transect spanned both sectors and it is likely that a large school of fish ensonified within this transect skewed mean density estimates compared to the other sectors. Estimating density within fish schools can be problematic and the authors note they are less confident in estimates derived during the daytime. After these two sectors in Toronto AOC, Hamilton Harbour AOC had the greatest density. Within the Hamilton Harbour AOC sectors, densities were greatest in the south-central and north sectors.

Study limitations

- This study had no volumetric correction of estimates of density and biomass. Without these corrections, comparing estimates from transects in 8 m vs 20 m depth would be inappropriate; the 2018 survey standardized this to ensure comparisons along similar depth contours. Also, given Hamilton Harbour AOC's anoxia problems, the actual amount of available habitat is smaller than is assumed in the study.
- Biomass estimates are dependent on mean length and weight information from the trawl data and as such estimates may vary among surveys and thus not be comparable. For example, the mean biomass from trawls in Hamilton Harbour AOC was greater than in the Toronto AOC, which would skew estimates. Due to this bias, estimated density rather than biomass has been the focus in more recent hydroacoustic surveys.
- Although seasonal (spring and summer), and night data were collected along with a suite of water quality variables, these data were never fully analyzed.

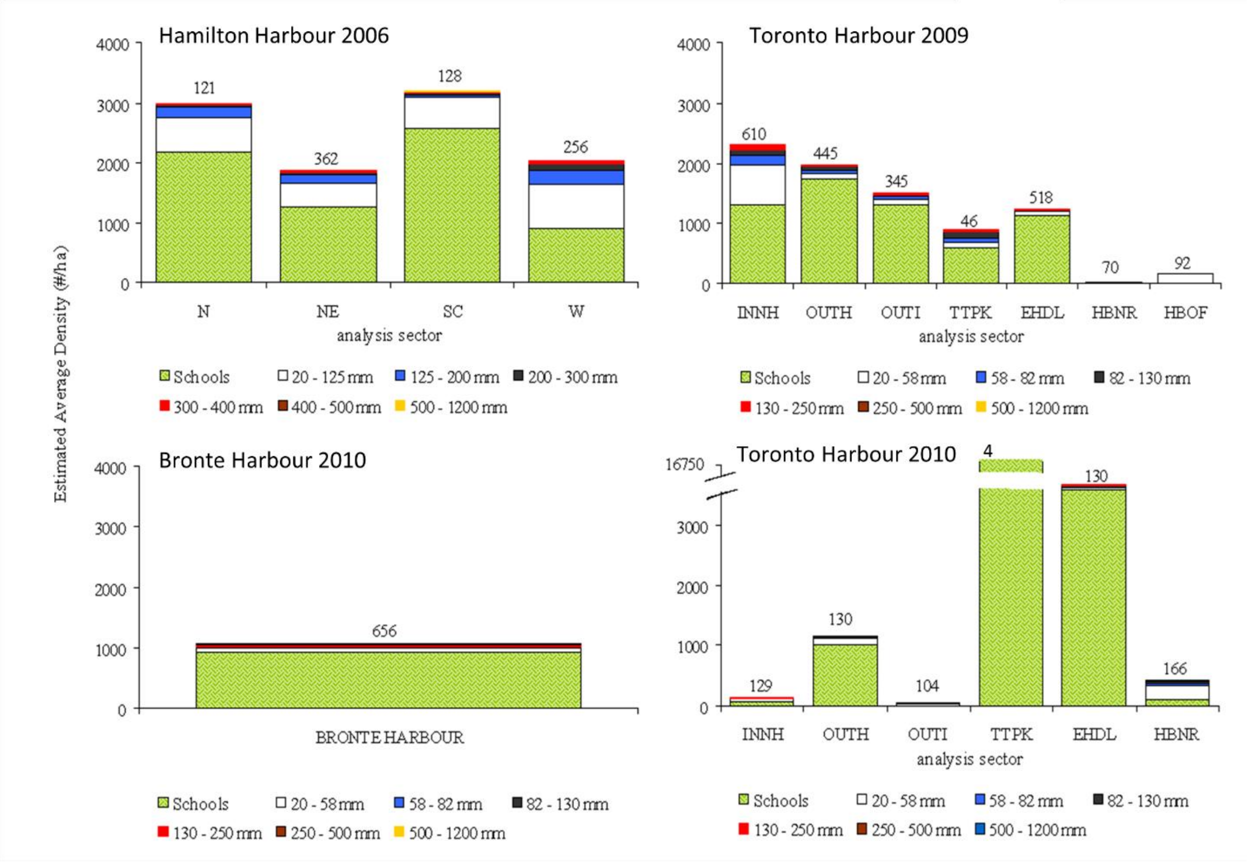

Figure 44. *Figure 5 reproduced from Leisti et al. (unpublished report). Estimated average fish density by sector and fish size (mm) calculated using the hydroacoustic data for the four harbour surveys. Sector names as follows: Hamilton Harbour AOC: north (N), north-east (NE), south central (SC), west (W); Toronto AOC: inner harbour (INNH); outer harbour (OUTH); outer islands (OUTI); Tommy Thompson Park (TTPK); Eastern Headlands (EHDL); Humber Bay nearshore (HBNR). The values above the columns indicate the number of 50 m horizontal transect segments (Elementary Distance Sampling Units) that comprise the datasets.*

2016 Survey, Midwood et al. (2019)

Both hydroacoustic and trawling data suggest that the majority of pelagic fish density and biomass are concentrated in the western part of the harbour, with peaks in the summer (Figures 44 and 45). Trawl data were collected only for validation, and low catch rates in some sectors limited our ability to conclude the patterns observed. Peaks in density corresponded with the high catch of young of year Alewife and Gizzard Shad, suggesting the harbour provides a nursery habitat for these species.

These results align with acoustic telemetry data that show Hamilton Harbour’s west sector frequently falls within areas of high residency for top predators (i.e., Northern

Pike, Largemouth Bass, Larocque et al. 2024). Abundant plankton productivity throughout the harbour can be a source of food for prey fish (Bowen and Currie 2017), in turn attracting predators. It was recommended that plankton community data be collected concurrently with hydroacoustics, which was completed in the subsequent 2018 survey, but the two datasets have not been combined yet for analysis.

Seasonally, both density and biomass were generally higher in the fall but had an overall peak in the western portion of the harbour in the summer. Larger-bodied fish were typically absent in the summer, though forage fish dominated density estimates every season. The hypoxic zone below the thermocline was an important factor dictating the depth distribution of fish, and the depth of this zone changed among seasons and transects, likely due to internal seiche (Flood et al. 2021). Most fish were restricted to the top 9 m of water during the summer and 14-18 m in the fall as the thermocline deepened (Figure 46). The thermocline was absent in the spring and no hypoxia was present, so fish were distributed throughout the water column. Habitat compression during the summer months may contribute to increased predation pressure on forage fishes by enhancing the foraging efficiency of pelagic top predators (e.g., Walleye; Brooks et al. 2022). Collectively, these results emphasize the need to address eutrophication issues that likely drive both hypolimnetic anoxia and the unequal distributions of lower trophic food-web transfer, factors which are presumed to be the main driver of unequal pelagic fish distributions in Hamilton Harbour AOC.

Study limitations

- There are no study-specific caveats in this study; however, the “Remaining Concerns and Uncertainty” in the summary section apply to these works as well.

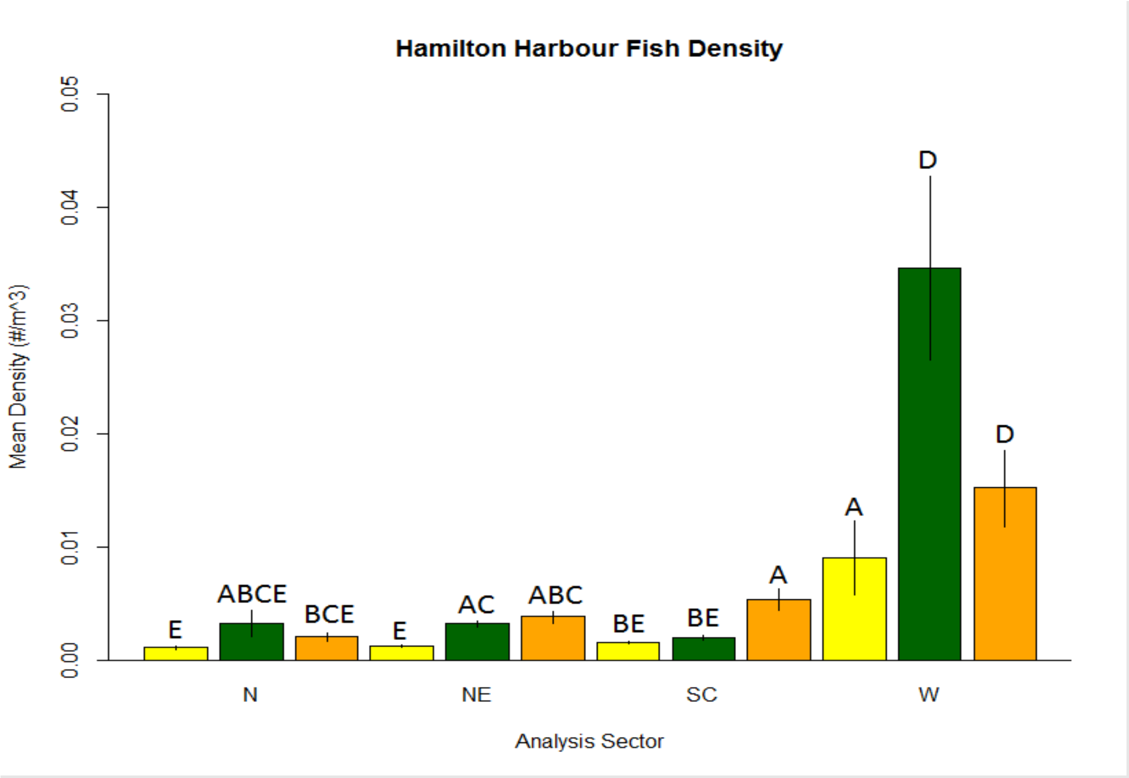

Figure 45. *Figure 7 reproduced from Midwood et al. (2019). Mean density (#/m^3) for each analysis sector [in Hamilton Harbour AOC] and season. Colours denote the seasons where yellow = spring, green = summer, and orange = fall. Error bars show the standard deviation. Different letters indicate significant differences in mean density across seasons and sectors.*

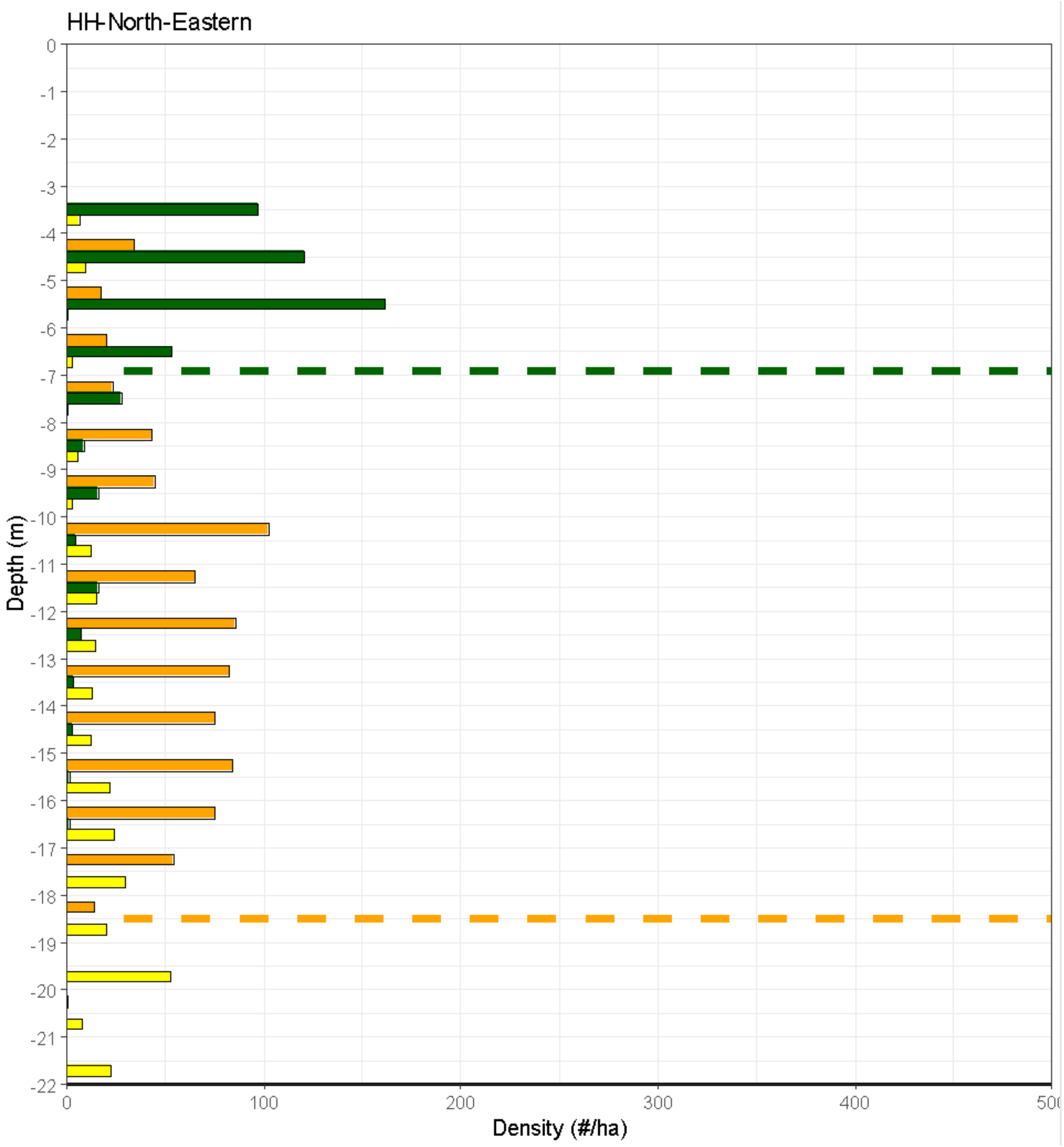

Figure 46. *Figure 13b reproduced from Midwood et al. (2019). Vertical distribution of fish density for the North-Eastern sector from the 2016 Hamilton Harbour AOC acoustic surveys generated from echo integration analysis of the acoustic backscatter for all fish > 2.9 cm (excluding schools). Data shown are the average estimated fish density by 1m depth bins by analysis sector and season (spring = yellow, summer = green, fall = orange). The average estimated thermocline depth for each sector in the summer (green dashed line) and fall (orange dashed line) are shown as is the maximum depth recorded during surveys in each region (black line).*

2018 Survey, Midwood et al. (2022)

Ten fish species were captured during the trawl survey. In the Hamilton Harbour AOC, the most common species were Alewife (n=539 fish), Gizzard Shad (n=30 fish), and Rainbow Smelt (n=20 fish). Catch per unit effort at 8 m mid-water trawls in the Toronto AOC (Inner Harbour and Outer Harbour) were significantly greater than either the Hamilton Harbour AOC or Lake Ontario (ANOVA ($F_{(3)}$=6.8, p=0.003; Tukey HSD Toronto vs Hamilton/Lake Ontario, p<0.01, Toronto vs Toronto Open Lake, p=0.08, Hamilton vs Lake Ontario vs Toronto Open Lake, p>0.96). These patterns were largely driven by higher catch of Alewife and Rainbow Smelt in the Toronto AOC (Inner Harbour and Outer Harbour) and are consistent with catches seen during the 2016 hydroacoustic surveys (Midwood et al. 2018, 2019).

Fish were detected in significantly fewer hydroacoustic transects, and there were lower density estimates in the Lake Ontario Open Coast sector compared with either the Toronto or Hamilton Harbour AOC. Non-parametric tests showed mean fish density was significantly higher in Toronto Inner Harbour (TO_IH), Toronto Outer Harbour (TO_OUTH), and Hamilton Harbour AOC North East (HH_NE), compared with other sectors (Figure 47).

Fish biomass estimated from hydroacoustics was highest in the Hamilton Harbour AOC West (HH_W sector) and generally higher in the Hamilton Harbour AOC compared to the Toronto AOC and the Lake Ontario Open Coast. Although not statistically tested, Toronto AOC sectors (TO_IH, TO_OH) seemed to be dominated by smaller fish (20-81 mm length), while Hamilton Harbour AOC sites had a more even split of small-bodied and medium-sized fish (81-250 mm length).

As observed in past summer and fall surveys, hypolimnetic anoxia was present in the Hamilton Harbour AOC but absent in Lake Ontario and the Toronto AOC. This anoxia also likely influences the vertical distribution of fishes in the harbour (Midwood et al. 2019; Brooks et al. 2022); therefore, it may be appropriate to compare fish densities (derived from hydroacoustics) on a per-volume basis both with the inclusion and exclusion of these hypolimnetic waters. This type of analysis would help partition the extent to which apparent differences in fish density between Hamilton and Toronto AOCs are driven by lower trophic productivity or simply the volume of habitat available to pelagic fishes.

Study limitations:

- Bay of Quinte was scheduled to be sampled as an appropriate reference for the Hamilton Harbour AOC (i.e., a sheltered embayment rather than an exposed embayment like the Toronto AOC), but weather and logistical issues prevented sampling, and therefore, there are no appropriate regional reference data at this time.
- Plankton and water quality data have yet to be synthesized into the hydroacoustic dataset.

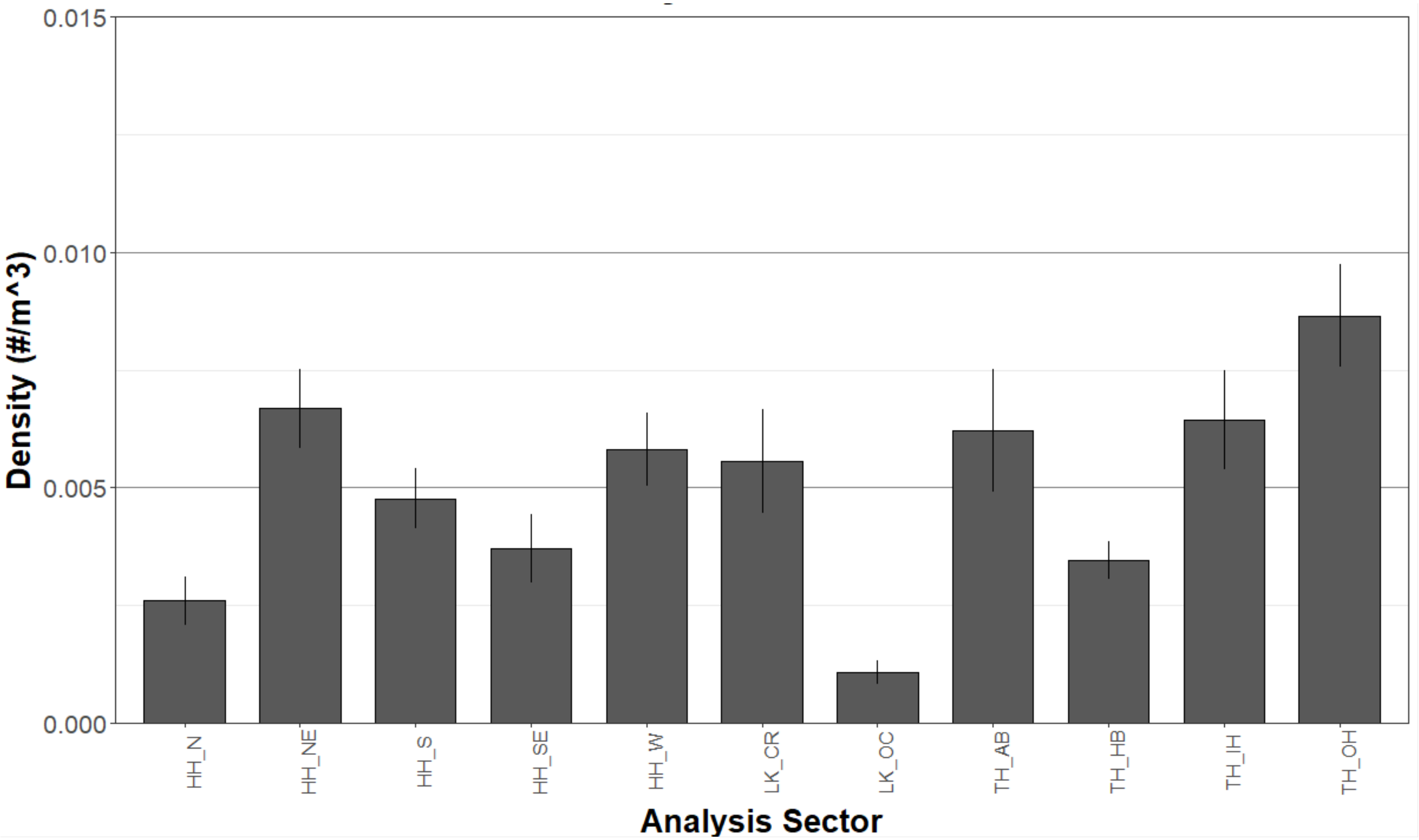

Figure 47. *Figure 38 reproduced from Midwood et al. (2022)*. *Estimates of fish density (#fish/m^3) based on the analysis of hydroacoustic pings in each analysis sector for fall 2018. See Table 6 for site code names.*

SUMMARY OF STATUS OF FP-2

Data collected using both boat electrofishing (section FP-2A) and trap nets (section FP-2B) were used to derive indices of biotic integrity (IBI) and assess whether IBI scores in the Hamilton Harbour AOC were meeting the delisting target of an overall IBI score of 55-60. For both datasets, IBI scores remained persistently below this target and lower than most similar ecosystems in Lake Ontario. IBI scores are calculated from a variety of fish community metrics. For the electrofishing IBI, the majority of metrics related to catch, richness, and production were found to now be comparable to, or lower than, those observed when the AOC was first listed. For the trap net IBI, high abundance and biomass of generalist species and comparatively low biomass of specialist and piscivorous fishes indicate a degraded system. Values of fish community metrics from both datasets were consistently below values observed in sheltered embayments in Lake Ontario used as reference sites. Within the AOC, there were clear spatial differences in fish community metrics, with generally higher IBI, total catch, and species richness at the west end of the harbour relative to the east. The north shore tended to be intermediate, but more recently (post-2012), fish assemblages in the north zone have worsened and are now more similar to those at the east end. Similar to FP-1, an important next step is to assess the relative effects of different ecosystem stressors on the fish community to help identify the major factors limiting population recovery. Given the noted differences among harbour zones, a more detailed evaluation of environmental conditions in the west, north, and east nearshore areas is also warranted (e.g., habitat supply, habitat quality, exposure, and dissolved oxygen). This would help to interpret fish catch and community metric scores and identify potential limitations to population recovery within zones of the harbour.

CRITERION FP-2A: ELECTROFISHING

SUMMARY

A long-term boat electrofishing-based dataset was used to assess trends through time in fish community metrics in the Hamilton Harbour Area of Concern (AOC) and compare metric values with those from other sheltered embayments in Lake Ontario. Fish community metrics related to catch, richness, and production were comparable to, or lower than measured when the system was first listed and assessed. Index of Biotic Integrity (IBI) scores remained consistently below targets for the AOC (i.e., <55-60) and below values observed in eastern Lake Ontario. Within the Hamilton Harbour AOC, there were clear differences in fish community metric values among harbour zones, with the highest values in the west zone, lowest in the east zone, and intermediate values in the north zone. Based on these boat electrofishing-derived fish community metrics, fish populations in the Hamilton Harbour AOC remain impaired.

KEY MESSAGES

- Electrofishing-based index of biotic integrity (IBI) scores in the Hamilton Harbour AOC are below delisting criteria targets indicating that fish populations remain impaired.
- Fish community metrics related to catch, richness, and production are now comparable to, or lower than measured when the system was first listed and assessed.
- Similar declines in non-native fish metrics are less reflective of improvements in fish community condition and more related to an overall trend of declining catch.
- Fish community condition in the Hamilton Harbour AOC remains more impaired than similar sheltered embayments found in eastern Lake Ontario.
- Limited temporal changes in fish community metrics in sheltered embayments in eastern Lake Ontario suggest local factors in the Hamilton Harbour AOC are limiting population recovery.
- Distinct IBI and fish community metric scores were found among zones within the Hamilton Harbour AOC, identifying differences in nearshore fish assemblages across the harbour.
- IBI, total catch, and species richness (among others) were highest in the west and lowest in the east with the north being intermediate; however, these positive fish community metrics have declined in the north zone in P4 indicating that the fish assemblages there have worsened and are now more similar to the east than the west.
- IBI and fish community metric scores in the west end of the Hamilton Harbour AOC tend to be comparable to values observed in degraded shallow systems found in western Lake Ontario.

REMAINING CONCERNS AND UNCERTAINTY

- Recent (post-2012) declines in fish community metrics are likely driven by multiple stressors; however, the magnitude of the effect of various stressors and the influence of ongoing ecosystem degradation versus shifting trophic structure remains unclear.

FUTURE MONITORING

- Continued monitoring in the Hamilton Harbour AOC and regional reference locations is necessary to support the assessment of criteria FP-2.
- Greater focus on night electrofishing surveys is necessary as they provide more representative catch and richness information.

RECOMMENDED ACTIONS

- DFO should attempt to partition the relative effect of different ecosystem limitations or stressors on the fish community; this can help identify the major factors limiting population recovery and potential interventions (e.g., habitat supply, habitat quality, forage base, piscivore mortality and predation; see General Discussion).
- DFO should quantify differences among zones within the harbour (e.g., amount of different habitat types, exposure, eutrophication impact, impacts from upwellings, etc.); this can help inform the interpretation of metric scores among zones and help identify zonal limitations to population recovery.
- DFO should investigate the habitat and community composition in the harbour proximate to the refuge areas identified in the watershed to identify impediments to recolonization.

BACKGROUND

Ecological indicators can help integrate complex biotic or ecosystem information into a single value that can be used to track temporal changes in ecosystem conditions and compare conditions in one location to other similar systems. In the early 1990s, a fish-based Index of Biotic Integrity (IBI) was developed specifically for littoral areas of three Great Lakes Areas of Concern based on boat electrofishing data (Minns et al. 1994). This IBI is derived from 12 fish community metrics broadly related to species richness, abundance and condition, or trophic composition. The resulting IBI score can in theory range from 0-100, with scores over 60 indicative of healthier ecosystems (Minns et al. 1994). The IBI has been found to correlate well with sources of degradation related to water quality, physical habitat supply, and the abundances of invasive species and top predators (Minns et al. 1994). Consequently, the IBI has been applied extensively in Great Lakes Areas of Concern (AOC) to assess the condition of fish communities (Smokorowski et al. 1998; Brousseau et al. 2011; Pratt and O’Connor 2011; Boston et al. 2016; Hoyle et al. 2018). In the Hamilton Harbour AOC in particular, the sole quantitative target for the fish populations beneficial use impairment is to: “*Attain an IBI of 55-60 for Hamilton Harbour and maintain the target score for two sequences of monitoring carried out a minimum of every three years*.” (HHRAP 2019, pg 8). As such, the IBI has been a key feature of past assessments of fish populations. These works noted increases in IBI scores in the early 1990s correlated to systemic reductions in total phosphorus, increased water clarity, and the completion of several habitat restoration projects (Smokorowski et al. 1998; Brousseau and Randall 2008; Boston et al. 2016). However, declines in IBI and metric values from 2006-2012 within Hamilton Harbour AOC were later documented and these coincided with the establishment of a novel invasive species (Round Goby) as well as increasing total of phosphorus and declining Secchi depth (Boston et al. 2016; Hiriart-Baer et al. 2016). This section summarizes recent updates to trends in IBI scores in Hamilton Harbour AOC with additional comparisons of AOC-specific IBI and metric values to those in similar ecotypes (i.e., sheltered embayments in eastern Lake Ontario; Bowlby and Hoyle 2017) or shallow littoral areas in western Lake Ontario.

METHODS

Data for this section were compiled from Fisheries and Oceans Canada’s long-term boat electrofishing dataset that used a standardized, distance-based (100-m transect completed in 300 seconds) sampling protocol. While sampling occurred at fixed transect locations, sampling depth was standardized to the 1.5 m depth contour (see Brousseau et al. 2005 for detailed methods). Fish community information at each transect wassummarized into fish community metrics (Tables 7 and 8), and these and other metrics were then used to derive the IBI as well as an adjusted IBI (IBI_{Adj}), which removes species more typically associated with offshore waters (Minns et al. 1994). A habitat productivity index (HPI) and a similarly adjusted version (HPI_{Adj}) were also calculated (Randall and Minns 2000). These indices are first-order measures of the productive capacity of an ecosystem, which at its core refers to the sustainable natural production of all fish species that is possible from the habitat (adapted from Minns et al. 2011). Interpretation of the metrics used to derive the IBI, as well as patterns in the IBI_{Adj}, HPI, and HPI_{Adj}, were used to help further contextualize the status of the fish community in the Hamilton Harbour AOC and observed patterns (or lack therefore) in the IBI itself.

Table 7. *List of fish community metrics and additional details for each metric. The Index of Biotic Integrity (IBI) is comprised of 12 metrics and these are marked with an *. Metrics that were not explicitly modelled were: the number of turbidity intolerant species, the percent of catch comprised of non-native and offshore species, and the percent biomass of generalist, specialist, and non-native species.*

Fish Community Metric	Metric Details
Habitat Productivity Index (HPI)	First order measure of productive capacity of an ecosystem (Randall et al. 2000)
Adjusted Habitat Productivity Index (HPI_{Adj})	HPI adjusted to remove offshore fish species
Index of Biotic Integrity (IBI)	Composite index made up of 12 metrics (Minns et al. 1994)
Adjusted Index of Biotic Integrity (IBI_{Adj})	IBI adjusted to remove offshore fish species
Total Catch	Total number of individual fish
Total Catch Native*	Number of native individual fish in the catch
Total Catch Non-Native	Number of non-native individual fish in the catch
Total Catch Offshore	Number of offshore individual fish in the catch
Species Richness	Total number of fish species captured
Native Species Richness*	Number of native species in the catch
Non-Native Species Richness*	Number of non-native species in the catch
Centrarchid Species Richness*	Number of native centrarchid species in the catch
Cyprinid Species Richness*	Number of native cyprinid species in the catch
Native Biomass*	Total biomass of native fish in the catch
Proportion Piscivore Biomass*	Proportion of total biomass comprised of piscivores
Proportion Offshore Biomass	% of total biomass comprised of offshore species
Richness of Turbidity Intolerant Species*	Number of turbidity intolerant species
Proportion Generalist Biomass*	% of total biomass comprised of generalist species
Proportion Specialist Biomass*	% of total biomass comprised of specialist species
Proportion Number Non-Native Fishes*	% of total numbers comprised of non-native species
Proportion Non-Native Biomass*	% of total biomass comprised of non-native species
Proportion Offshore Catch	% of total numbers comprised of offshore species

Similar to section FP-1A, temporal trends in IBI scores and fish community metrics were analyzed among four time stanzas (P1: pre-1994, P2: 1995-2004, P3: 2005-2012, and P4: 2013-2021), and both overall and zonal (west, north, east) fish community metric values in the Hamilton Harbour AOC were compared with baseline reference conditions from sheltered embayments in the eastern (East-Ref; P1-P4) and western (West-Ref; P3 and P4) basins of Lake Ontario (see Figure 2 in section FP-1A for locations of transects, zones, other sampling locations). Briefly, West-Ref locations include Jordan Harbour and Frenchman's Bay, which are heavily impacted by agricultural and urban development, respectively. East-Ref locations were primarily located in the Bay of Quinte, but also included West Lake in Prince Edward County; this part of Lake Ontario has fewer anthropogenic impacts, but fish populations in the Bay of Quinte AOC were assessed as impaired during P1. Within the harbour, the west zone tends to be shallower and is closest to Cootes Paradise, the north is slightly more exposed, but still has large beds of submerged aquatic vegetation, and the east has the highest level of exposure with typically less vegetation cover. All temporal trend analyses for the fish community metrics used a repeated measure ANOVA with Time Stanza and Location (Hamilton-overall, Hamilton-zones, east and west and reference areas) as fixed effects and transect and sampling time period (day or night) included as random effects. When fixed effects were significant, the lsmeans function (lsmeans package; Lenth 2016) was used to examine pairwise differences between Time Stanza, Location, or their interaction. These works are presented in more detail in Turner et al. (in review) with high-level summaries relevant to the assessment of the status of fish populations provided here. The model output can be found in Appendix C.

Table 8. *Desired response for each fish community metric if fish community condition was improving (↑ = increasing, ↓ = decreasing, — = no change) in the Hamilton Harbour AOC between time stanza P1 (pre-1994) and P4 (2013-2021). Observed response for the entire Hamilton Harbour AOC (overall), among harbour zones, and at sheltered embayments in eastern Lake Ontario (East-Ref) are shown.*

		Hamilton Harbour AOC Zone				
Metric	*Desired Response*	*Overall*	*West*	*North*	*East*	*East-Ref*
Habitat Productivity Index (HPI)	↓	↓	↓	↓	—	—
Adjusted Habitat Productivity Index (HPI$_{\text{Adj}}$)	↓	↓	↓	↓	—	—
Index of Biotic Integrity (IBI)	↑	—	—	—	—	—
Adjusted Index of Biotic Integrity (IBI$_{\text{Adj}}$)	↑	—	—	—	—	—
Total Catch	↑	↓	↓	↓	↓	—
Total Catch Native	↑	↓	—	↓	—	—
Total Catch Non-Native	↓	↓	↓	↓	↓	—
Total Catch Offshore	↓	↓	↓	↓	↓	↓
Species Richness	↑	↓	↓	↓	—	—
Native Species Richness	↑	↓	—	↓	—	—
Non-Native Species Richness	↓	↓	↓	↓	↓	↓
Centrarchid Species Richness	↑	↓	↓	↓	—	—
Cyprinid Species Richness	↑	↓	—	—	↓	—
Native Biomass	↑	—	—	—	—	↓
Proportion Piscivore Biomass (PPB)	↑	—	—	—	—	—
Proportion Offshore Biomass	↓	—	—	↑	—	—

SUMMARY OF FINDINGS

Index of Biotic Integrity (IBI)

IBI scores in the Hamilton Harbour AOC were consistently below the 55-60 target, indicating that this criterion has never been met since 1988 (Figure 48; Table 9). There was no change in IBI score between time stanzas (P1 to P4) within Hamilton Harbour AOC or East-Ref. Across all time stanzas, East-Ref had consistently higher IBI scores, whereas West-Ref IBI scores (when available: P3 and P4) were comparable to overall scores in the Hamilton Harbour AOC. Across all time stanzas, after some improvements from P1 to P2, the majority of fish community metric values in the Hamilton Harbour AOC have since declined such that they are now either comparable (IBI, IBI_{Adj}, PPB and Native Biomass) or lower to values seen in P1 (all other metrics; Table 8 and Table 9). Three metrics showed similar declines from P1 to P4 in East-Ref (Native Biomass, Non-native Richness, Total Catch Offshore), while the majority of metrics in that area remained constant (Table 8). Temporal data for the West-Ref were more limited and most metrics did not change from P3 to P4 (Table 9). See Table 9 for a summary of the mean (with standard deviation) metric values among time stanzas and locations.

Within the harbour, there were distinct zonal differences in fish community metric values (i.e., metric values tended to be highest in the west and lowest in the east), and temporal patterns among zones were generally consistent. The north zone had the greatest number of metrics that declined between P1 and P4 (10 of 16 metrics; Table 8). While the east zone had the fewest metrics with declines from P1 to P4 (5 of 16 metrics; Table 8), it also had the lowest initial values for most metrics among zones (Table 9). Declines in some metric values can be indicative of improvements in fish community conditions (e.g., Non-native Richness), and these metrics are discussed in detail below. For the IBI, values during P1 were consistent among zones, and while within-zone values changed little (the sole change being a decrease in IBI score from P2 to P4 in the east), differences among zones were apparent with the west having higher IBI scores than the east and north zones in both P2 and P4 (IBI scores in the west and north were comparable and both higher than east in P3; Figure 1).

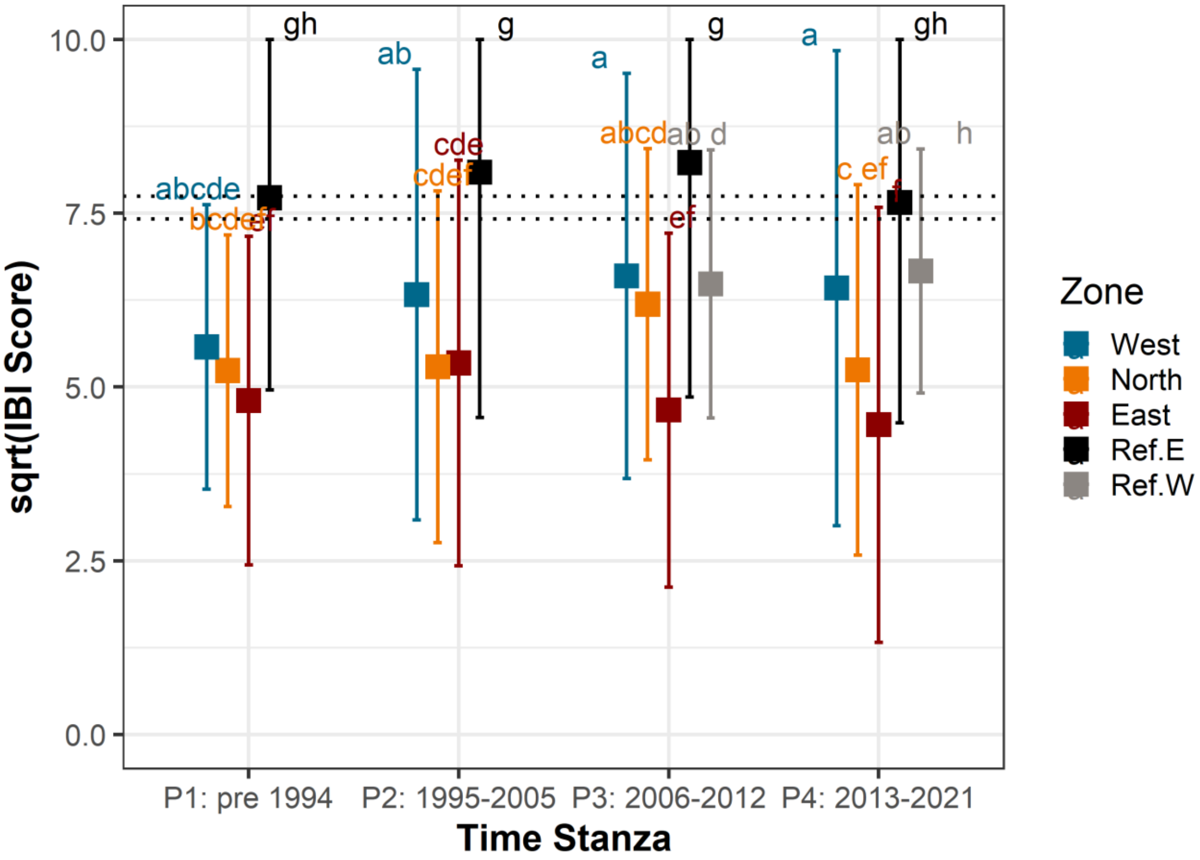

Figure 48. *Temporal changes in Index of Biotic Integrity (IBI) scores (mean ± confidence intervals) within the Hamilton Harbour Area of Concern (west (blue), north (orange), east (red)) and in regional reference areas (west reference [Ref.W] = grey, east reference [Ref.E] = black). Values were square root transformed to meet model assumptions of normality of residuals and equal variance. Analysis are based on a repeated measure ANOVA with Time Stanza and Location as fixed effects and transect and sampling time period (day or night) included as random effects. Plot shows values predicted from the best fit model (i.e., least-squares means). Dashed horizontal lines indicate the target range of 55-60 for the fish population delisting criteria. Means with different letters are considered significantly different (p<0.05).*

Native fishes

Nearly all IBI metrics related to native fishes (4 of 5 metrics) showed overall declines in Hamilton Harbour AOC from P1 to P4 with declines occurring in at least one zone while others remain unchanged (Table 8). In contrast, while East-Ref showed some temporal variance in some of these metrics (e.g., catch of native fishes), only native biomass declined from P1 to P4, and the other four metrics related to native fishes remained unchanged. Native species catch and richness values in all three zones in Hamilton Harbour AOC were consistently lower than East-Ref across all time stanzas and all metrics had dropped below values seen at the West-Ref areas by P4 (although there was still some overlap between the west zone and West-Ref; Figure 49). The overall decline in native fish richness and catch between P1 and P4 was largely driven by declines in the north zone (particularly between P3 and P4) since both the west and east were not significantly different between these two time periods (Table 8 and Table 9). Significant declines in the catch of Brown Bullhead, Yellow Perch, and Largemouth Bass in the north zone are likely driving these overall trends (FP-1A; see Appendix A for a full list of species assignments as native/non-native).

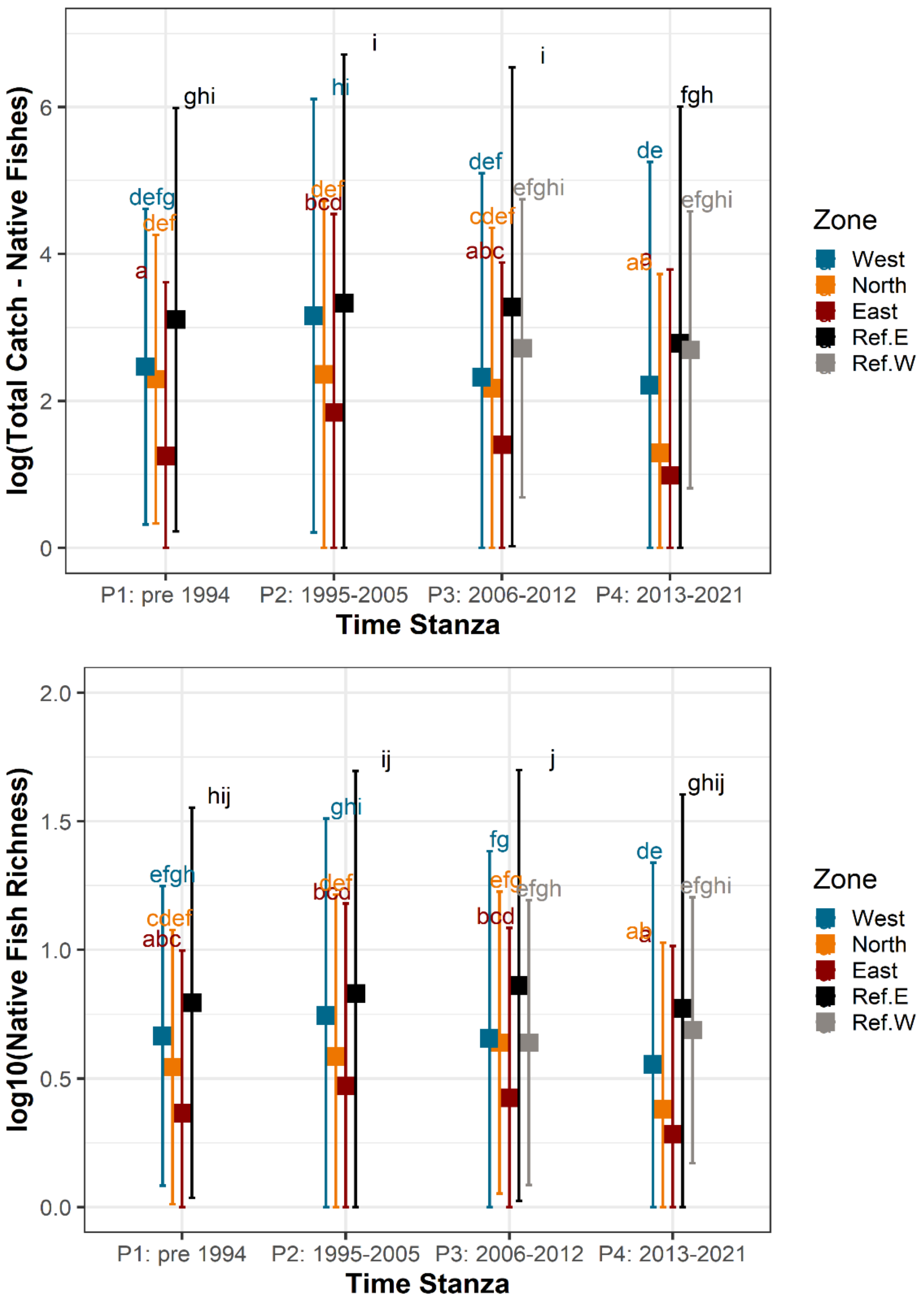

Figure 49. *Temporal changes in mean (± confidence intervals) native species catch (top panel) and richness (bottom panel) for the Hamilton Harbour Area of Concern (west (blue), north (orange), east (red)) and in regional reference areas (west reference [Ref.W] = grey, east reference [Ref.E] black). Plots show values predicted from the best fit model (i.e., least-squares means). Richness data were* $\log_{10}$ *transformed and catch data were* $\log_e$ *(ln) transformed to meet model assumptions of normality of residuals and equal variance. Analysis are based on a repeated measure ANOVA with Time Stanza and Location as fixed effects and transect and sampling time period (day or night) included as random effects. Means with different letters are considered significantly different (p<0.05).*

While Boston et al. (2016) noted increases in Centrarchid richness in the Hamilton Harbour AOC between 1988-2013 at sites with some habitat enhancement, it does not appear that these gains have been maintained, and instead, overall and among zones catch and richness values for Centrarchids are lower than, or comparable, to their lowest levels observed in the AOC. Centrarchid richness, catch, and encounter rates in the Hamilton Harbour AOC were more similar to West-Ref areas (i.e., comparable catch, similar richness in P3, with declines in east and north in P4) but were consistently below those in the East-Ref (Figure 50; Table 9; see Section FP-1A Figure 10). Such spatial-temporal patterns were also evident for specific Centrarchid species, with depressed encounter rates of Largemouth Bass in the north and east zones relative to the west zone and the two reference areas (see Section FP-1A). The catch of sunfishes significantly declined from P2-P3 at the east and west zones and also in the East-Ref area. While it has not changed in P4, catch in the Hamilton Harbour AOC remains significantly below the East-Ref area.

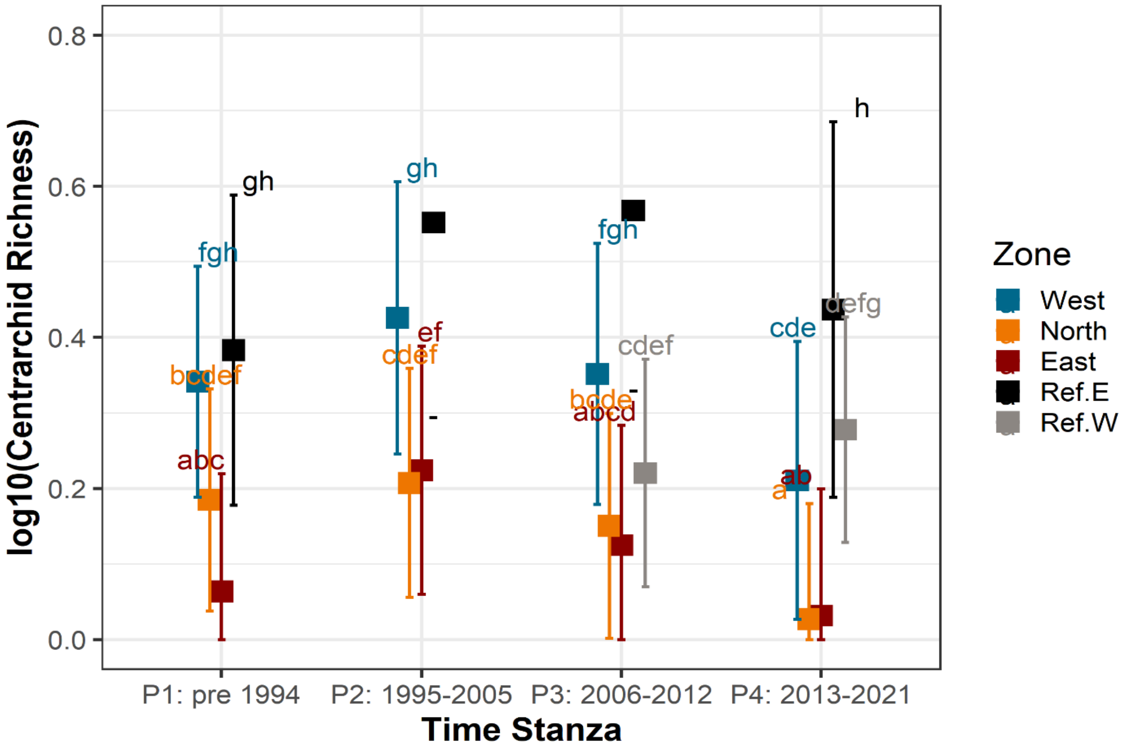

Figure 50. *Temporal changes in mean (± confidence intervals) Centrarchid species richness for the Hamilton Harbour Area of Concern (west (blue), north (orange), east (red)) and in regional reference areas (west reference [Ref.W] = grey, east reference [Ref.E] = black). Data were* $\log_{10}$ *transformed to meet model assumptions of normality of residuals and equal variance. Analysis are based on a repeated measure ANOVA with Time Stanza and Location as fixed effects and transect and sampling time period (day or night) included as random effects. Means with different letters are considered significantly different (*$p<0.05$*). Plot shows values predicted from the best fit model (i.e., least-squares means).*

Top predators

Establishing a more balanced trophic structure for fishes in the Hamilton Harbour AOC is a long-standing objective and increasing the proportion of top predators to >0.20 of biomass (PPB) is thought to provide suitable top-down control (Hoyle and Yuille 2016). There is no evidence of a change in PPB between P1 and P4 in the Hamilton Harbour AOC or either reference area; however, during P3, the mean value for the west zone did exceed 0.20, which matched increases at this time in the East-Ref (Figure 51). Values in all Hamilton Harbour AOC zones had dropped below 0.20 as of P4 and were comparable to West-Ref values in P3 and P4. Across all time stanzas East-Ref PPB values were well above 0.20 and consistently higher than those observed in the Hamilton Harbour AOC (Figure 51). Persistently low PPB in the Hamilton Harbour AOC was one of the driving factors behind efforts to stock Walleye into the system, and while increases in PPB in electrofishing catch have not manifested, there is evidence for some modest increases in this metric in Trap Net data (see section FP-2B), but it still remains below the 0.20 threshold. A lack of increase in this metric is not surprising given declines in catch of top predators, like Largemouth Bass and Smallmouth Bass, and the lack of increase in catch of already marginal Northern Pike (see section FP-1A).

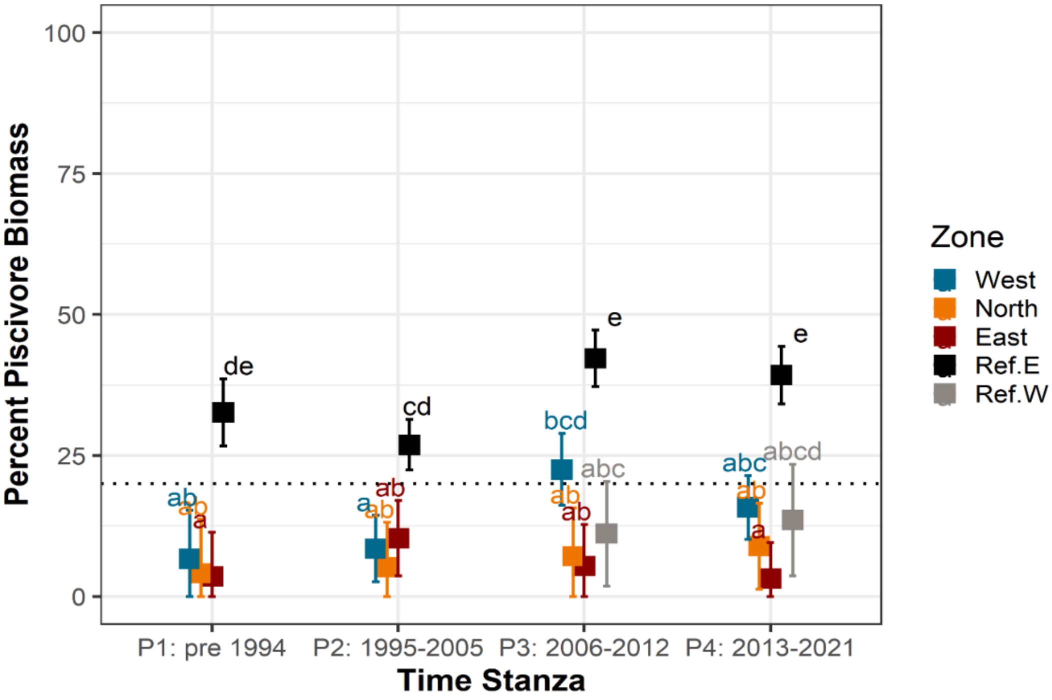

Figure 51. *Temporal changes in mean (± confidence intervals) of the percent of biomass comprised of top predators for the Hamilton Harbour Area of Concern (west (blue), north (orange), east (red)) and in regional reference areas (west reference [Ref.W] = grey, east reference [Ref.E] = black). Means with different letters are considered significantly different (p<0.05). Analysis are based on a repeated measure ANOVA with Time Stanza and Location as fixed effects and transect and sampling time period (day or night) included as random effects. Plot shows values predicted from the best fit model (i.e., least-squares means). Overall model fit for the percent piscivore biomass was poor, so results should be interpreted with caution.*

Non-native fishes

For the majority of metrics, the observed trends are counter to what might be expected if fish community conditions were improving. The main exceptions were metrics related to the catch and richness of non-native species, both of which declined. Such declines have been previously documented (Brousseau and Randall 2008) and as of 2013, were largely attributed to declines in Common Carp and Alewife (Boston et al. 2016). This trend has continued into P4 with even lower catch and richness of non-native species than any earlier time stanza, largely driven by continued declines in catch of Common Carp (see FP-1A). While catch and richness of non-native fishes in the Hamilton Harbour AOC have declined from P1 to P4, values have remained consistent at the West-Ref area from P3 to P4, such that in P4 it is now higher than overall values for the Hamilton Harbour AOC (except for west zone of Hamilton Harbour AOC; Table 9; Figure 52). In contrast, catch and richness at the East-Ref areas have remained low through all time stanzas (albeit non-native richness in P4 is lower than P1), and while the overall richness of non-native fishes remains higher in the Hamilton Harbour AOC, catch in P4 is now comparable across all harbour zones (Figure 52).

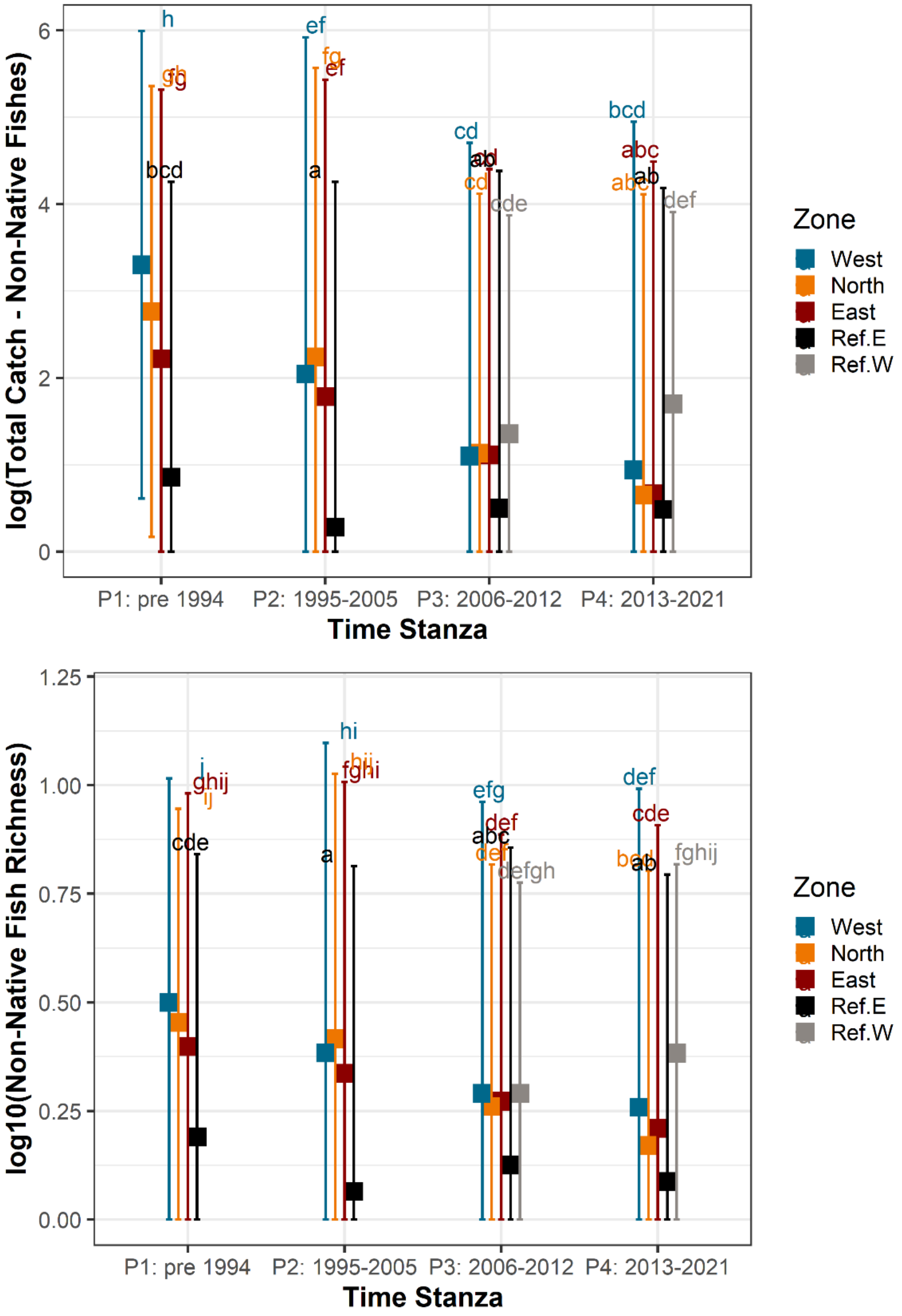

Figure 52. *Temporal changes in mean (± confidence intervals) non-native species catch (top panel) and richness (bottom panel) for the Hamilton Harbour Area of Concern (west (blue), north (orange), east (red)) and in regional reference areas (west reference [Ref.W] = grey, east reference [Ref.E] = black). Richness data were log*$_{10}$ *transformed and catch data were log*$_{e}$ *(ln) transformed to meet model assumptions of normality of residuals and equal variance. Analysis are based on a repeated measure ANOVA with Time Stanza and Location as fixed effects and transect and sampling time period (day or night) included as random effects. Means with different letters are considered significantly different (p<0.05). Plots show values predicted from the best fit model (i.e., least-squares means).*

Offshore fishes

While the Hamilton Harbour fish community is made up of both nearshore and offshore fish assemblages, an overabundance of offshore species in the nearshore catch is an indication of habitat impairment for nearshore fish species. Several previous works have noted the comparatively high rates of capture of offshore fish species (e.g., Alewife, Gizzard Shad) in the Hamilton Harbour AOC relative to other similarly sheltered embayments (Boston et al. 2016). In healthier ecosystems, the catch of offshore species is, in general, less than 10% of the total catch (numbers and biomass). Temporal trends in the total catch of offshore fishes were similar to the overall total catch in the Hamilton Harbour AOC (declining from P1-P2 and P2-P3; stable from P3-P4). The proportion of biomass comprised of offshore fishes similarly declined between P1 and P3 (Figure 53). In P3, the total catch and proportion of biomass of offshore fishes were comparable across all three zones in the Hamilton Harbour AOC to both regional reference areas. During P4, catch values became distinct in the West-Ref from all other areas except the west zone of the Hamilton Harbour AOC, but they remained consistent and similar in the Hamilton Harbour AOC and East-Ref (Figure 53). As a proportion of total catch, however, the catch of offshore species in the Hamilton Harbour AOC was comparable to West-Ref areas and consistently higher across all time stanzas than East-Ref (Table 9). A marked change occurred in P4 in terms of the proportion of biomass, with significant increases from P3 in the west and north zones of the harbour; these were largely driven by increased capture of Gizzard Shad in these zones (see FP-1A). All zones of the harbour and the West-Ref area had significantly higher proportions of offshore biomass in P4 relative to the East-Ref.

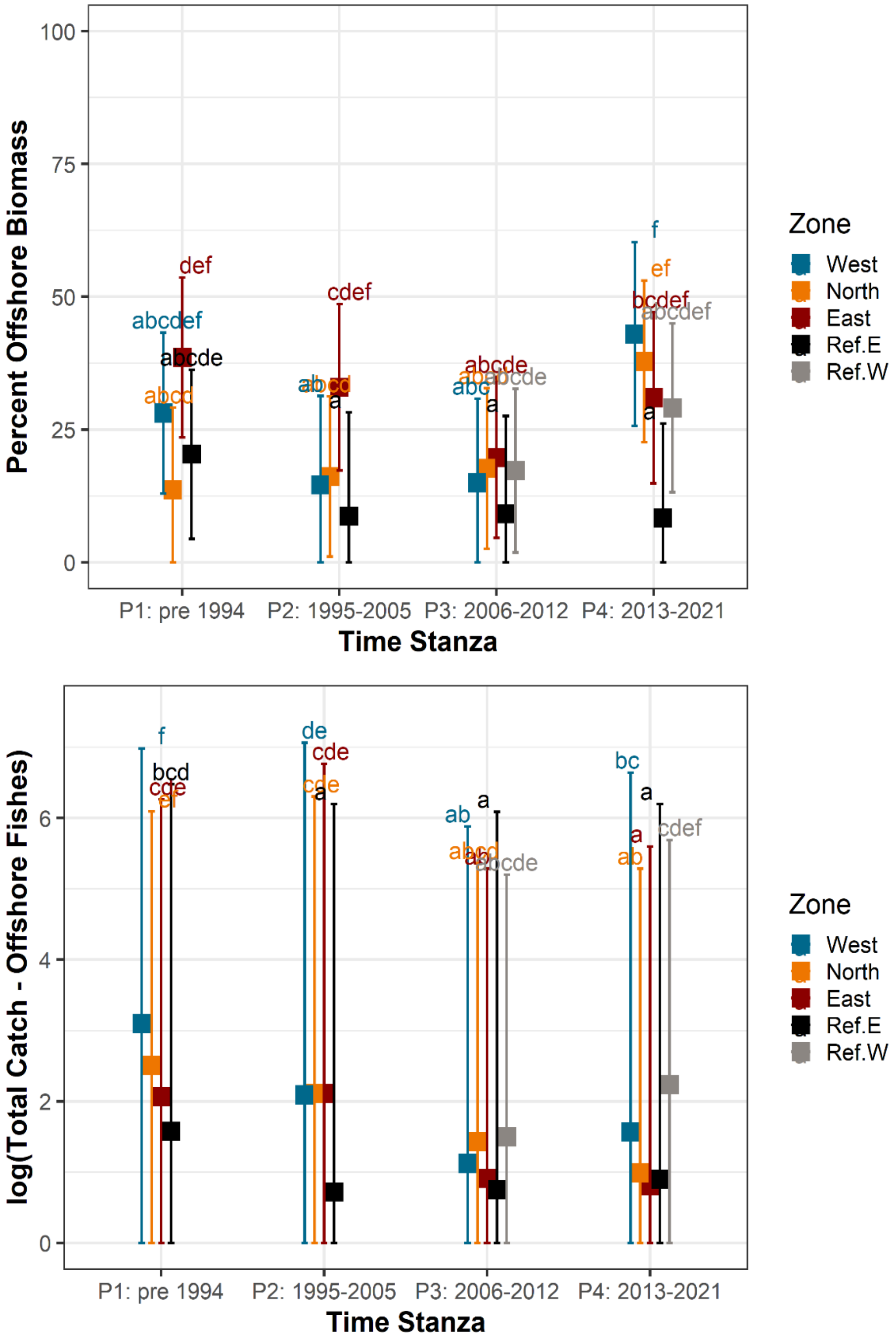

Figure 53. *Temporal changes in mean (± confidence intervals) percent of biomass comprised of offshore species (Top Panel) and catch of offshore fishes (Bottom Panel) in the Hamilton Harbour Area of Concern (west (blue), north (orange), east (red)) and in regional reference areas (west reference [Ref.W] = grey, east reference [Ref.E] = black). Catch data were* $\log_e$ *(ln) transformed to meet model assumptions of normality of residuals and equal variance. Analysis are based on a repeated measure ANOVA with Time Stanza and Location as fixed effects and transect and sampling time period (day or night) included as random effects. Means with different letters are considered significantly different (p<0.05). Plots show values predicted from the best fit model (i.e., least-squares means).*

Habitat Productivity Index (HPI)

When first listed, the Hamilton Harbour AOC had lower species richness and higher biomass compared to other similar sites in Lake Ontario (Smokorowski et al. 1998); this was evident during P1 for the HPI (a surrogate index of production). However, from P1 to P4, while HPI values at the East-Ref areas did not change, there was an overall decline in the Hamilton Harbour AOC that was largely driven by declines in HPI in the west and north zones from P2 to P3 and P4 (Figure 54; Table 8), consistent with declines in Common Carp (see FP-1A). In contrast, HPI values at the West-Ref areas increased significantly from P3-P4, becoming distinct from values in East-Ref and north and east zones of the Hamilton Harbour AOC (Figure 54). Declines in the Hamilton Harbour AOC were even more stark for the HPI_{Adj}, with both the west and north zones showing an additional drop from P3 to P4 (Figure 53). This more recent decline in the HPI_{Adj} suggests that the contribution of offshore fishes to productivity has increased during P4 and offsets continuing declines in nearshore fishes when the non-adjusted HPI is used (Figure 54). The catch of Gizzard Shad, an offshore omnivorous species, was higher during P4 in the west zones, which supports the notion of a shift in the source of productivity (see Section FP-1A). Overall, declines in HPI and HPI_{Adj} suggest that the productive capacity of the west and north zones (for nearshore fishes in particular) has declined since P1.

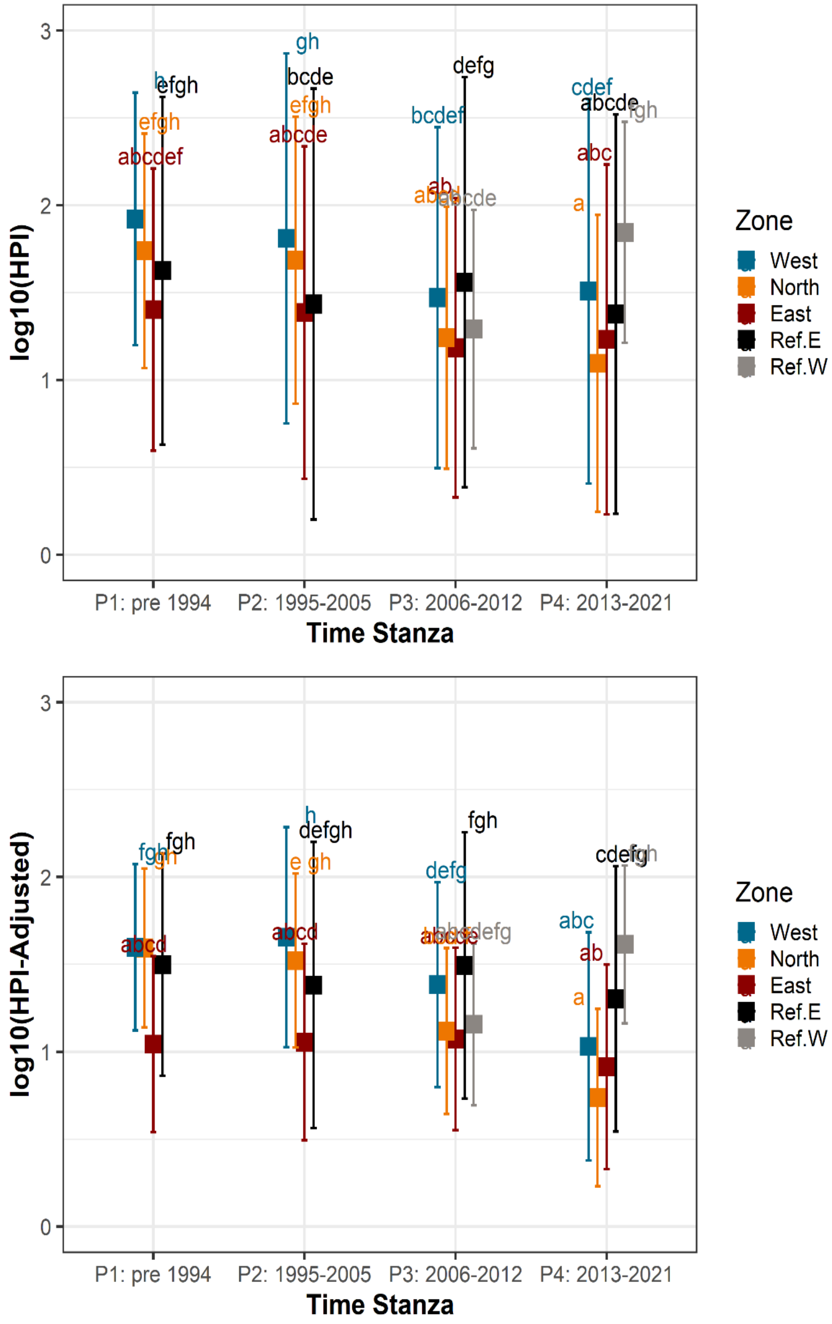

Figure 54. *Temporal changes in the mean (± confidence intervals) habitat productivity index (HPI; top panel) and the adjusted HPI (HPI_{Adj}, which captures the HPI value after removing predominantly offshore fishes; bottom panel) for the Hamilton Harbour Area of Concern (west (blue), north (orange), east (red)) and in regional reference areas (west reference [Ref.W] = grey, east reference [Ref.E] = black). Data were $\log_{10}$ transformed to meet model assumptions of normality of residuals and equal variance. Analysis are based on a repeated measure ANOVA with Time Stanza and Location as fixed effects and transect and sampling time period (day or night) included as random effects. Means with different letters are considered significantly different (p<0.05). Plots show values predicted from the best fit model (i.e., least-squares means).*

DISCUSSION

There is no single component of the fish community that is contributing to persistently low IBI scores in the Hamilton Harbour AOC. Rather, catch, richness, and production (HPI) in the Hamilton Harbour AOC are now all comparable to, or lower than, what was observed when the system was first listed and assessed. Overall, IBI, and the majority of fish community metrics, remain lower than other similar sheltered embayments (e.g., East-Ref areas). While the west zone of the harbour, generally the best scoring sector within the system, is largely comparable to shallow, degraded areas in western Lake Ontario (e.g., West-Ref areas), the most recent data from the north and east zones suggest they are in poorer condition than these sites. Such spatial differences within the Hamilton Harbour AOC are not surprising based on distinct fish communities that have been previously documented among the three zones that were assessed (Boston et al. 2016; Maynard et al. 2022; section FP-1B).

Based on a review of IBI and associated metrics in 2018 (Gardner Costa et al. 2022) and previous studies (e.g., Randall and Minns 2002), species richness and total catch of native fishes are major contributing factors to persistently low IBI scores in the Hamilton Harbour AOC. Continued declining trends in catch and richness of native fishes are thus concerning since they are evidence of persistent ecosystem impairment that appears to be shifting the system further away from its delisting targets. Several key discussion points related to patterns in fish community metrics are similarly relevant for other sections within this report and are discussed in a more integrated manner in the General Discussion section (e.g., spatial differences within the harbour, persistent sources of ecosystem degradation, non-native species control, and continued urbanization). Here, we focus primarily on providing a brief discussion of IBI- and fish community metric-specific topics.

Temporal patterns in the Hamilton Harbour AOC

Many of the patterns documented herein, particularly those from earlier time stanzas, have been presented in previous works. Improvements in IBI and fish community metrics from P1 to P2 were thought to be linked to harbour-wide declines in total phosphorus and improvements in water clarity during P1 and the completion of habitat restoration works (Smokorowski et al. 1998; Boston et al. 2016; Hiriart-Baer et al. 2016). Since P2, water quality parameters in the harbour have shown limited improvements, with total phosphorus levels actually increasing (Visha et al. 2021). Similarly, while some modifications to physical habitat have occurred (e.g., Farr Island Reef creation in 2010 and the Piers 5-7 shoreline changes completed in 2022), no major habitat creation or restoration works have been undertaken in the nearshore zone of the harbour since P2 (although improvements to Windermere Basin in lower Red Hill Creek have been implemented). Early improvements in ecosystem condition did not persist and past work has documented declines in IBI scores during the P2-P3 period (Boston et al. 2016). In addition to the lack of improvement in nutrient concentrations, biotic pressures were also hypothesized to be a primary driver of these declines (Boston et al. 2016) due to egg predation and competition from Round Goby, and predation by Double-crested Cormorants (*Phalacrocorax auritus*). During P4, fish community metrics within the Hamilton Harbour AOC have either continued to decline or have not changed. Round Goby numbers, however, have declined during this period (see Section FP-1A and Appendix E) and Double-crested Cormorant nest numbers have remained mostly stable, with some interannual variability (J. Quinn; unpublished data). Further declines in fish community metric values in P4, albeit with no change in IBI scores specifically, are thus suggestive of either the ongoing degradation of the ecosystem itself (i.e., increased eutrophication, changes in habitat condition or supply) or a shift in the trophic structure of the system (i.e., novel biotic interactions, increased competition); however, the specific drivers and their magnitude of effect on fish community metrics remains unknown.

Comparison to other areas in Lake Ontario

Within Lake Ontario regional differences in ecosystem condition are well established and largely driven by differences in land use modification within watersheds with higher levels of urbanization in the western part of the basin, and consequently, greater ecosystem degradation (e.g., Chow-Fraser 2006; Croft-white et al. 2017; Hoyle et al. 2018). Previous studies have noted lower IBI scores and fish community conditions in the Hamilton Harbour AOC relative to similar sheltered embayments (Brousseau and Randall 2008; Bowlby and Hoyle 2017; Hoyle et al. 2018). For example, from 2006-2016, electrofishing-based IBI scores averaged 48.0 in the Hamilton Harbour AOC, while those in the Upper Bay of Quinte, were 72.5 (Hoyle et al. 2018). Based on the results presented herein, IBI and fish community metric scores in the Hamilton Harbour AOC remain lower than other regions of Lake Ontario, the East-Ref in particular. While sites in the East-Ref have frequently been assessed as being in “good” condition, the two sites that comprise the West-Ref group are degraded relative to other areas in Lake Ontario in particular (Hoyle et al. 2018) and the Great Lakes more generally (Chow-Fraser 2006; Croft and Chow-Fraser 2007). Fish community metrics scores in the west zone of the Hamilton Harbour AOC frequently match conditions in the West-Ref, suggesting the west zone is comparable to other degraded ecosystems in the Great Lakes. The north and east zones, however, tend to be in even poorer condition than the West-Ref areas, suggesting factors other than just watershed development are limiting fish community conditions. One potential factor is their level of exposuresince the prevailing south-westerly winds in the harbour will have a greater influence on the north and east zones; however, additional study is required to confirm this supposition. Comparing conditions in the Hamilton Harbour AOC with other regions of Lake Ontario can help place the harbour into larger regional contexts. It also has the added benefit of helping to assess whether changes in the Hamilton Harbour AOC are linked to local or regional factors. While there have been clear changes in fish community condition within the Hamilton Harbour AOC throughout the entire time series, such changes were not evident in the East-Ref area. Rather, metric values in the East-Ref were largely stable. This suggests that declines in fish community metrics in the Hamilton Harbour AOC were driven more by changes in local ecosystem conditions than lake-wide factors; however, as noted, identification of the specific drivers, particularly those causing declines from P3 to P4, requires further study.

Non-native species metrics

Non-native fishes, such as Common Carp, have been a long-standing impediment to fish population recovery in the Hamilton Harbour AOC. The reduced catch, richness, and biomass of non-native fishes observed in the present assessment are thus positive signs and should increase the overall IBI score. The absence of improvements in IBI scores, however, suggests that declines in other metric values (e.g., total catch, or native species richness) are counterbalancing any gains that may have been realized from reductions in non-native fishes. Recent modeling work noted that reductions in non-native fish catch would have the greatest impact on IBI scores if they encouraged recovery of the native fish community (Gardner Costa et al. 2022), by potentially reducing competition (e.g., Round Goby) or allowing habitats to recover (e.g., Common Carp). Metrics related to solely the native fish community, however, have not shown any signs of improvement, so declines in the catch of non-native species may be less reflective of improvements in fish community condition and more indicative of an overall trend in declining catch and richness of fishes in general for the Hamilton Harbour AOC. Declining trends for non-native fishes are also largely driven by declines in the catch of Common Carp since the catch of Rudd and Goldfish is actually increasing (FP-1A). Management of non-native fishes is thus important to the future recovery of native fish populations. The Cootes Paradise Fishway has been instrumental in reducing Common Carp biomass within the Hamilton Harbour AOC (Boston et al. 2016), and while IBI scores may not immediately respond to such changes, the indirect benefits of reduced numbers of non-native fishes make their management within the harbour an essential element of fish population recovery.

Day/night considerations

There can be marked differences in catch, species richness, and IBI scores between day and night electrofishing surveys, with typically higher values for all metrics at night (C. Boston, unpublished data). In an effort to incorporate this variance into the current assessment, the time of sampling (day vs night) was directly incorporated into models as a random effect. This was important as effort during the day and night was not always consistent among sampling regions or time stanzas. While night transects in the Hamilton Harbour AOC have been found to periodically yield IBI scores in excess of the target (55-60), the incorporation of day surveys would drive mean values below the target. In less degraded systems, like those in the East-Ref, integrated day and night values consistently yield IBI scores at or above Hamilton Harbour AOC targets, so targets should still be attainable in a healthy ecosystem when day surveys are included. One challenge, however, is that in the Hamilton Harbour AOC, we see a fair number of zero or very low catch transects during day surveys. While inherently an indication of considerable ecosystem degradation, zero catch transects are not informative for assessments of the composition of the fish community, since fishes may still use the surveyed habitat during the evening. Focusing on surveys solely during the night increases the likelihood of capturing a more representative fish community that at least partially relies on nearshore habitats. In a degraded ecosystem like the Hamilton Harbour AOC, catch at night and resulting derived metrics like the IBI still largely indicate ongoing impairment even during the best-case targeted sampling (C. Boston, unpublished data). Sampling during both the day and night also poses logistical challenges since a single field crew must allocate greater effort to sample one area. As such, in order to support more spatially comprehensive surveys, future monitoring in the Hamilton Harbour AOC and similar regional ecosystems should focus mostly on night surveys.

Table 9. *Summary of sampling effort and fish community metrics by time stanza for the overall Hamilton Harbour Area of Concern (Hamilton Harbour AOC), among zones within the Hamilton Harbour AOC (west, north, east), and at baseline reference areas in the eastern (East-Ref) and western (West-Ref) basins of Lake Ontario. All values are mean with standard deviation. Sampling in the West-Ref area only occurred in P3 and P4.*

Stanza	Fish Community Metric	Hamilton Harbour AOC	West	North	East	East-Ref	West-Ref
P1: pre 1994	Sampling Effort (# Transects)	121	36	33	52	84	
	Habitat Productivity Index	76.2 ± 74.8	101.2 ± 70.6	93.6 ± 87.6	47.9 ± 58.8	65.5 ± 45.6	
	Adjusted Habitat Productivity Index	52.4 ± 64.0	64.5 ± 66.0	75.4 ± 79.5	29.3 ± 41.2	49.8 ± 38.1	
	Index of Biotic Integrity	28.7 ± 14.2	32.2 ± 12.7	29.6 ± 14.2	25.7 ± 14.8	62.8 ± 16.5	
	Adjusted Index of Biotic Integrity	15.7 ± 12.9	17.2 ± 12.5	20.3 ± 14.1	11.6 ± 11.3	47.8 ± 19.9	
	Total Catch (#)	46.2 ± 59.3	68.8 ± 71.4	51.3 ± 50.8	27.2 ± 49.0	50.3 ± 51.0	
	Total Catch Native (#)	11.8 ± 18.1	15.3 ± 19.4	18.6 ± 23.0	4.9 ± 9.7	43.7 ± 46.7	
	Total Catch Non-Native (#)	34.4 ± 52.5	53.5 ± 67.1	32.7 ± 39.5	22.3 ± 44.9	6.6 ± 24.1	
	Total Catch Offshore Fish (#)	33.0 ± 52.7	51.9 ± 67.7	30.3 ± 39.1	21.6 ± 45.1	14.7 ± 31.3	
	Species Richness (#)	4.5 ± 2.6	6.1 ± 2.4	5.0 ± 2.6	3.2 ± 2.0	6.9 ± 2.8	
	Native Species Richness (#)	2.6 ± 1.9	3.8 ± 1.8	2.9 ± 1.8	1.6 ± 1.5	6.1 ± 2.5	
	Non-Native Species Richness (#)	2.0 ± 1.0	2.3 ± 1.0	2.1 ± 1.2	1.6 ± 0.8	0.8 ± 0.8	
	Centrarchid Species Richness (#)	0.6 ± 1.0	1.3 ± 1.3	0.7 ± 0.7	0.2 ± 0.4	1.7 ± 1.0	
	Cyprinid Species Richness (#)	0.6 ± 0.7	0.6 ± 0.6	0.7 ± 0.7	0.6 ± 0.7	0.7 ± 0.7	
	Proportion Piscivore Biomass (%)	4.4 ± 13.7	5.5 ± 9.2	4.4 ± 15.5	3.6 ± 15.2	35.3 ± 29.9	
	Native Biomass (g)	2.1 ± 3.4	2.4 ± 3.0	3.0 ± 4.4	1.2 ± 2.6	4.8 ± 3.7	
	Richness of Turbidity Intolerant Species (#)	0.3 ± 0.5	0.4 ± 0.5	0.3 ± 0.5	0.2 ± 0.4	1.0 ± 0.8	
	Proportion Generalist Biomass (%)	53.0 ± 41.9	56.2 ± 38.0	68.6 ± 34.5	40.8 ± 45.6	21.1 ± 25.9	
	Proportion Specialist Biomass (%)	41.0 ± 41.2	38.3 ± 37.9	26.9 ± 32.5	51.8 ± 45.7	42.3 ± 30.8	
	Proportion Number Non-Native Fishes (%)	66.3 ± 30.6	66.8 ± 27.3	60.5 ± 33.8	69.7 ± 30.6	11.9 ± 19.7	
	Proportion Non-Native Biomass (%)	65.6 ± 34.1	70.7 ± 25.6	61.4 ± 34.8	64.6 ± 38.7	13.4 ± 24.3	
	Proportion Offshore Catch (%)	56.1 ± 34.7	60.5 ± 31.9	51.6 ± 34.7	55.8 ± 36.9	26.2 ± 27.0	
	Proportion Offshore Biomass (%)	29.8 ± 35.3	31.1 ± 35.9	14.3 ± 18.4	38.9 ± 39.9	22.3 ± 25.9	

Stanza	Fish Community Metric	Hamilton Harbour AOC	West	North	East	East-Ref	West-Ref
P2: 1995-2005	Sampling Effort (# Transects)	271	116	65	90	133	
	Habitat Productivity Index	65.4 ± 54.6	78.0 ± 51.0	76.3 ± 67.1	41.4 ± 39.7	36.7 ± 26.3	
	Adjusted Habitat Productivity Index	49.1 ± 50.8	62.9 ± 51.8	56.8 ± 59.6	25.7 ± 31.4	34.1 ± 23.6	
	Index of Biotic Integrity	36.8 ± 17.0	42.3 ± 15.6	31.4 ± 15.3	33.6 ± 18.2	66.4 ± 15.8	
	Adjusted Index of Biotic Integrity	25.2 ± 18.0	32.4 ± 17.7	22.1 ± 15.4	18.0 ± 16.6	61.2 ± 18.6	
	Total Catch (#)	42.2 ± 41.5	53.4 ± 43.2	41.8 ± 45.9	28.0 ± 30.5	45.3 ± 45.8	
	Total Catch Native (#)	23.4 ± 29.9	35.5 ± 35.7	17.6 ± 24.8	12.2 ± 16.6	44.6 ± 46.0	
	Total Catch Non-Native (#)	18.7 ± 30.9	17.9 ± 27.9	24.2 ± 39.5	15.8 ± 27.0	0.7 ± 2.1	
	Total Catch Offshore Fish (#)	21.3 ± 33.0	21.1 ± 32.3	24.3 ± 40.4	19.3 ± 27.7	3.2 ± 9.8	
	Species Richness (#)	5.4 ± 2.5	6.5 ± 2.2	5.2 ± 2.3	4.0 ± 2.4	6.7 ± 2.8	
	Native Species Richness (#)	3.7 ± 2.1	4.9 ± 1.9	3.3 ± 1.8	2.6 ± 1.9	6.4 ± 2.8	
	Non-Native Species Richness (#)	1.6 ± 1.0	1.6 ± 0.9	1.9 ± 1.1	1.4 ± 1.1	0.2 ± 0.5	
	Centrarchid Species Richness (#)	1.3 ± 1.2	2.0 ± 1.3	0.8 ± 0.8	0.9 ± 0.9	2.7 ± 1.1	
	Cyprinid Species Richness (#)	0.6 ± 0.7	0.6 ± 0.7	0.6 ± 0.7	0.5 ± 0.7	0.9 ± 1.0	
	Proportion Piscivore Biomass (%)	8.7 ± 19.3	8.8 ± 16.2	5.7 ± 15.4	10.7 ± 24.8	27.3 ± 27.0	
	Native Biomass (g)	1.8 ± 1.9	2.2 ± 1.9	2.1 ± 2.0	1.2 ± 1.7	2.1 ± 1.8	
	Richness of Turbidity Intolerant Species (#)	0.4 ± 0.6	0.4 ± 0.6	0.4 ± 0.5	0.5 ± 0.6	0.8 ± 0.8	
	Proportion Generalist Biomass (%)	54.0 ± 39.0	61.8 ± 34.0	65.7 ± 34.5	35.5 ± 41.6	19.9 ± 25.0	
	Proportion Specialist Biomass (%)	34.0 ± 35.5	29.4 ± 30.9	25.5 ± 30.3	46.1 ± 41.3	52.0 ± 29.8	
	Proportion Number Non-Native Fishes (%)	39.2 ± 34.1	30.4 ± 29.7	46.3 ± 34.2	45.3 ± 37.0	3.6 ± 11.7	
	Proportion Non-Native Biomass (%)	54.8 ± 38.3	53.9 ± 36.6	56.8 ± 39.0	54.5 ± 40.3	3.1 ± 13.6	
	Proportion Offshore Catch (%)	42.1 ± 34.5	33.8 ± 31.3	42.6 ± 35.7	52.4 ± 35.1	9.4 ± 17.9	
	Proportion Offshore Biomass (%)	23.0 ± 32.3	16.5 ± 27.0	18.1 ± 27.0	34.8 ± 38.6	7.7 ± 15.0	

Stanza	Fish Community Metric	Hamilton Harbour AOC	West	North	East	East-Ref	West-Ref
P3: 2006-2012	Sampling Effort (# Transects)	194	85	47	62	122	36
	Habitat Productivity Index	44.9 ± 49.7	58.6 ± 57.7	27.2 ± 22.4	39.4 ± 48.1	59.9 ± 45.4	33.0 ± 29.9
	Adjusted Habitat Productivity Index	37.1 ± 43.4	49.1 ± 49.8	21.7 ± 19.4	32.4 ± 43.1	52.8 ± 38.5	23.2 ± 17.9
	Index of Biotic Integrity	39.8 ± 19.5	46.6 ± 16.4	41.5 ± 14.4	29.1 ± 22.2	70.8 ± 14.5	45.6 ± 11.8
	Adjusted Index of Biotic Integrity	29.9 ± 18.7	37.2 ± 19.3	30.5 ± 11.9	19.5 ± 17.4	65.0 ± 16.5	35.7 ± 14.7
	Total Catch (#)	16.8 ± 16.4	20.3 ± 18.5	16.3 ± 12.2	12.3 ± 15.2	49.0 ± 39.1	33.6 ± 31.5
	Total Catch Native (#)	11.8 ± 12.3	15.1 ± 14.7	12.1 ± 9.9	7.1 ± 8.2	46.3 ± 38.1	26.2 ± 30.4
	Total Catch Non-Native (#)	5.0 ± 9.5	5.2 ± 9.9	4.2 ± 4.9	5.2 ± 11.3	2.7 ± 8.0	7.4 ± 10.5
	Total Catch Offshore Fish (#)	5.5 ± 9.3	5.4 ± 9.8	6.1 ± 5.9	5.0 ± 10.8	4.3 ± 8.7	8.2 ± 10.4
	Species Richness (#)	4.8 ± 2.9	5.5 ± 2.8	5.1 ± 2.7	3.7 ± 2.8	8.1 ± 2.9	5.4 ± 2.4
	Native Species Richness (#)	3.6 ± 2.3	4.2 ± 2.3	4.0 ± 2.1	2.5 ± 2.2	7.6 ± 2.6	4.2 ± 2.0
	Non-Native Species Richness (#)	1.2 ± 1.0	1.3 ± 1.1	1.1 ± 1.0	1.2 ± 1.0	0.6 ± 0.7	1.2 ± 0.8
	Centrarchid Species Richness (#)	1.0 ± 1.3	1.6 ± 1.4	0.6 ± 0.9	0.5 ± 0.9	3.1 ± 1.2	0.9 ± 1.0
	Cyprinid Species Richness (#)	0.6 ± 0.7	0.5 ± 0.7	1.0 ± 0.8	0.6 ± 0.7	1.1 ± 1.0	0.9 ± 0.7
	Proportion Piscivore Biomass (%)	13 ± 25.5	22.1 ± 30.5	6.7 ± 19.9	5.3 ± 16.6	42.8 ± 27.9	8.9 ± 21.8
	Native Biomass (g)	2.3 ± 3.0	3.7 ± 3.7	1.6 ± 1.4	1.0 ± 1.7	4.2 ± 3.6	1.8 ± 2.4
	Richness of Turbidity Intolerant Species (#)	0.5 ± 0.7	0.4 ± 0.6	0.7 ± 0.8	0.4 ± 0.6	1.1 ± 1.0	0.4 ± 0.5
	Proportion Generalist Biomass (%)	47.9 ± 39.7	41.7 ± 35.4	59.9 ± 36.4	47.3 ± 45.8	20.0 ± 23.8	44.0 ± 35.3
	Proportion Specialist Biomass (%)	32.9 ± 35.3	33.9 ± 34.1	29.1 ± 29.8	34.5 ± 40.8	36.4 ± 27	47.1 ± 37.7
	Proportion Number Non-Native Fishes (%)	26.2 ± 28.4	20.9 ± 22.9	20.5 ± 20.3	37.7 ± 36.2	4.9 ± 12.9	23.2 ± 23.3
	Proportion Non-Native Biomass (%)	32.0 ± 36.2	25.9 ± 29.6	23.5 ± 28.1	46.7 ± 45.0	6.7 ± 17.3	23.8 ± 30.5
	Proportion Offshore Catch (%)	26.9 ± 27.0	27.2 ± 27.5	29.8 ± 22.0	24.1 ± 29.6	8.2 ± 14.2	27.0 ± 24.2
	Proportion Offshore Biomass (%)	17.6 ± 27.8	15.9 ± 25.5	17.7 ± 24.3	20.0 ± 33.1	8.3 ± 15.4	17.9 ± 25.5

Stanza	Fish Community Metric	Hamilton Harbour AOC	West	North	East	East-Ref	West-Ref
P4: 2013-2021	Sampling Effort (# Transects)	319	136	74	109	148	29
	Habitat Productivity Index	42.0 ± 46.7	57.3 ± 55.5	25.7 ± 34.0	34.1 ± 35.6	44.2 ± 35.5	89.1 ± 95.5
	Adjusted Habitat Productivity Index	22.1 ± 28.6	25.7 ± 30.4	14.2 ± 21.3	22.8 ± 29.6	39.5 ± 33.3	49.4 ± 42.2
	Index of Biotic Integrity	35.8 ± 19.1	45.1 ± 16.4	32.8 ± 16.2	26.4 ± 19.0	63.6 ± 13.9	41.8 ± 16.7
	Adjusted Index of Biotic Integrity	17.3 ± 16.6	22.7 ± 18.3	15.5 ± 13.8	11.8 ± 14.0	56.9 ± 18.1	25.2 ± 16.9
	Total Catch (#)	11.5 ± 23.4	19.1 ± 33.5	6.5 ± 6.4	5.3 ± 7.2	32.5 ± 28.0	22.8 ± 17.0
	Total Catch Native (#)	8.9 ± 21.7	15.8 ± 31.5	4.4 ± 4.7	3.2 ± 4.5	29.7 ± 27.7	14.7 ± 14.8
	Total Catch Non-Native (#)	2.6 ± 4.6	3.4 ± 5.1	2.1 ± 3.4	2.1 ± 4.4	2.8 ± 7.6	8.1 ± 11.6
	Total Catch Offshore Fish (#)	5.3 ± 8.6	8.1 ± 11.2	3.2 ± 3.8	3.2 ± 5.6	5.4 ± 9.6	13.0 ± 15.3
	Species Richness (#)	3.2 ± 2.5	4.4 ± 2.8	2.5 ± 2.0	2.1 ± 1.8	6.8 ± 2.7	5.0 ± 2.4
	Native Species Richness (#)	2.3 ± 2.0	3.3 ± 2.2	1.9 ± 1.6	1.3 ± 1.3	6.3 ± 2.5	3.6 ± 2.1
	Non-Native Species Richness (#)	0.9 ± 0.9	1.1 ± 1.0	0.7 ± 0.8	0.9 ± 0.9	0.4 ± 0.6	1.3 ± 0.8
	Centrarchid Species Richness (#)	0.5 ± 0.9	0.9 ± 1.2	0.1 ± 0.4	0.1 ± 0.4	2.3 ± 1.3	0.9 ± 0.8
	Cyprinid Species Richness (#)	0.3 ± 0.5	0.4 ± 0.6	0.3 ± 0.6	0.2 ± 0.4	0.7 ± 0.8	0.4 ± 0.5
	Proportion Piscivore Biomass (%)	10.0 ± 21.7	15.8 ± 24.2	9.2 ± 24.6	3.5 ± 12.7	40.2 ± 33.9	15.2 ± 25.4
	Native Biomass (g)	3.2 ± 5.3	5.3 ± 7.2	1.6 ± 2.0	1.7 ± 2.3	3.2 ± 3.1	6.6 ± 8.9
	Richness of Turbidity Intolerant Species (#)	0.3 ± 0.5	0.4 ± 0.5	0.2 ± 0.5	0.2 ± 0.5	1.0 ± 0.9	0.3 ± 0.5
	Proportion Generalist Biomass (%)	38.2 ± 40.4	33.2 ± 35.2	38.2 ± 40.5	44.4 ± 45.5	17.9 ± 27.4	39.4 ± 35.1
	Proportion Specialist Biomass (%)	43.9 ± 42.5	47.3 ± 39.5	41.8 ± 42.0	41.1 ± 46.4	41.9 ± 35.7	42.0 ± 35.5
	Proportion Number Non-Native Fishes (%)	26.1 ± 32.1	20.0 ± 23.5	22.9 ± 31.0	35.9 ± 39.3	7.4 ± 16.8	35.0 ± 31.0
	Proportion Non-Native Biomass (%)	32.0 ± 38.0	25.1 ± 31.4	25.5 ± 34.3	45.3 ± 44.3	11.9 ± 23.8	36.7 ± 33.2
	Proportion Offshore Catch (%)	44.6 ± 38.1	46.8 ± 35.6	46.0 ± 39.0	41.0 ± 40.6	15.7 ± 21.9	48.5 ± 32.0
	Proportion Offshore Biomass (%)	38.7 ± 40.8	43.6 ± 39.5	38.6 ± 41.1	32.5 ± 41.8	7.8 ± 17.3	30.5 ± 31.0

CRITERION FP-2B: TRAP NETTING

SUMMARY

An Ontario provincial standard fisheries assessment methodology known as nearshore fish community index netting (NSCIN) was used to assess the nearshore fish communities and ecosystem health in Lake Ontario / St. Lawrence River ecoregion (2006-2021) on a rotating basis, including the Hamilton Harbour Area of Concern (AOC). An index of biological integrity (IBI) was developed based on the NSCIN survey to assess and compare the contemporary nearshore fish communities and ecosystem health among geographic areas as well as changes within embayments. The IBI was based on 11 metrics representing aspects of fish assemblage integrity, including: species richness, trophic structure, and abundance/biomass of species groups (e.g., piscivores). Hamilton Harbour AOC IBI scores were classified as ‘fair’ in all sampling years. Sub-metrics, like the proportion of piscivore and specialist biomass, remain below the levels in similar sheltered reference embayments, such as the Upper Bay of Quinte, indicating an impaired ecosystem. Walleye stocked in 2012 into the Hamilton Harbour AOC showed survival in the trap net gear over multiple years and cohorts. Stocking and ongoing sampling in alternating years continues.

KEY MESSAGES

- Index of biotic integrity (IBI) scores in the Hamilton Harbour AOC were categorized as “fair” throughout the sampling period and were lower than IBI scores at unimpaired reference sites, indicative of an impaired sheltered embayment.
- The proportion of piscivore biomass (PPB) in Hamilton was lower than at other sheltered embayments with relatively lower catches of Smallmouth and Largemouth Bass.
- The proportion of total fish community biomass represented by specialist species (PSPE) in Hamilton was lower than other sheltered embayments, with lower catches of native species including Bluegill, Pumpkinseed, Black Crappie, and Yellow Perch.
- Non-native fishes (i.e., White Perch, Goldfish, Common Carp, and Rudd) were found in higher abundance at Hamilton relative to other Lake Ontario embayments.
- Stocked Walleye have shown good survival through recruitment into trap net gear since 2012.
- The species composition and high total biomass in Hamilton Harbour correlate to those with a hyper-eutrophic system, high nutrient inputs, and low submerged aquatic vegetation.
-

BACKGROUND

Hamilton Harbour is a designated Great Lakes Area of Concern (AOC) with multiple identified Beneficial Use Impairments (BUIs) or environmental challenges identified by the Remedial Action Plan. This includes BUI #3 Degradation of fish and wildlife populations, which is currently listed as impaired. The Ontario Ministry of Natural Resources and Forestry (OMNRF) is committed to supporting the monitoring and restoration of Great Lake AOCs, including Hamilton Harbour, under the Canada-Ontario Agreement. The Lake Ontario Management Unit conducts a nearshore community index netting program (NSCIN) in Hamilton Harbour as well as other Lake Ontario and St. Lawrence River embayments of varying exposure types (sheltered, exposed, transitional, riverine). Sampling of multiple embayments allows for the comparison of fish communities and ecosystem health, including comparing AOCs like Hamilton Harbour to reference sites designated as unimpaired (i.e., Bay of Quinte). An index of biological integrity (IBI) was developed based on the NSCIN survey to assess and compare the contemporary nearshore fish communities and ecosystem health among geographic areas as well as changes within embayments. The IBI was based on 11 metrics representing aspects of fish assemblage integrity (Hoyle and Yuille 2016), including: species richness, trophic structure, and abundance/biomass of species groups (e.g. piscivores). Hamilton Harbour historically supported prominent commercial and recreational fisheries from the 1800s through to the early 1900s (Holmes and Whillans 1984). The fish community consisted of coldwater species such as Cisco and Lake Whitefish (*Coregonus clupeaformis*), and cool and warmwater species such as Northern Pike, Black Bass (*Micropterus* sp.), Yellow Perch, Suckers (*Catostomidae*), and periodic catch of Walleye (Holmes and Whillans 1984; Holmes 1988). This section aims to summarize and compare trends in trap netting species catches and fish assemblage metrics between Hamilton Harbour and reference embayments across time.

METHODS

Ontario Nearshore Fish Community Index Netting (NSCIN) methodology

The NSCIN protocol is a provincial standard fisheries assessment methodology that uses 6-foot trap nets set overnight and is designed to evaluate the relative abundance and other biological attributes of fish species that inhabit the littoral area (Stirling 1999). Originally designed for application in Ontario Inland Lakes, this program has been implemented in the Lake Ontario/St. Lawrence River ecoregion by the OMNRF for two decades (Ontario Ministry of Natural Resources and Forestry (OMNRF) 2020). The methodology allows for relative comparison of fisheries assessment benchmarks or targets among areas and trends through time, and can be sensitive enough to detect ecological change (Lester et al. 1996). As this is a passive, live-release methodology, a subsample of fish may also be selected for more detailed biological sampling (e.g., condition, age, maturity, diet), providing further insight into the status and health of the fish community.

As outlined in the NSCIN protocol (Stirling 1999), field sampling occurs from August 1 to whenever the surface water temperature cools to 13^{o}C. Suitable trap net sites are chosen from randomly selected UTM grids that contain shorelines in the nearshore area. Although site selection varied annually, detailed grids within the Hamilton Harbour AOC can be found in Beech and Brown (2021). Though the gear is suitable for a variety of nearshore habitat types, standard net setting criteria are required (e.g., water depth, orientation to shore, net separation distances), and the gear is not suitable for open-coastal areas. The number of trap net sites depends on the relative size of the area to be sampled and each trap net site is “fished” for approximately 24 hrs. For each trap net, fish species are identified and counted, and a subsample of fish are kept for detailed biological sampling (Beech and Brown 2021). Up to 30 individuals of one species may be kept, but the specific number depends on the program objectives and the need for updated local contaminant information. The minimum fish size captured with this gear is approximately 90 mm in length due to the 44 mm black polypropylene stretch mesh.

NSCIN was first initiated in Lake Ontario on the upper Bay of Quinte (Trenton to Deseronto), West Lake, and Weller’s Bay in 2001 and was expanded to include the middle and lower reaches of the Bay of Quinte (Deseronto to Lake Ontario) in 2002. In 2006, the NSCIN program was expanded to include the Hamilton Harbour and Toronto AOC thanks to partnerships developed with Fisheries and Oceans Canada and the Toronto and Region Conservation Authority. NSCIN was further expanded to other Lake Ontario nearshore areas in subsequent years (Figure 55 and Table 10).

Table 10. *Sampling information, exposure index (opening/surface area), and embayment classification of Lake Ontario embayments sampled by OMNRF (2001-2006 not included). Opening refers to the width of the connection between the embayment and Lake Ontario. See Bowlby and Hoyle (2017) for a more detailed description of the exposure index as it related to the embayment classification.*

Embayment	Average Number of Sampling Sites	Number of Years Sampled	Years Sampled	Surface Area (km^2)	Opening	Exposure Index	Embayment Classification
Toronto Harbour (TH)	24	9	2006, 2007, 2010, 2012, 2014, 2016, 2018, 2019, 2022	14.3	1,960	137.1	Exposed
Prince Edward Bay (PE)	25	3	2009, 2013, 2017	101.9	9,247	90.7	Exposed
Presqu'ile Bay (PB)	14	2	2008, 2015	9.7	726	75	Exposed
Lower Bay of Quinte (LB)	11	3	2009, 2011, 2019	75.1	5,513	73.4	Transitional
North Channel (NC)	25	1	2009	130.2	5,939	45.6	Transitional
Hamilton Harbour (HH)	23	10	2006, 2008, 2010, 2012, 2014 -2016, 2018, 2019, 2021	21.0	88	4.2	Sheltered
West Lake (WL)	22	3	2007, 2013, 2017	19.1	27	1.4	Sheltered
East Lake (EL)	17	3	2007, 2013, 2017	11.6	21	1.8	Sheltered
Wellers Bay (WB)	24	3	2008, 2015, 2022	19.1	86	4.5	Sheltered
Upper Bay of Quinte (UB)	36	14	2007-2019, 2022	129.0	1,033	8	Sheltered
Middle Bay of Quinte (MB)	29	3	2009, 2011, 2019	62.7	884	14.1	Sheltered

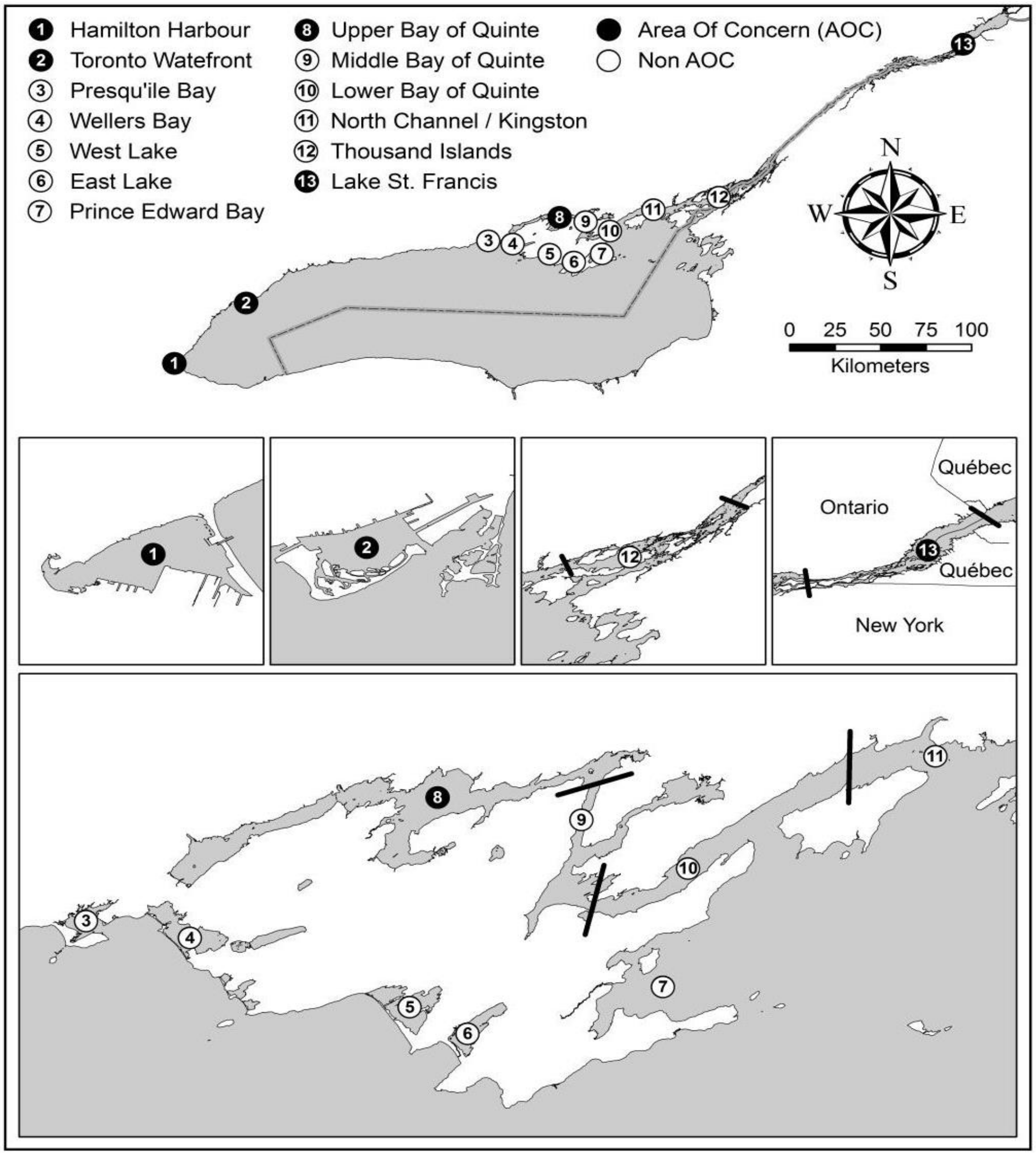

Figure 55. *Map of NSCIN sampling areas on Lake Ontario (n=11) and St. Lawrence River (n=2). Upper panel: Lake Ontario and the St. Lawrence River with filled circles indicating designated Great Lakes Areas of Concern (AOCs); middle panel: northeastern Lake Ontario and the Bay of Quinte sampling areas. Solid lines depict borders between upper, middle, and lower Bay of Quinte, North Channel/Kingston, Thousand Islands, and Lake St. Francis (Hoyle and Yuille, 2016).*

Fish assemblage metrics, IBI, and restoration targets

Using the NSCIN data collected from 2001-2013, fish assemblage metrics were selected, and the trap net-based IBI was developed (Hoyle and Yuille 2016). The IBI used 10 of the 12 metrics described by Minns et al. (1994) for fish assemblages in

AOCs using boat electrofishing. IBI classes can be described as follows: 0-20 very poor, 20-40 poor, 40-60 fair, 60-80 good, and 80-100 excellent ecosystem health. The number of intolerant species and the number of native cyprinids were not included as metrics because of the inability of NSCIN trap nets to capture small fish (i.e., most cyprinids). The number of piscivore species was added as a metric to reflect habitat diversity and trophic function. The approach in which metrics were generated and IBI values calculated is described by Hoyle and Yuille (2016). Using this approach, fish assemblage metrics and IBI scores were generated using NSCIN data collected from all embayments sampled between 2006 and 2021.

The 11 metrics and IBI scores were evaluated to provide comparisons to relevant reference sites and to develop restoration targets for the nearshore fish population in Hamilton Harbour and the Toronto AOC (Hoyle and Yuille 2016; Hoyle et al. 2017; Bowlby and Hoyle 2017). Through these studies, it was determined that the degree of exposure of an embayment to Lake Ontario influences fish species composition and abundance. The Hamilton Harbour AOC was classified as a sheltered embayment and relevant reference sites were identified (i.e., Upper Bay of Quinte, Middle Bay of Quinte, Wellers Bay, East Lake, and West Lake). For NSCIN sampling between 2006-2021, the 11 metrics and IBI scores for each embayment category (sheltered, exposed, transitional; Hoyle and Yuille 2016) were generated and compared to those in the Hamilton Harbour AOC and compared between two time stanzas (2006-2012 and 2013-2021) to be consistent with previous sections.

RESULTS

Hamilton Harbour was sampled 10 times between 2006 and 2021 with an average of 23 (range 19-24) sites visited per sampling event (Table 10). Reference sheltered embayments (Upper and Middle Bay of Quinte, West Lake, East Lake, and Weller’s Bay) were sampled periodically from 2006 to 2021. All sampling occurred during the standard NSCIN time frame.

Relative abundance trends (mean catch per trap net) for all species in Hamilton Harbour were summarized (Table 11). The highest overall catch per unit effort occurred in 2015 (928 fish) and conversely, the lowest occurred in 2012 (187 fish). Species richness ranged from 21 to 28. Brown Bullhead and White Perch were consistently two of the most abundant species. In comparison, the most abundant species in other sheltered embayments included centrarchid species such as Pumpkinseed, Largemouth Bass, and Bluegill, as well as Brown Bullhead (Table 12, Table 13a/b). In Hamilton Harbour, the rarest species in the most recent survey period (2021) were Bigmouth Buffalo (*Ictiobus cyprinellus*), Black Crappie (*Pomoxis nigromaculatus*), Freshwater Drum, and White Sucker. Starting in 2012 and 2014, the non-native Rudd and native American Eel (*Anguilla rostrata*), respectively, were detected for the first time in the sampling period and remained part of the fish community from then on. Hamilton Harbour had a notably increased abundance of Channel Catfish, White Perch, Brown Bullhead, Rudd, and Goldfish since 2012 compared to other sheltered embayments (Table 12, Table 13a/b).

Table 11. *Species-specific abundance trends (mean catch per trap net and standard deviation) in the Hamilton Harbour AOC. Annual number of net lifts, number of unique species, and total catch per net lift are also indicated.*

	Year									
Species	**2006**	**2008**	**2010**	**2012**	**2014**	**2015**	**2016**	**2018**	**2019**	**2021**
Longnose Gar	0.47 (0.9)	0.71 (1.08)	0.28 (0.61)	0.67 (1.09)	0.17 (0.38)	0.54 (0.78)	0.75 (0.99)	0.5 (0.83)	0.5 (1.06)	0.56 (0.99)
Spotted Gar			0.04 (0.2)							
Bowfin	0.58 (0.96)	1.17 (1.52)	2.42 (2.95)	1.17 (1.13)	1.54 (2.15)	0.83 (0.82)	1.33 (1.52)	0.88 (0.85)	1.17 (1.24)	1.44 (1.85)
Alewife				0.04 (0.2)	0.71 (2.69)	13.75 (57)				
Gizzard Shad	3.42 (2.99)	0.5 (0.78)	2.38 (7.37)	2.12 (2.17)	1.21 (2.5)	0.33 (0.48)	1.71 (3.48)	2.08 (2.78)	0.58 (1.06)	3.74 (6.02)
Rainbow Trout	0.05 (0.23)	0.04 (0.2)								
BrownTrout					0.04 (0.2)					
Lake Trout	0.05 (0.23)									
Coregonus sp.				0.25 (1.22)						
Northern Pike	1.11 (2.4)	1.08 (1.95)	1.08 (1.44)	0.29 (0.91)	0.25 (0.44)	0.54 (0.78)	0.54 (0.66)	0.33 (0.64)	0.71 (0.91)	0.39 (0.78)
Muskellunge		0.04 (0.2)								
Suckers	0.05 (0.23)									
Quillback		0.04 (0.2)			0.08 (0.28)				0.08 (0.28)	
White Sucker	0.11 (0.46)	0.21 (0.51)	0.46 (1.28)	0.29 (0.75)	2.17 (5.13)	0.62 (1.53)	0.04 (0.2)	0.08 (0.28)	0.04 (0.2)	0.17 (0.39)
Bigmouth Buffalo	0.05 (0.23)				0.04 (0.2)	0.04 (0.2)		0.04 (0.2)		0.04 (0.21)
Silver Redhorse		0.04 (0.2)								
Shorthead Redhorse	0.11 (0.46)	0.04 (0.2)	0.25 (0.9)							
Greater Redhorse					0.08 (0.28)	0.04 (0.2)			0.04 (0.2)	
Minnows		0.04 (0.2)								
Goldfish	0.32 (0.67)	0.92 (1.53)	2.71 (3.13)	0.88 (1.48)	0.58 (0.83)	1.08 (1.53)	3.46 (6.79)	4.83 (5.04)	1.5 (1.69)	0.83 (1.56)
Common Carp	4.47 (4.56)	3.92 (4.88)	2.2 (3.29)	1.21 (1.44)	2.25 (3.63)	2.38 (3.28)	4.33 (4.97)	4.04 (5.31)	3.17 (3.68)	2.78 (3.63)
Rudd				0.04 (0.2)		0.38 (0.92)	3.96 (4.07)	14.8 (22.67)	13.5 (29.37)	6.57 (8.79)
Black Bullhead	0.05 (0.23)									
Brown Bullhead	380.8 (615)	189.3 (308)	482.7 (1430)	76.3 (237.5)	251.7 (394)	753.8 (2375)	339.5 (1018)	355.6 (708)	291.2 (366)	286.6 (641)
Channel Catfish	34.8 (76.8)	15.9 (23.8)	8 (15.73)	14.2 (34.3)	49.6 (171.7)	11.25 (20.3)	12.96 (24.3)	3.92 (8.94)	4.42 (7.03)	5.35 (11.42)
American Eel					0.08 (0.41)	0.12 (0.34)	0.04 (0.2)	0.12 (0.45)	0.08 (0.28)	0.35 (1.07)
White Perch	48.4 (105.9)	34.88 (36.1)	84.4 (150.8)	69.9 (210.6)	169.3 (160)	132 (147.2)	110.9 (142)	210.6 (329)	129.4 (229)	32.7 (40.32)
White Bass	2 (3.14)	1.75 (3.39)	1.46 (4)	0.29 (0.69)	0.75 (2.05)	0.58 (1.02)	0.5 (0.72)	0.5 (1.14)	1.92 (2.48)	0.74 (1.39)
Morone sp.										0.04 (0.21)
Rock Bass	0.58 (1.17)	1.08 (1.82)	1.48 (2.49)	1.17 (1.49)	2 (2.59)	1.04 (2.22)	3.33 (4.35)	2.5 (3.49)	1.08 (2.21)	1.09 (1.95)
Green Sunfish	0.05 (0.23)									

	Year									
Species	**2006**	**2008**	**2010**	**2012**	**2014**	**2015**	**2016**	**2018**	**2019**	**2021**
Pumpkinseed	0.68 (1.42)	1.12 (2.33)	3.33 (7.23)	2.04 (3.38)	1 (2.32)		0.67 (1.24)	1 (1.41)	0.08 (0.28)	3.74 (12.32)
Bluegill	4.05 (6.58)	3.21 (5.88)	9.08 (13.69)	14.42 (16.7)	14.96 (16.6)	3.42 (4.76)	17.33 (18)	17.25 (22.9)	5.58 (6.51)	30.3 (64.88)
Smallmouth Bass	0.11 (0.32)		0.12 (0.34)				0.08 (0.28)	0.04 (0.2)		
Largemouth Bass	0.26 (0.56)	0.17 (0.38)	0.33 (0.56)	0.25 (0.44)	0.12 (0.34)	0.08 (0.28)	0.17 (0.48)	0.38 (0.58)	0.08 (0.28)	0.74 (1.63)
Black Crappie	2.32 (5.24)	0.17 (0.64)	0.42 (0.65)	0.58 (0.88)	0.08 (0.28)		0.58 (0.88)	0.58 (0.88)	0.5 (1.02)	0.22 (0.67)
Yellow Perch	0.11 (0.32)	0.62 (1.81)	4.16 (10.46)	0.25 (0.53)	1.08 (1.61)	0.71 (1.97)	0.58 (0.65)	0.46 (0.93)	0.04 (0.2)	0.61 (0.94)
Walleye	1.05 (2.17)	0.17 (0.38)	0.04 (0.2)		2.46 (3.09)	2.04 (2.22)	4.62 (12.23)	1.83 (3.07)	6.96 (8.33)	3.44 (5.81)
Round Goby	0.05 (0.23)									
Freshwater Drum	1.37 (2.73)	1.71 (3.5)	1.24 (2.52)	0.33 (0.96)	1.08 (2.22)	1.88 (3.03)	1.33 (2.84)	0.46 (1.06)	1.75 (3.18)	0.22 (0.67)
Common Carp x Goldfish							0.25 (0.61)		1.96 (2.58)	1.44 (2.74)
Tilapia								0.08 (0.28)		
Iridescent Shark Catfish								0.04 (0.2)		
Catch per net lift	488	259	609	187	503	928	509	623	466	384
Number of net lifts	19	24	24	24	24	24	24	24	24	23
Number of species	28	25	22	21	25	23	23	25	24	24

Table 12. *Species-specific mean catch per trap net and standard deviation for exposed embayments, transitional areas, sheltered embayments (excluding the Hamilton Harbour AOC), and the Hamilton Harbour AOC, 2006-2012 and 2013-2021.*

	2006-2012				**2013-2021**			
Species	**Hamilton Harbour**	**Sheltered Embayments**	**Exposed Embayments**	**Transitional**	**Hamilton Harbour**	**Sheltered Embayments**	**Exposed Embayments**	**Transitional**
Longnose Gar	0.53 (0.92)	0.96 (2.47)	0.15 (0.38)	0.35 (0.79)	0.5 (0.84)	1.91 (4.28)	0.09 (0.29)	0.67 (0.82)
Spotted Gar	0.04 (0.2)							
Bowfin	1.33 (1.64)	0.58 (1.02)	0.54 (1.11)	0.55 (0.82)	1.2 (1.4)	0.9 (1.66)	1.24 (1.9)	0.33 (0.52)
Alewife	0.04 (0.2)		5.27 (10.8)		7.23 (29.82)	0.08 (0.28)	6.04 (9.82)	
Gizzard Shad	2.11 (3.33)	2.15 (6.79)	1.03 (1.71)	0.4 (0.59)	1.61 (2.72)	0.49 (1.35)	0.97 (2.93)	0.83 (0.98)
Chinook Salmon			0.08 (0.28)					
Rainbow Trout	0.05 (0.22)		0.04 (0.2)				0.06 (0.24)	
Atlantic Salmon							0.04 (0.21)	
Brown Trout		0.03 (0.19)	0.06 (0.31)		0.04 (0.2)		0.09 (0.27)	
Lake Trout	0.05 (0.23)	0.03 (0.17)						
Lake Whitefish		0.03 (0.17)						
Coregonus sp.	0.25 (1.22)							
Northern Pike	0.89 (1.68)	0.85 (1.16)	1.17 (1.68)	0.5 (0.67)	0.46 (0.7)	0.44 (0.69)	1.08 (1.45)	0.33 (0.52)
Muskellunge	0.04 (0.2)					0.03 (0.17)	0.04 (0.2)	
Chain Pickerel							0.04 (0.2)	
Mooneye		0.03 (0.17)						
Suckers	0.05 (0.23)							
Quillback	0.04 (0.2)	0.03 (0.17)			0.08 (0.28)	0.03 (0.17)	0.04 (0.2)	
White Sucker	0.27 (0.75)	1.21 (1.63)	2.05 (3.15)	3.16 (3.46)	0.52 (1.29)	0.46 (0.91)	0.99 (1.92)	0.5 (0.84)
Bigmouth Buffalo	0.05 (0.23)				0.04 (0.21)			
Silver Redhorse	0.04 (0.2)	0.44 (1.42)	0.06 (0.24)	0.24 (0.62)		0.4 (0.93)	0.04 (0.21)	
Shorthead Redhorse	0.13 (0.52)	0.21 (0.61)	0.04 (0.2)			0.27 (0.64)		
Greater Redhorse		0.19 (0.59)			0.06 (0.23)	0.33 (0.85)		
River Redhorse		0.13 (0.46)				0.25 (0.73)	0.25 (1)	
Moxostoma sp.		0.43 (1.15)				0.08 (0.37)		
Carps and Minnows	0.04 (0.2)							
Goldfish	1.2 (1.7)		0.04 (0.2)	0.14 (0.38)	2.05 (2.91)		0.25 (1.03)	

Species	2006-2012				2013-2021			
	Hamilton Harbour	Sheltered Embayments	Exposed	Transitional	Hamilton Harbour	Sheltered Embayments	Exposed	Transitional
Common Carp	2.95 (3.54)	0.25 (0.57)	2.19 (3.43)	0.54 (0.91)	3.16 (4.08)	0.28 (0.56)	1.53 (2.1)	0.17 (0.41)
Golden Shiner		0.12 (0.4)	0.1 (0.38)	0.21 (0.57)		0.13 (0.36)	0.04 (0.2)	0.33 (0.82)
Spottail Shiner		0.07 (0.25)						
Fallfish						0.03 (0.17)		
Rudd	0.04 (0.2)	0.03 (0.19)			7.83 (13.16)			
Black Bullhead	0.05 (0.23)							
Brown Bullhead	282.26 (647.65)	33.73 (61.4)	56.15 (149.94)	11.7 (18.24)	379.74 (917.04)	6.59 (9.45)	58.49 (129.07)	2.33 (3.61)
Channel Catfish	18.23 (37.65)	1 (1.86)	0.1 (0.37)	0.82 (1.79)	14.58 (40.62)	0.73 (1.97)	0.1 (0.33)	0.5 (0.84)
American Eel		0.13 (0.41)		0.21 (0.57)	0.13 (0.46)	0.31 (0.79)	0.1 (0.36)	0.5 (0.84)
White Perch	59.4 (125.83)	4.33 (9.8)	0.3 (1.02)	0.35 (0.51)	130.82 (174.63)	3.73 (10.94)	0.16 (0.49)	2.33 (2.88)
White Bass	1.37 (2.81)	0.14 (0.43)	0.14 (0.43)		0.83 (1.47)	0.14 (0.42)	0.09 (0.27)	0.17 (0.41)
Morone sp.					0.04 (0.21)			
Sunfishes						0.04 (0.2)		
Rock Bass	1.08 (1.74)	2.39 (3.71)	6.26 (9.82)	4.52 (7.4)	1.84 (2.8)	4.09 (7.15)	4.34 (6.94)	12.83 (29.5)
Green Sunfish	0.05 (0.23)							
Pumpkinseed	1.8 (3.59)	33.31 (52.63)	11.23 (21.59)	13.73 (21.73)	1.3 (3.52)	22.26 (28.52)	7.07 (13.29)	17.67 (37.48)
Bluegill	7.69 (10.71)	70.22 (90.09)	3.34 (5.91)	4.17 (5.41)	14.81 (22.26)	59.71 (71.75)	3.51 (5.08)	3.33 (3.67)
Smallmouth Bass	0.12 (0.33)	0.95 (2.12)	0.27 (0.68)	1.17 (2.22)	0.06 (0.24)	0.33 (0.83)	0.9 (1.46)	
Largemouth Bass	0.25 (0.49)	3.97 (5.71)	2.44 (5.76)	1.84 (2.03)	0.26 (0.6)	4.01 (5.32)	1.15 (2.27)	1.17 (1.6)
Black Crappie	0.87 (1.85)	7.62 (10.52)	0.58 (1.24)	0.69 (0.93)	0.39 (0.75)	4.32 (5.81)	0.81 (1.35)	0.33 (0.52)
Lepomis sp.						0.17 (0.45)		
Yellow Perch	1.29 (3.28)	2.42 (4.37)	6.07 (14.92)	3.59 (5.61)	0.58 (1.05)	2.3 (4.42)	1.4 (3.01)	13.5 (27.04)
Walleye	0.42 (0.92)	3.05 (3.85)	0.44 (0.74)	1.36 (1.85)	3.56 (5.79)	2.27 (3.18)	0.27 (0.6)	3 (2.28)
Round Goby	0.05 (0.23)							
Freshwater Drum	1.16 (2.43)	3.19 (5.78)	0.76 (1.25)	1.66 (3.47)	1.12 (2.17)	0.93 (1.59)	0.39 (0.79)	0.5 (0.55)
Common Carp x Goldfish					1.21 (1.98)		0.16 (0.36)	
Tilapia					0.08 (0.28)			
Iridescent Shark Catfish					0.04 (0.2)			

Table 13a. *Species-specific mean catch per trap net for selected species in all Lake Ontario embayments (2001-2006 not included), 2006-2012 and 2013-2021. North Chanel (NC) was not sampled in 2013-2021.See Table 1 for details on site letter codes.*

	2006-2012											2013-2022									
Species	HH	EL	WB	WL	UB	MB	LB	NC	TH	PE	PB	HH	EL	WB	WL	UB	MB	LB	TH	PE	PB
Longnose Gar	0.53	2.44	0.97	1.42	1.08	0.33	0.32	0.44	0.1	0.33	0.07	0.5	2.84	1.17	2.21	1.94	0.07	0.67	0.1	0.06	0.08
Bowfin	1.33	0.28	0.39	0.17	0.59	0.81	0.59	0.32	0.32	1.08	0.89	1.2	0.47	0.33	0.19	1.19	1.8	0.33	0.43	2.81	2.06
Gizzard Shad	2.11			0.13	2.51	2.16	0.4		1.06	0.92		1.61		0.38	0.04	0.61	0.2	0.83	1.41	0.12	0.08
Northern Pike	0.89	1.33	0.55	1.31	0.64	1.09	0.49	0.6	1.16	0.67	1.7	0.46	0.47	0.25	0.54	0.42	0.53	0.33	1.03	0.31	1.56
Muskellunge	0.04															0.03					0.04
White Sucker	0.27	1	0.71	0.38	0.92	2.22	3.43	1.32	2.85	0.25	0.63	0.52	0.25	0.92	0.17	0.5	0.5	0.5	1.25	0.31	0.81
Shorthead Redhorse	0.13				0.23	0.03			0.04							0.31	0.03				
Silver Redhorse	0.04				0.6	0.07	0.17	0.44		0.08	0.04					0.43	0.2		0.04		
Greater Redhorse					0.19							0.06				0.37	0.07				
Goldfish	1.2						0.14		0.04			2.05							0.25		
Common Carp	2.95	0.17	0.42	0.13	0.21	0.35	0.48	0.72	3.12	0.25	0.37	3.16	0.12	0.12	0.27	0.26	0.93	0.17	2.41	0.19	0.46
Golden Shiner				0.06	0.08	0.19	0.21			0.17	0.04					0.11	0.23	0.33			0.04
Rudd	0.04					0.03						7.83									
Brown Bullhead	282	19.1	10.2	23.5	35.2	44.7	11.2	15.12	63.5	27.7	55.4	380	6.62	2	6.96	7.62	3.2	2.33	77.5	20.9	39.3
Channel Catfish	18.2	0.06		0.06	1.1	1.14	0.64	1.52	0.1			14.6			0.12	0.76	1.13	0.5	0.1		
American Eel			0.2	0.14	0.13	0.11	0.21					0.13			0.04	0.36	0.47	0.5	0.1		0.1
White Perch	59.4	0.17	0.75	6.09	3.73	6.75	0.5	0.04	0.4	0.17	0.11	131	0.06	0.04	2.73	5.12	3.3	2.33	0.15		0.21
White Bass	1.37		0.04		0.11	0.19			0.14			0.83			0.12	0.14		0.17	0.1	0.06	
Rock Bass	1.08	1.78	5.15	1.87	2.18	2.11	4.14	7.16	2.2	4.67	24.1	1.84	2.59	6.46	4.31	4.01	4.87	12.8	3.72	5.88	4.81
Pumpkinseed	1.8	38.5	16.2	16.2	34.2	42.3	15.3	2.88	11	5.25	18.2	1.3	16.8	3.92	11.8	26.2	44.9	17.7	9.13	5.75	3.6
Bluegill	7.69	42.2	82.2	55.1	96.6	27.1	4.57	1.36	1.92	12.3	0.15	14.8	24.6	45.5	42.9	77.6	52.9	3.33	1	18.2	1.21
Smallmouth Bass	0.12	2.5	1.6	1.5	0.76	0.63	0.55	2.4	0.06		1.11	0.06	0.5	0.96	0.29	0.24	0.03		0.12		2.46
Largemouth Bass	0.25	1.89	2.9	1.38	5.18	3.31	2.05	0.32	2.18	4.17	1.74	0.26	2.69	1.88	1.79	4.18	12.1	1.17	0.54	1.75	2.08
Black Crappie	0.87	0.11	0.2	4.22	10.9	6.38	0.74	0.4	0.62	0.25	0.74	0.39	0.06	0.08	3.56	5.37	6.9	0.33	0.42	0.75	1.63

	2006-2012											2013-2022									
Species	HH	EL	WB	WL	UB	MB	LB	NC	TH	PE	PB	HH	EL	WB	WL	UB	MB	LB	TH	PE	PB
Yellow Perch	1.29	0.33	0.14	0.75	3.54	2.04	3.82	2	7.57	1.42	4.7	0.58	0.97	0.08	0.35	3.58	2.1	13.5	1.77	1.81	0.46
Walleye	0.42	1.83	2.32	1.75	2.25	5.38	1.47	0.6	0.23	0.58	0.7	3.56	1.12	0.92	1.17	2.93	3.53	3	0.27	0.44	0.21
Freshwater Drum	1.16	0.17	0.2	0.15	2.74	6.03	1.49	2.84	0.96	0.33	0.41	1.12	0.06			1.02	1.13	0.5	0.57		0.04
Common Carp x Goldfish												1.21							0.16		

Table 13b. *Species-specific standard deviation for selected species in all Lake Ontario embayments (2001-2006 not included), 2006-2012 and 2013-2021. North Chanel (NC) was not sampled in 2013-2021. See Table 1 for details on site letter codes.*

	2006-2012											2013-2022									
Species	HH	EL	WB	WL	UB	MB	LB	NC	TH	PE	PB	HH	EL	WB	WL	UB	MB	LB	TH	PE	PB
Longnose Gar	0.92	2.97	1.98	1.96	3.52	0.79	0.54	1.8	0.29	0.65	0.27	0.84	2.43	2.41	3.44	5.89	0.25	0.82	0.31	0.25	0.27
Bowfin	1.64	0.57	0.64	0.36	1.12	1.26	0.86	0.56	0.88	2.02	1.09	1.4	0.86	0.87	0.48	2.14	3.07	0.52	0.84	3.35	3.29
Gizzard Shad	3.33			0.35	7.4	7.8	0.59		1.71	1.73		2.72		1.24	0.2	1.66	0.48	0.98	4.24	0.34	0.28
Northern Pike	1.68	1.03	0.69	1.34	1.01	1.56	0.66	0.76	1.71	0.78	2.48	0.7	0.74	0.44	0.72	0.7	0.68	0.52	1.44	0.6	1.88
Muskellunge	0.2															0.17					0.2
White Sucker	0.75	1.91	0.95	0.74	1.22	2.84	3.72	1.65	4.41	0.45	0.79	1.29	0.45	1.59	0.62	0.97	0.86	0.84	2.44	0.6	1.53
Silver Redhorse	0.2				1.93	0.27	0.48	1.04		0.29	0.19					0.96	0.66		0.21		
Shorthead Redhorse	0.52				0.66	0.19			0.2							0.71	0.18				
Greater Redhorse					0.59							0.23				0.93	0.25				
Goldfish	1.7						0.38		0.2			2.91							1.03		
Common Carp	3.54	0.38	0.78	0.42	0.55	0.67	0.8	1.24	4.85	0.62	0.56	4.08	0.33	0.34	0.57	0.57	1.14	0.41	3.02	0.4	1.12
GoldenSshiner				0.24	0.27	0.61	0.57			0.58	0.19					0.34	0.5	0.82			0.2
Rudd	0.2					0.19						13.16									
Brown Bullhead	648	30.5	16.4	33.4	68.9	77.2	17.3	24.6	198	44.1	64.6	917	7.8	2.54	12.5	10.8	4.02	3.61	190	20.5	62
Channel Catfish	37.7	0.24		0.24	2.2	1.76	1.32	3.68	0.37			40.6			0.34	2.17	2.24	0.84	0.33		
American Eel			0.45	0.38	0.44	0.36	0.57					0.46			0.2	0.94	0.9	0.84	0.32		0.42
White Perch	126	0.51	1.42	11.7	9.72	13.7	0.66	0.2	1.4	0.58	0.32	175	0.25	0.2	6.07	15.9	7.25	2.88	0.47		0.59
White Bass	2.81		0.2		0.37	0.55			0.43			1.47			0.34	0.44		0.41	0.28	0.25	
Rock Bass	1.74	3.59	4.42	1.99	4.11	3.32	6.55	13.37	3.81	5.14	38.52	2.8	2.54	6.58	5.48	8.97	7.53	29.5	6.21	8.66	7.53
Pumpkinseed	3.59	52.8	24.7	8.77	50.2	81.1	24	5.75	22.6	4.79	34.2	3.52	9.65	5.87	12.1	36.2	68.3	37.5	18.5	4.27	7.38
Bluegill	10.7	39.7	103	47.5	133	28.9	5.51	4.74	5.17	14.3	0.46	22.3	9.57	35.3	27.8	110	51.5	3.67	2.81	18.4	2.95
Smallmouth Bass	0.33	4.48	2.91	2.87	1.99	1.45	0.87	4.91	0.27		2.29	0.24	1.15	1.68	0.85	0.69	0.18		0.42		3.54
Largemouth Bass	0.49	1.88	5.74	1.78	7.2	4.93	2.21	0.75	5.5	9.3	3.28	0.6	2.85	3.72	2.21	5.7	15.4	1.6	1.74	2.46	3.22

	2006-2012											2013-2022									
Species	HH	EL	WB	WL	UB	MB	LB	NC	TH	PE	PB	HH	EL	WB	WL	UB	MB	LB	TH	PE	PB
Black Crappie	1.85	0.32	0.48	4.16	15.9	7.79	0.89	1.12	1.14	0.62	2.26	0.75	0.25	0.28	2.72	7.72	9.74	0.52	0.74	0.86	2.8
Yellow Perch	3.28	0.84	0.43	2.04	5.99	4.06	5.77	4.47	19.6	2.54	8.53	1.05	1.34	0.28	0.76	7.18	2.73	27	3.54	4.42	1.27
Walleye	0.92	1.58	2.02	2.31	3.05	6.81	1.96	1.08	0.43	1	1.1	5.79	1.17	1.02	1.4	4.26	5.44	2.28	0.64	0.73	0.46
Freshwater Drum	2.43	0.38	0.45	0.38	5.38	10.1	3	6.75	1.49	0.89	0.64	2.17	0.25			1.75	1.8	0.55	1.08		0.2
Common carp x Goldfish												1.98							0.38		

IBI scores and corresponding fish assemblage metrics were calculated for each of the 11 embayments sampled and summarized by embayment type (sheltered, exposed, and transitional) during two separate time stanzas, 2006-2012 and 2013-2021 (Figure 56 and Table 14). Hamilton Harbour had low IBI scores, categorized in the “fair” IBI classification, in both time stanzas. Changes in fish assemblage metrics between the time stanzas in Hamilton were within one standard deviation except for the number of non-native species (SNIN) and biomass of native species (BNAT). There were increases (within one standard deviation) in non-native species metrics (PBNI, PNNI), native species metrics (SNAT, NNAT), and percent generalist biomass (PGEN). Percent specialist biomass (PSPE) decreased but remained within one standard deviation (Table 14, Figure 57) and there was minimal change in the percent piscivore biomass (PPB) in Hamilton between the time stanzas (Table 14, Figure 58).

Compared to reference sheltered embayments and other embayment types, Hamilton Harbour had the lowest average IBI score in both time stanzas, with no evidence for temporal changes (Table 14). In the most recent time stanza, native species metrics (except for SNAT) and all non-native species metrics increased beyond one standard deviation in Hamilton compared to reference sheltered embayments (Table 14, see contrast column). Hamilton also had lower PPB, PSPE, percent centrarchid biomass (PCEN), and higher PGEN compared to reference sheltered embayments (all exceeding one standard deviation).

Table 14. *Mean raw metrics and IBIs (± standard deviation), and IBI class benchmarks for exposed embayments, transitional areas, sheltered embayments (excluding the Hamilton Harbour AOC), and the Hamilton Harbour AOC, 2006-2012 and 2013-2021. Contrast column indicates if Hamilton Harbour AOC metrics and IBI is within 1 standard deviation of sheltered embayments in 2013-2021.*

		2006-2012				**2013-2022**				
Metric	**Description**	**Hamilton Harbour AOC**	**Sheltered Emb.**	**Exposed Emb.**	**Trans. Areas**	**Hamilton Harbour AOC**	**Sheltered Emb.**	**Exposed Emb.**	**Trans. Areas**	**Contrast**
Species Richness										
SNAT	Number of native species	7 (2)	8 (3)	7 (2)	6 (3)	8 (3)	9 (2)	6 (2)	8 (4)	↔
SNIN	Number of non-native species	2 (1)	1 (1)	1 (1)	0 (1)	3 (1)	1 (1)	1 (1)	1 (1)	↑
SCEN	Number of centrarchid species	2 (2)	4 (2)	3 (1)	2 (2)	2 (1)	4 (1)	2 (2)	3 (2)	↓
SPIS	Number of piscivore species	2 (1)	2 (1)	2 (1)	2 (1)	2 (1)	3 (1)	2 (1)	3 (1)	↔
Trophic Structure										
PPIS	Percent piscivore biomass	14 (16)	27 (22)	33 (26)	30 (22)	15 (14)	35 (22)	34 (30)	59 (21)	↔
PGEN	Percent generalist biomass	72 (23)	27 (29)	38 (27)	26 (28)	66 (21)	15 (16)	44 (31)	12 (17)	↑
PSPE	Percent specialist biomass	14 (14)	46 (28)	29 (20)	44 (30)	19 (16)	50 (24)	23 (24)	29 (19)	↓
Abundance / biomass										
NNAT	Number of native individuals	322 (826)	179 (411)	95 (86)	42 (34)	430 (1147)	121 (124)	84 (184)	59 (100)	↑
BNAT	Biomass of natives	131 (208)	50 (106)	25 (22)	20 (16)	139 (254)	25 (20)	31 (70)	17 (10)	↑
PNNI	Percent non-native numbers	28 (21)	10 (17)	12 (20)	2 (4)	23 (24)	4 (10)	16 (26)	13 (17)	↑
PBNI	Percent non-native biomass	20 (18)	10 (15)	8 (16)	7 (16)	50 (18)	5 (10)	22 (28)	7 (9)	↑
IBI		**45 (10)**	**66 (15)**	**60 (11)**	**62 (12)**	**50 (10)**	**71 (9)**	**52 (16)**	**58 (13)**	↔
IBI – class		**Fair**	**Good**	**Good**	**Good**	**Fair**	**Good**	**Fair**	**Fair**	

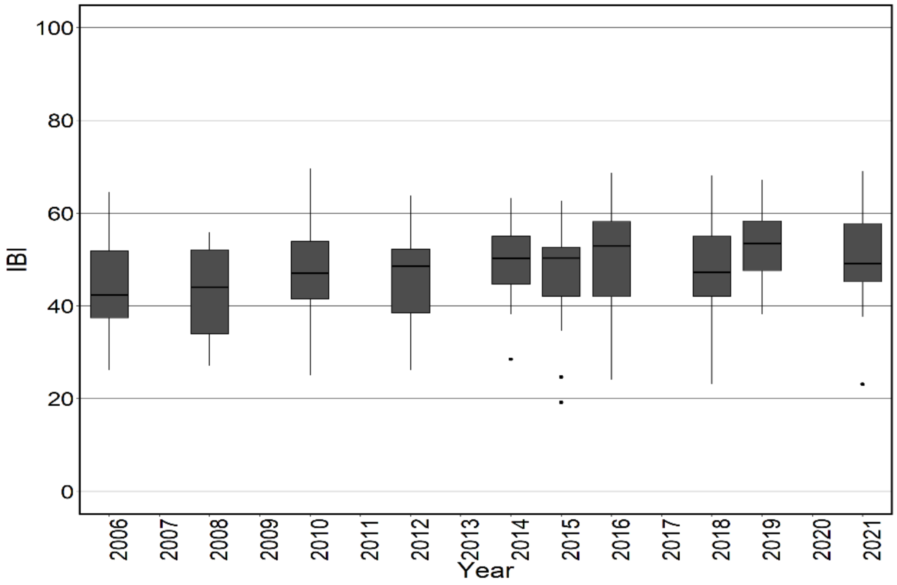

Figure 56. *Box-whisker plots (median and upper and lower quartiles) of the Index of biotic integrity (IBI), as a measure of ecosystem health in the nearshore trap net surveys in Hamilton Harbour through time (2006-2021). IBI classes can be described as follows: 0-20 very poor, 20-40 poor, 40-60 fair, 60-80 good, and 80-100 excellent ecosystem health.*

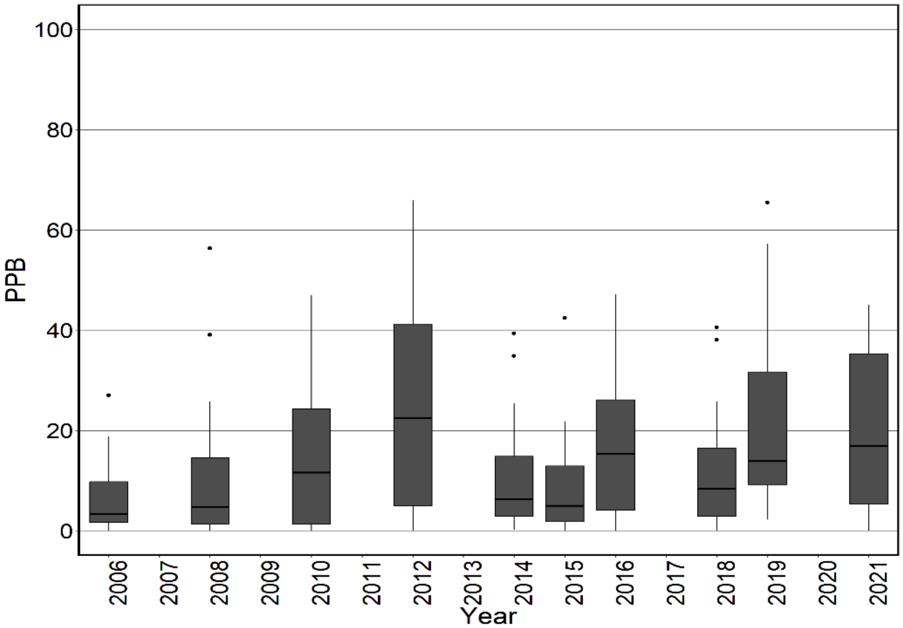

Figure 57. *Box-whisker plots (median and upper and lower quartiles) of the proportion of total fish community biomass represented by piscivore species (PPB) in the nearshore trap net surveys in Hamilton Harbour through time (2006-2021). A PPB>20 is indicative of a balanced trophic structure (depicted by a solid line). Piscivore species included Longnose Gar, Bowfin, Northern Pike, Smallmouth Bass, Largemouth Bass, Walleye, and American Eel.*

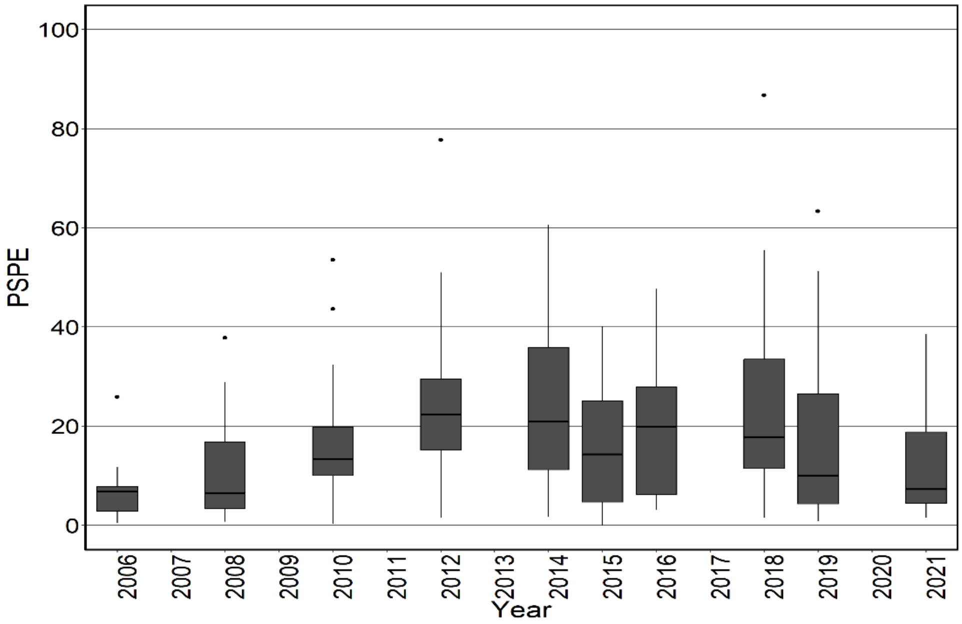

Figure 58. *Box-whisker plots (median and upper and lower quartiles) of the total fish community biomass represented by specialist species (PSPE) in the nearshore trap net surveys in the Hamilton Harbour (2006 – 2021). A PSPE >40 is indicative of a healthy aquatic ecosystem (depicted by a solid line). Specialist species included White Sucker, Gizzard Shad, Freshwater Drum, Bigmouth Buffalo, White Perch, White Bass, Pumpkinseed, Bluegill, Black Crappie, Rock Bass, and Yellow Perch.*

DISCUSSION

Extensive work has been conducted to develop fish community indicators of ecosystem health (i.e., IBI) for Lake Ontario and the St. Lawrence River and assess the environmental factors that influence them (Hoyle and Yuille 2016; Bowlby and Hoyle 2017). It was determined that the degree of exposure of an embayment influences IBI scores and related indicators leading to the classification of embayments into types (i.e., sheltered, transitional, exposed). Sheltered embayments generally had the highest IBI scores compared to other embayment types averaging 66 and 71 in the two respective time stanzas (Table 14). Although Hamilton Harbour is a sheltered embayment, IBI scores remained low throughout the time series, never exceeding a score of 53 (Figure 56). There was a slight increase in the average IBI score between the earlier and later timeframe (from 47 to 50) but it remained within the “fair” category (Table 14). These trends suggest that the Hamilton Harbour fish community and aquatic ecosystem remain impaired.

IBI scores in previous analyses were positively influenced by native, piscivore, and centrarchid species richness, and percent specialist biomass (PSPE) and negatively influenced by non-native species metrics and percent generalist biomass (PGEN) (Hoyle and Yuille 2016). Hamilton Harbour had a much higher average catch per unit effort and percent biomass of generalist species including Common Carp, Channel Catfish, Goldfish, Rudd, and Brown Bullhead, relative to other sheltered embayments. Rudd, Goldfish, and Common Carp-Goldfish hybrids, in particular, were rarely caught in other embayments. The increase in Common Carp-Goldfish hybrids in recent years may be due to increased hybridization but also may result from improved awareness and identification by field staff. Hamilton Harbour also had lower PSPE than unimpaired sheltered embayments, with lower average catches of native specialist species including Bluegill, Pumpkinseed, Black Crappie, and Yellow Perch. White Perch had increased catches in Hamilton compared to other sheltered embayments; however, it is non-native, pollution tolerant, and negatively interacts with native species when hyperabundant (Hoyle et al. 2012). A high diversity of specialist species (>40% biomass) is believed to reflect a healthy aquatic ecosystem (Hoyle et al. 2018). At no point was a PSPE of >40% observed in Hamilton (Figure 58).

The biomass of piscivore species (PPB) has a positive influence on aquatic ecosystem health. When the fish community is composed of less than 20% piscivores, it is indicative of a degraded aquatic ecosystem (Bowlby and Hoyle 2017). Hamilton Harbour was below this PPB threshold in seven out of ten sampling years (Figure 57). Compared to reference sheltered embayments, Hamilton had decreased catches of Largemouth Bass, Smallmouth Bass, Longnose Gar, and American Eel, however, American Eel catches increased in 2021 (Table 12). Average catches of Northern Pike were comparable to reference sheltered embayments. Walleye catches increased between the first and second time stanza and were slightly higher compared to reference sheltered embayments in the second time stanza, indicating the survival of stocked Walleye that were released starting in 2012 (Appendix D).

The species composition and high total biomass in Hamilton Harbour correlate with a hyper-eutrophic system, high nutrient inputs, and low submerged aquatic vegetation (Hoyle and Yuille 2016). Bowlby and Hoyle (2017) and Hoyle and Yuille (2016) found through Principal Component Analysis that the Hamilton Harbour fish community was different from other Lake Ontario embayments between 2006 and 2013, and was attributed to the high abundance of Channel Catfish, Common Carp, Brown Bullhead, and White Perch and low abundance of White Sucker and Smallmouth Bass. This finding further underscores that a positive shift in the fish community has yet to occur. At the time of these studies, Rudd and Goldfish were less prominent but now have high mean catch rates and further contributed to the distinct fish community in Hamilton Harbour. Delisting criterion for fish populations identified specific shifts in the fish community that were deemed desirable, "*…from [one] indicative of eutrophic environments (e.g. White Perch, Alewife, bullheads, and carp) to a self-sustaining community more representative of a mesotrophic environment with a balanced trophic composition that includes top predators (e.g. Northern Pike, Largemouth Bass and Walleye) and other native species (e.g. Suckers, Yellow Perch and sunfishes)*" (HHRAP) 2019; pg. 8). Currently, Hamilton Harbour remains below BUI targets for IBI with relatively high abundances and biomass of non-native and generalist species and low biomass of piscivore and specialist species compared to reference sheltered embayments.

GENERAL DISCUSSION

This report integrates various data sources, existing publications, and works in development, to provide a current assessment of the status of fish populations within the Hamilton Harbour Area of Concern (AOC). Based on evaluations of these lines of evidence from several partners, fish populations in the Hamilton Harbour AOC are not meeting established delisting criteria. Despite some improvements in the late 1990s and early 2000s, the majority of catch and metric values, as well as richness, have declined and are now at or below levels observed when the harbour was first listed as an AOC. Furthermore, the nature of these changes (i.e., declines in catch, richness, and biomass) make it clear that holistic recovery of native fishes with a focus on increasing their diversity will be essential to meeting delisting criteria (Gardner Costa et al. 2022).

The harbour ecosystem is complex and has changed considerably since the initial listing. At that time, there were five main components identified as requiring remediation to support the recovery of fish populations: habitat losses, hypoxia, nutrient inputs, sediment inputs, and contaminated sediments (Holmes 1988). While there have been improvements in some of these components (e.g., declines in ammonia, localized habitat enhancement, confinement of contaminated sediments at Randle Reef, upgrades to wastewater treatment plants (WWTP), reducing combined sewer overflows), persistent eutrophication, seasonal hypoxia, sedimentation, sediment contamination, and habitat loss and degradation still pose challenges to fish population recovery. Additional ecosystem changes have also occurred since the Hamilton Harbour AOC was listed, notably, the introduction of novel aquatic invasive species, continued urban expansion and population increases in its watersheds, and long-term leakages from combined sewer overflows; these have further contributed to changes in fish populations. Finally, previously unknown sources of impairment have also since become evident and, while some are likely not AOC-specific (e.g., chemicals of emerging concern, climate change, aquatic invasive species), they can nevertheless affect the ability of fish populations within the AOC to recover. Given the dynamic nature of the Hamilton Harbour AOC ecosystem, making causal links between changes in a specific ecosystem component or source of impairment to the response of a fish species or the fish community is challenging. Suffice it to say, many species that previously showed some improvement are now in decline. Future works should thus attempt to: determine how existing and emerging stressors may be limiting population recovery, identify which stressor(s) may be amenable to remediation, and, if a stressor is both limiting and challenging to remediate, quantify its effect to help contextualize the recovery potential of fish populations based on ecosystem conditions within the Hamilton Harbour AOC.

Among sections within this report, there were common themes related to spatial-temporal patterns in fish populations and those are presented here in an integrated manner as “findings”. Similarly, some ecosystem components were consistently related to limiting fish population recovery or have contributed to declines during the assessment period (1988-2021), which are presented here in an integrated manner as "stressors and limitations". Finally, we conclude with some integrated recommendations to inform future actions in support of fish population recovery within the Hamilton Harbour AOC; additional and more specific recommendations are also presented in the individual sections. As a reminder, most analyses focused on comparisons among time stanzas (P1: pre-1994, P2: 1995-2004, P3: 2005-2012, and P4: 2013-2021), which were defined based on major ecosystem events in the Hamilton Harbour AOC (see Turner et al. in review).

FINDINGS

Within the Hamilton Harbour AOC there are clear differences in catch and community metric values among spatial zones, with typically higher values at the west end.

- The West zone of the harbour typically has the highest catch and metric values while the East zone has the lowest, which is consistent with other studies (Boston et al. 2016; Midwood et al. 2019; Maynard et al. 2022; Larocque et al. 2024).
- Catch and metric values in the North zone tended to be more similar to the West in earlier time periods, but during P4 (2013-2021) it was often more similar to the East zone.
- Specific habitat (i.e., extent, composition, distribution) differences among zones have not been quantified, but will be under Beneficial Use Impairment 14 (Fish and Wildlife Habitat); telemetry-linked habitat works indicate greater habitat heterogeneity in the west end as well as high residency by many fishes (Larocque et al. 2024)
- Detailed assessment of habitat availability, habitat suitability, and food availability among zones is warranted. This would help identify species and assemblages (and consequently fish community metric scores) that would be predicted to occur based on zonal habitat conditions. Potential factors influencing differences in catch and community metric values within the zones are detailed here.
    - The West zone sampling locations are proximate to Cootes Paradise and Grindstone Creek marshes that provide considerable sheltered warmwater habitat and are further away from the two major WWTP outfalls (although influenced by Dundas WWTP) than those in the North and East zones.
    - The East zone is presumed to have limited sheltered habitat, but wildlife islands have been found to provide some protection (Croft-White et al. 2022) and to be used by more nearshore fishes than west islands (Maynard et al. 2022); wildlife islands are not analogous to the marshes at the west end of the harbour and the thermal profile behind the islands is unclear. The East zone is the receiving area for two major WWTPs but is also adjacent to the canal where large incursions of water from Lake Ontario (up to 0.98% of harbour volume in daily exchange) can push into the system via this canal (Kohli 1979).
    - The East zone is thought to be influenced by upwellings of hypolimnetic waters (Flood et al. 2021; see Hypoxia section below). While this is also

  true for the West zone, the West has more areas where fishes could find refuge during upwellings. Similarly, due to prevailing winds, higher fetch or exposure values in the East may inherently reduce fish community metric scores (Hoyle et al. 2018) and fish catch (J. Midwood, unpublished data); access to shelter at the west end may mitigate these effects.
  - The North zone has extensive beds of submerged aquatic vegetation (SAV; Gardner Costa et al. 2019) and, in the past, was identified as a potential area for remediation (due to both the presence of SAV and lower sediment toxicity; Holmes 1988). This zone has limited sheltered habitat but is more proximate to marshes at the west end than the East zone. Declines in fish populations and fish community metrics in the North zone from P3 to P4 (section FP-2A) could be explained by the more abrupt transition from nearshore in the North and East zones to deeper waters, which could increase predation pressure by more pelagic-oriented top predators (e.g., Walleye); this requires confirmation. Upwellings of oxygen-poor waters likely also affect the North zone, but the magnitude and spatial extent are unclear.
- Sheltered habitat is thought to be limiting in the East zone. If there are no opportunities to create more of this habitat type, it is likely that species that require this type of habitat will remain absent from that part of the Hamilton Harbour AOC.

Declines in catch of specific species and fish community metric values were evident from P2 (1995-2004) to P3 (2005-2012).

- Declines in overall biomass and catch of native fishes, as well as Index of Biotic Integrity (IBI) scores from P2 to P3, have been noted previously and were hypothesized to be driven in part by competition with Round Goby and predation by Double-Crested Cormorants (*Phalacrocorax auritus*; Boston et al. 2016).
- Similar declines in IBI and fish community metrics (FP-2A), including declines in species-specific encounter rates and catch (e.g., Largemouth Bass, Pumpkinseed; FP-1A) and the disappearance from the harbour of benthic species (e.g., Johnny Darter (FP-1B)), are documented in this report.
- Declines from P2 to P3 may be related to changes in the trophic state and linkages within the Hamilton Harbour AOC (i.e., increased nutrients, establishment of novel aquatic invasive species, and re-establishment of a native avian predator).
  - Since P2, there has been an increase in Total Phosphorus, despite remedial efforts to reduce nutrient inputs to the harbour (Visha et al. 2021); this is contributing to ongoing eutrophication issues within the AOC.
  - Since the early 2000s (mid-P2), there has been an increase in the frequency of high biomass harmful or nuisance blooms of cyanobacteria and flagellate phytoplankton (Munawar and Fitzpatrick 2018).

Declines in catch of some species and fish community metric values were evident from P3 (2005-2012) to P4 (2013-2021).

- Declines for important native fish species (e.g., White Sucker, Brown Bullhead, Smallmouth Bass, and Yellow Perch; FP-1A) and community metrics (e.g., native species richness; IBI-adjusted; FP-2A) were observed from P3 to P4.
- There is limited evidence for marked changes in fish community metrics or catch from P3 to P4 in the East-Ref areas, suggesting that factors negatively affecting fish populations in P4 in the Hamilton Harbour AOC were local. Potential factors influencing differences in catch and community metric values between these two time stanzas are discussed here.
    - Round Goby abundance has declined in the annual minnow trap sampling program (Young et al. 2010; McCallum et al. 2014; S. Balshine unpublished data, section FP-1A; Appendix E), but it is difficult to assess trends for this species within the other long-term sampling programs due to gear biases and resulting low catch rates.
    - Nest numbers for Double-Crested Cormorants have largely remained stable (although at slightly higher numbers than during P3; J. Quinn, unpublished data; (Gilroy 2019). As opportunistic feeders, the composition of their diet typically reflects species availability, with Alewife and Round Goby being the primary prey source for the Hamilton Harbour AOC colony during P3 (King et al. 2017). Given noted declines in both these species in the harbour, foraging by cormorants may have since shifted to other species or areas inside (e.g., Windermere Basin) or outside of the Hamilton Harbour AOC. As such, the magnitude of effects from avian predation (including all avian predators) in P4 are unclear and require further study.
    - To our knowledge, there have been no significant declines in the amount of physical habitat in the system during this period, and, at least in Cootes Paradise, emergent vegetation has been increasing (Appendix G), so changes in habitat supply is likely not the main driver.
    - Higher water levels in some years during P4 may have contributed to lower areal coverage of SAV (Gardner Costa et al. 2019) but may also increase access for some species to important spawning habitat (i.e., flooded emergent vegetation), notably in Cootes Paradise, Grindstone Creek and Red Hill Creek marshes (e.g., Northern Pike; Budgell et al. 2023).
    - There is no evidence for marked declines in lower trophic productivity, with zooplankton biomass remaining among the highest in the Great Lakes (Bowen and Currie 2017; Bowen et al. 2018), so changes in forage opportunities are likely not the main driver.
    - Since P3, one major change in the system in terms of predation and competition has been the successful establishment of stocked Walleye (stocking began in 2012), but to date, there has been no evidence of natural recruitment into the system.

- Regardless of the driving factors, the condition of the fish community in the Hamilton Harbour AOC is impaired, and the trends in some metrics and catch statistics indicate greater impairment in P4 compared to P1.

Low native fish species richness and abundance are a major limiting factor for population recovery.

- Low species richness and total catch of native fishes are key indicators of fish population impairment and contribute to persistently low IBI scores (Gardner Costa et al. 2022; FP-2A).
- Of the 12 native species assessed, 6 have experienced significant declines in catch or probability of capture through electrofishing surveys between P1 and P4 (see Table 2 in FP-1A).
- Of the 12 native species assessed, 8 experienced significant declines in catch or probability of capture through electrofishing surveys between P3 and P4 (see Table 3 in FP-1A).
- Native species richness and catch both declined from a peak during P2, with catch declining from P2 to P3 and richness from P3 to P4 (FP-2A); the absolute number of native fishes has also declined with 43 fishes encountered during P1-P3 and 33 in P4 (FP-1B).
- The percentage of offshore species (e.g., Alewife, White perch, and Gizzard Shad) contributing to catch and biomass in the Hamilton Harbour AOC is higher than at East-Ref areas (25-60% vs <10%; FP-2A) and is indicative of nearshore fish habitat impairment.
- While species-specific actions (i.e., control of aquatic invasive species, stocking or recovery of a top predator) are important, a more holistic recovery of native fish populations will be required to meet delisting criteria (Gardner Costa et al. 2022).

Top predators are in lower abundance than desired to provide top-down control.

- Establishing a more balanced trophic structure for fishes in the Hamilton Harbour AOC is a long-standing objective and increasing the proportion of top predators to >0.20 is thought to provide suitable top-down control (Hoyle and Yuille 2016).
- Trap net data have shown improvements in the proportion of biomass comprised of piscivores (PPB) in some years (3 out of 10 exceeding 0.20), but the overall trend indicates no improvement between P3 and P4 despite the contribution of stocked Walleye (FP-2B); similarly, PPB values from electrofishing data have not improved (FP-2A). Neither data set indicates PPB consistently meets the 0.20 target.
    - Differences between the electrofishing and trap-net datasets are not surprising given the effective sampling depth and differences in active and passive capture methods for top predators like Walleye (Portt et al. 2006).
- Walleye stocking efforts have increased their abundance in the harbour (FP-1A and FP-2A) from P3 to P4.

- Other top predators, Northern Pike and Smallmouth Bass in particular, have shown declines in catch and catchability (FP-1A and FP-2B) with highly variable recruitment (Appendix G; Budgell et al. 2023).
- Identification of recruitment limitations for top predators within the Hamilton Harbour AOC is important to support their recovery; however, with overall reductions in fish catch, forage opportunities may also be an equally important limitation for top predators as habitat or recruitment.

Sampling gear selectivity has the potential to influence fish catch and thus the interpretation of fish population condition.

- Fishing gear selection is important because all gear types are biased for or against some species (Portt et al. 2006). An assessment of fish populations needs to ensure fishes of interest can be consistently captured, which means using a range of gear types.
    - Several gear types were used in the present assessment, particularly in section FP-1B.
    - Differences in catchability are also likely important factors driving inconsistencies in species-specific trends from electrofishing (FP-1A) and trap net (FP-2B) data sources (e.g., Brown Bullhead, White Perch, and Largemouth Bass); however, these gear types can provide a complementary assessment of the fish population when taken together.
- In addition to gear, time of day and seasonality can affect capture and encounter rates (Larocque et al. 2020; Gardner Costa et al. 2022); electrofishing analysis underway indicates marked changes in catch and resulting IBI scores when sampling during the day or night as well as by season (C. Boston, unpublished data).
    - To account for this, we analyzed electrofishing data with a focus on late-spring and summer (May-August) sampling and used timing (day/night) as a random effect.
    - Exploring species-specific differences in diel catch in reference areas as well as in the Hamilton Harbour AOC may further help to identify the fish community assemblage observed in reference areas during the day that is lacking in the harbour.
    - Knowing which fish are absent during the day can help identify environmental factors that limit catch during the daytime, with factors such as cover (e.g., SAV or overhead cover) potentially serving to attract fishes, while water temperatures and or exposure may limit their presence.
    - Electrofishing catches from night surveys are higher in species richness and abundance and although this is true for all levels of SAV (e.g., none to dense), there were still more zero catch events during the day in the Hamilton Harbour AOC than at reference embayments. This is likely indicative of impairment as this is not observed in other reference sampling areas, but zero catch is less informative of fish community condition.

    - In the near-term, the Fisheries and Oceans Canada electrofishing program will focus on night sampling, which should provide sufficient catch rates while also allowing increased sampling effort in areas outside of the Hamilton Harbour AOC.
- Changing conductivity levels can impact catchability of fishes using boat electrofishing (Hill and Willis 1994).
    - From P1 to P4, mean conductivity measured during sampling in the Hamilton Harbour AOC increased significantly from 535 to 680 µS/s, markedly higher than values in the East-Ref (P1-P3 = 253-272 µS/s) and higher than the West-Ref (P3 = 458 µS/s; no P4 data were available for conductivity outside of the AOC). Increased conductivity is likely due to the use of road salt in the watersheds and is correlated with urbanization (Eyles et al. 2013) but may also be influenced by changes in the timing and amount of riverine or wastewater inputs.
    - While the Fisheries and Oceans Canada electrofishing protocol is standardized to amperage, the vessel operators do “correct” from the recommended average amperage, going either higher or lower depending on fish response to maintain equal catchability and minimize fish harm.
    - This practice will have reduced the bias associated with conductivity, and changes in conductivity have likley limited impact on observed changes in catchability.

STRESSORS AND LIMITATIONS

Understanding the linkages between changes in a specific environmental condition and the response of a fish species or the fish community are essential to both identify potential recovery actions and stressors that limit fish population recovery. The former will guide future works within the Hamilton Harbour AOC while the latter will help to contextualize future assessments. At present, direct linkages have not been made, sohere we review potential stressors or limitations to fish population recovery. They can be generally grouped into abiotic (e.g., water quality, hypoxia) and biotic (e.g., aquatic invasive species, predation) sources. Developing a conceptual framework of how these factors act (and interact) to impair fish population condition would be beneficial for future assessments and remediation planning. The main stressors and associated limitations within the Hamilton Harbour AOC that can potentially impact fish populations are discussed below.

Contaminants

- BUI #1 (restrictions on fish consumption) remains impaired in the Hamilton Harbour AOC; hotspots for contamination from coal tar, mercury, polychlorinated biphenyls (PCB), and polycyclic aromatic hydrocarbons (PAH) have been identified at Randle Reef and in Windermere Arm (Marvin et al. 2000 in Visha et al. 2021).

- There have been improvements in contaminant burden, particularly for mercury and, to a lesser extent, PCBs (Visha et al. 2018a, 2018b, 2021); however, PCB levels in the Hamilton Harbour AOC remain among the highest surveyed (Visha et al. 2021) in Great Lakes AOCs.
- While BUI#1 guidelines are focused on human consumption, they are also indicative of the exposure of fishes within the Hamilton Harbour AOC to these contaminants, which may have population-level impacts (e.g., PCB levels in some fish are above those observed to cause effects on mortality, growth, and reproduction in some species; Neff et al. 2016; Berninger and Tillitt 2019).
- The spatial extent and magnitude of effect on fish populations from other sources of contamination, notably chemicals or contaminants of emerging concern (e.g., hormones, pesticides, pharmaceuticals, and lifestyle compounds, among others), are unknown; many of these chemicals are found in urban aquatic systems (Fairbairn et al. 2018) with the extent of development and distance from point sources being predictors of their presence (Kiesling et al. 2019).
- Contaminants of emerging concern can impair reproduction, growth, and survival and thus limit fish population recovery, but are generally less documented (see Baker et al. 2022 for some examples).

Water quality

- Eutrophication remains a major challenge in the system; trends in total phosphorus initially declined in the mid to late 1990s but increased again during the time series and are currently similar to or slightly lower than those seen during the initial AOC listing but with an increased proportion of soluble reactive phosphorus (Visha et al. 2021).
- Few water quality parameters have changed enough to indicate an improvement in the water quality of the harbour (Figure 59), although declines in ammonia are a positive sign.
- Mobilization of internally-loaded phosphorus from sediments (Markovic et al. 2019) may limit changes in water quality in the short term despite improvements to wastewater treatment.
- Limited exchange rates with oligotrophic Lake Ontario likely cannot resolve issues with water quality without more effort to reduce catchment inputs (Molot et al. 2022); however, catchment inputs may be less manageable as a source than WWTP inputs.
- Increased urbanization within the Hamilton Harbour AOC watersheds will increase inputs to WWTPs and stormwater ponds and this poses a continuing challenge to improving water quality in the harbour (Government of Ontario 2022).
    - Combined sewer overflow systems in the City of Hamilton can discharge untreated wastewater to the harbour during heavy precipitation events; there have been well-documented examples of long-term discharges. However, efforts are underway to reduce the frequency and magnitude of these discharges.

  - Increases in conductivity in the harbour observed during electrofishing surveys are likely linked to increased urbanization within the Hamilton Harbour watershed (Eyles et al. 2013; Figure 60); direct impacts are unclear, but some freshwater fishes are sensitive to levels above those observed in the harbour (e.g., Blackside Dace (*Chrosomus cumberlandensis*; Hitt et al. 2016), as are some benthic macroinvertebrates.
- While extensive public works have been completed or are underway to upgrade the treatment of wastewater effluent that enters the harbour, noticeable water quality and ecosystem improvements are likely to take decades. Consequently, water quality impairments, eutrophication, and hypolimnetic hypoxia are likely to continue to pose challenges to fish population recovery in the near-term.

Hypoxia

- Seasonal hypolimnetic hypoxia is a long-standing issue in the Hamilton Harbour AOC (Polak and Haffner 1978; Piccinin and Harris 1980 in Dermott et al. 2007; Hiriart-Baer et al. 2016) and there is no evidence that the frequency or severity of hypoxia events have changed significantly over the past 30 years; however, there is some indication that conditions may be slightly less severe, with an increasing trend in mean dissolved oxygen in recent years (Figure 59; D. Depew unpublished data).
- Outside of the Spencer Creek watershed, few species identified as “sensitive” to low dissolved oxygen were observed in the harbour and watersheds (FP-1B).
- Periodic upwellings of anoxic hypolimnetic waters may act to reduce habitat suitability in nearshore areas. The magnitude of upwellings is greatest at the west and east end of the harbour; the North zone is also affected although the extent to which it reaches the shore is unclear (Flood et al. 2021).
- At deeper bathymetric depths (~7 m), upwellings were rarely found to reach the surface, which allowed individuals to find waters with sufficient dissolved oxygen by moving up into a narrower band of water column (Brooks et al. 2022).
- It is currently unknown the extent to which these upwellings push into nearshore areas (i.e., up to the shoreline) and reduce suitability in the entire water column (i.e., situations where moving up in the water column would not provide refuge). Past works have documented periodic anoxia as shallow as 3.5 m (Dermott et al. 2007).
- Habitat compression caused by hypoxia may actually benefit top predators like Walleye by reducing foraging effort (Brooks et al. in review) since prey fishes are concentrated in the oxygenated epilimnetic waters (Midwood et al. 2019).
- Seasonal hypolimnetic hypoxia is unlikely to be resolved in the near-term and remains an ongoing limitation for fishes in the Hamilton Harbour AOC, particularly those that rely on cooler waters during stratification (e.g., coldwater fishes like Cisco; FP-1B).
- Hypoxic upwellings have also been implicated as a main factor limiting the recovery of fall spawning coldwater fishes (Bowlby et al. 2016). Their

prevalence/frequency, timing, and intensity will continue to limit the recovery of some species and their populations in the system.

Forage – lower trophic

- Lower trophic production within the Hamilton Harbour AOC varies seasonally, but some spatial heterogeneity does exist, with typically higher phytoplankton biomass in the west and central zones. Zooplankton biomass, however, shows little or no spatial differences indicating little top-down control on their population (Currie et al. 2024).
- Despite high nutrient levels, Hamilton Harbour AOC has less phytoplankton biomass than expected (Currie et al. 2018).
- Hypoxia, physical habitat variability, and reduced water clarity (i.e., light attenuation) may limit phytoplankton (Hiriart-Baer et al. 2016; Currie et al. 2018).
- Since 2000, cyanobacteria biomass events have become more common, but mixed blooms of flagellates dominate biomass (Munawar et al. 2017).
- Hamilton Harbour has a high biomass of zooplankton (higher than the rest of the Great Lakes) that has remained largely stable since the early 2000s (Bowen et al. 2019); including increases in invasive predatory zooplankton *Bythotrephes*, indicative of limited top-down planktivory in the system.
- Relatively weak relationships among phytoplankton, zooplankton, and planktivorous fish biomass have been documented (Currie et al. 2018), suggesting disruptions in energy transfer up the food chain and the likelihood that planktivorous fishes are not fully capitalizing on available zooplankton productivity (Hossain et al. 2017).
- Some zooplankton taxa may seek refuge from predation during the day in the hypoxic hypolimnion and thus may not be fully accessible as a forage base for planktivorous fishes (Bowen and Currie 2017).
- Gape-limiting predation of large invasive predatory zooplankton (e.g., *Bythotrephes*) may affect earlier life stages or smaller planktivorous fishes (Straile and Halbich 2000).
- Diets of the dominant planktivorous fishes would help to determine trophic energy pathways in the fish community.
- Given considerably lower trophic production in the system and noted declines in nearshore fish productivity (as evidenced by recent declines in the HPI_{Adj}), it is likely that the forage base is not a limiting factor for all fishes, nor the primary causal mechanism for the recent declines in catch and persistent fish community impairment.

Forage – benthic invertebrates

- Species and production of benthic invertebrates are affected by contaminated sediments and hypoxia in the Hamilton Harbour AOC.
- In the early 2000s, oligochaetes dominated most samples and were the only macrobenthic invertebrates found in the deepest parts of the harbour; chironomids were the second most commonly captured invertebrate, with peak density at 7 m depth (and rare or absent beyond 9 m; Dermott et al. 2007). The

presence of these orders of invertebrates and the absence of other species usually indicate a highly degraded habitat (Krieger 1984).
- Zebra mussels were largely absent from depths greater than 8 m, and their biomass was greatest along the north shore (Dermott et al. 2007).
- Invertebrates increased in density from 1964 to 1984 but declined by the early 2000s; improvements in chironomid taxa richness in 2002 at some locations suggested improved water quality relative to the 1980s; (Dermott et al. 2007).
- Ephemeroptera, Trichoptera, Odonata, and Coleoptera were absent from benthic samples in 2002 and 2004; the presence of these species is indicative of less degraded ecosystems (Kutcher and Bried 2014).
- Benthic invertebrate sampling in 2014 found declines in number of young and hatched cocoons of *Tubifex tubifex* (oligochaetes) since 2000 surveys – values were more comparable to those observed in 1990; there was also a decline in the invertebrate mites (Pionidae) since 2000. Severely toxic sediments at the west, north, and east zones of the harbour were identified (Milani and Grapentine 2016).
- As of 2014 (and supported by work from the early 2000s), benthic foraging opportunities are limited for most fishes, particularly in areas affected by hypoxia, and diet data for most benthivorous fishes are lacking.
- Additional surveys of benthic invertebrate composition and density within the harbour are required to understand the spatial distribution of forage for benthic fishes.

Aquatic Invasive Species

- Numerous aquatic invasive fish species (AIS) are established in the Hamilton Harbour AOC including Alewife, Round Goby, Goldfish, Common Carp, Rudd, Rainbow Smelt, Sea Lamprey, and White Perch.
- These species may directly compete with other native fishes, consume eggs of native fishes (e.g., Round Goby and White Perch), or have more indirect effects through habitat modification (e.g., Common Carp or Rudd removing SAV).
- Reducing populations of non-native fishes is thus critical for supporting the recovery of fish populations, although their reduction alone will not achieve AOC targets (i.e., recovery also requires increases in the catch of native fishes; Gardner Costa et al. 2022).
- The catch of Alewife and Round Goby declined recently (P2-P3 and P3-P4, respectively); however, White Perch remain stable and hyperabundant compared to other similar areas (FP-1A and Appendix E).
- Cootes Paradise Fishway has been an effective means of controlling non-native Common Carp populations and catch of this species has continued to decline into P4.
- Catch of Rudd and Goldfish have increased (FP-1A) and may counterbalance the declines in Common Carp.
- Sea Lampreys are actively controlled and observations of this species in the harbour are limited (FP-1B).

- Reductions in catch and richness of non-native fishes acts to improve overall IBI and IBI_{Adj} scores; however, declines in other metric values (e.g., total catch, or native species richness) offset these improvements.
- Declines in catch and richness for non-native fishes track with overall declines in catch and richness for all species may be less indicative of improvements in fish populations and more reflective of systemic changes in fish abundance.
- Management options for Rudd and Goldfish should be explored; this may include active removal (i.e., capture and removal from the harbour or at the Cootes Paradise Fishway) or more passive exclusion from spawning habitats (i.e., physical barriers; Piczak et al. 2023b).

Predation

- Walleye were present only in limited numbers until 2013 when a large cohort of individuals stocked as fingerlings in 2012 became established (FP-2B). Stocking continued in 5 out of 8 years between 2013-2020 with variable stocked biomass and survival (Appendix D).
- Successive stocking events in 2016 and 2018 have also yielded large classes of adult Walleye (see section FP-2B) that are primarily resident in the harbour except during the summer (Brooks et al. 2017; Larocque et al. 2024).
- As low-light predators, conditions in the harbour are well suited for Walleye and they have thrived with some of the highest growth rates in Lake Ontario (Brooks et al. In review).
- Ring-billed Gull are the most numerous colonial bird species and, along with Double-Crested Cormorants, nesting is actively discouraged. Alewife and Rainbow Smelt have been identified as important aquatic prey for Ring-Billed Gull in other systems (Chudzike et al 1994 in Morris et al. 2011), and Alewife and Round Goby were the top species consumed by Double-Crested Cormorants in P2 and P3 (Somers et al. 2003; King et al. 2017). There is limited recent knowledge (i.e., during P4) about the diet selection of avian predators and it is important to document given declines in populations of their preferred forage species.
- Determining the preferred prey of Walleye, other piscivores, and avian predators as well as their preferred foraging habitats, is important for quantifying their potential effects on native fishes (e.g., declines in catchability [FP-1A] and richness [FP-2B] of smaller bodied fish like Cyprinids) as well as the suppression of non-native forage fishes.
- For Walleye, a bioenergetics approach (after Mayo et al. 1998) could help identify prey selection (but also requires a detailed assessment of Walleye diet and growth rates).
- An exploration of current trophic interactions in the harbour could also identify the role of predation in the system; repeating a study from the mid-2000s that used stable isotopes (Ryman 2009) including lower-trophic baselines, could help partition the effect of changes in predation; alternately growth and size spectrum models could be employed (see Benoit et al. 2021).

Habitat loss and impairment

- A major limitation for fish population recovery is the substantial historical loss of physical habitat (e.g., infilling of tributaries and wetlands, removal of aggregate material) and the degradation of the remaining habitats (e.g., sedimentation of shoals, eutrophication, and water quality impairment). Hamilton Harbour AOC has experienced all of these stressors, and an assessment of fish habitat (BUI#14) is currently underway to describe the quantity and quality of fish habitat.
- Access to different habitat types is not equal across the harbour and this is likely a key contributing factor for differences in fish population condition among harbour zones.
- The extent of connectivity (i.e., availability of movement corridors with suitable habitat) among distinct habitat ecotypes within the Hamilton Harbour AOC and to other locations in Lake Ontario is unclear but is an important consideration to support dispersal and recolonization of species currently in low abundance.
- In the future, assessment of fish habitat should occur prior to the assessment of fish populations so the results of these works can be used to inform the population assessment.
- Opportunistic creation or remediation of aquatic habitat in the Hamilton Harbour AOC is essential but should be carefully reviewed by technical experts. Some potential options are discussed briefly in the recommendations section.

RECOMMENDATIONS

1) Recommend determining habitat supply and limitations among harbour zones and for the entire AOC so opportunities for habitat improvement can be explored.

- A detailed assessment of habitat availability and habitat suitability among Hamilton Harbour AOC zones is warranted; this would help identify the species and assemblages (and consequently fish community metric scores) that would be predicted to occur based on zonal habitat conditions.
- Similar habitat assessment in other parts of Lake Ontario would help characterize systemic differences.
- Gardner Costa et al. (2022) noted that increasing native species richness and abundance may best be accomplished through the restoration of wetland habitats and enhancement of habitats within the harbour. Many smaller-bodied native fishes (e.g., Cyprinids or Centrarchids) are also found within the watersheds, which suggests that if habitat conditions can be improved in the harbour, there are source populations to support recolonization (FP-1B).
- The east zone of the harbour has limited sheltered habitat and thus cannot support large populations of fishes reliant on nearshore, sheltered habitat; the creation of deeper sheltered habitat behind the islands (i.e. depths of 3-5 m) could support the recovery of warmwater fishes in this area.
- The area around Carroll’s Point was historically identified as an area that could be rehabilitated (Holmes 1988), but it is likely conditions have worsened since listing given the loss of floating and submerged vegetation at the mouth of Grindstone Creek. Bypassing waters from Grindstone Creek directly into the harbour could improve water clarity in this area and promote the recovery of aquatic vegetation.
- The north shore of the harbour was also an area identified historically that could be potentially rehabilitated. Recently, the fish assemblages along the north shore have become more similar to the poorer east zone of the harbour, however, the extent to which changes may be abiotic or biotic habitat-related (which will drive opportunities for habitat remediation) needs to be explored.
- Recent telemetry work has identified spatially restricted populations for species like Smallmouth Bass, which also have a small, localized population (Larocque et al. 2023). When opportunities for habitat creation arise within the harbour, tailoring works for such spatially limited fishes (e.g., shallow, protected areas with suitable substrate – see Larocque et al. 2024) could help to expand their range within the system. As top predators, expanding the range of Smallmouth Bass in particular, could help to balance the food web.
- Quantification of the number of different habitat types within the Hamilton Harbour AOC paired with an understanding of fish habitat and food-web associations would help to prioritize habitat types required to support the recovery of focal fish species and ultimately improve specific fish community metrics; such prioritization would help inform the design of habitat creation or remediation projects.

- Consensus-based partnerships have proven helpful in facilitating habitat creation and restoration actions in other Great Lakes AOC (e.g., Aquatic Habitat Toronto in the Toronto and Region AOC; see Piczak et al. 2022), and a similar approach could be explored for Hamilton Harbour.

2) Recommend developing a conceptual framework for stressors and limitations.

- Given the myriad of stressors and limitations to fish population recovery within the Hamilton Harbour AOC, a review of these stressors and their potential effect is required.
- Such an approach could involve the development of a conceptual framework to identify linkages among stressors and their mechanism of effect on fishes; a review of this framework could follow a multi-disciplinary Delphi approach with expert feedback to identify the most important stressors or limitations (Dey et al. 2022).
- Once identified, we can seek to characterize the following: the spatial extent of the stressor within the harbour, magnitude of its impact, fish species or life stages that are likely to be most affected, potential options for limiting or mitigating the stressors, and the magnitude of population-level consequences of the stressor.
- Such an approach would help resolve the main limitation of this assessment – the lack of an explicit link between stressors and fish population impairment.

3) Recommend spatially explicit nearshore monitoring of dissolved oxygen during the summer to determine extent of effect of upwellings into nearshore (<2 m) waters.

- Upwellings of hypoxic hypolimnetic waters have the potential to reduce habitat suitability for littoral species.
- The frequency with which these upwellings push into nearshore areas (<2 m or up to the shoreline) and also reduce habitat suitability in the entire water column (i.e., situations where moving to other regions the water column would not provide refuge) remains unclear.
- Finer-scale spatial mapping of hypoxia limitations throughout the harbour is required.
- This is a critical area of further study since it will identify areas within the harbour that have impaired habitat as a result of hypoxia and consequently may be expected to have more impaired fish populations. Potential mitigation measures (e.g., berms or barriers) can be considered in highly affected areas, or supporting large-scale hypolimnetic aeration treatments to reduce the hypoxia zone.

4) Recommend assessing recruitment potential for key native species.

- Given clear declines in catch and richness of native fishes, assessing the role of recruitment limitations is warranted.

- Considerable data are available throughout the harbour (see FP-1B) and these datasets can be explored for evidence of recruitment trends in early life stages and also to aid in the identification of potential impediments to recruitment.
- For example, recruitment by Northern Pike may be limited by water levels (see Budgell et al. in review) or water quality (see Appendix G), and exploring age classes in relation to annual changes in water levels could assess this hypothesis.
- Assess the effectiveness of barriers currently in place in the Grindstone Creek Marshes (e.g., brushes and vertical bars), specifically in relation to depth considerations and permanent connections to the stream for native species recruitment (e.g., Northern Pike); successful recruitment may be limited with young-of-year being unable to leave the system when waters become too shallow and/or warm.
- Given clear spatial zonal differences within the Hamilton Harbour AOC, an assessment of the capacity (i.e., availability and amount of suitable habitat) for these zones to support the recruitment of various species guilds would help identify zonal habitat limitations.
- Given increased catch of aquatic invasive species (e.g., Goldfish and Rudd), the potential roles of competition, niche overlap, and resource limitations between native and non-native fishes could be explored.

5) Recommend exploration of potential food web effects from introduction and ongoing stocking of Walleye*.*

- Recovery of top-predators like Walleye is essential to provide greater top-down control on overly abundant forage species (e.g., White Perch, Gizzard Shad) and thus improve the trophic structure in the Hamilton Harbour AOC.
- Walleye stocking has been successful at establishing an adult population in the harbour, although natural recruitment has not been documented.
- Recent declines in catch of both non-native and native and the richness of native fishes in the Hamilton Harbour AOC coincide with Walleye re-introduction but also other factors.
- Understanding how the food web, trophic linkages, and fate of nutrients in the Hamilton Harbour AOC may have shifted is essential to determining the effect the reintroduction of a new top-predator has on the rest of the fish community.

6) Recommend a review of sustainable levels and sources of mortality to reduce pressure on declined native and piscivorous species.

- Some base level of mortality is to be expected from most sampling gear and invasive experimental procedures.
- Harm reduction strategies may include: reducing soak time for passive gear, ensuring electrofishing power output is tailored to local habitat conditions (i.e., conductivity, substrate composition), ensuring fish are handled for a short period of time and with their welfare top of mind (i.e., wet surfaces, sufficient aeration in holding water, net mesh that reduces skin damage [knotless]), and non-lethal methods of diet analysis such as lavage methods.

- Limiting take of populations of fishes that may be marginal (e.g., top predators in general, but Northern Pike and Smallmouth Bass in particular) could help jump-start their recovery, and seeking alternatives to lethal sampling in all survey protocols is a key part of this.
- Creel surveys would help determine the potential influence of recreational angling on populations of native fishes.

7) Recommend review of how contaminants in more marginal species (e.g., top predators in general) are determined.

- To support safe consumption practices for wild-caught fishes, assessing their contaminant burden and consequently, the risk of eating wild-caught fishes is essential.
- Current practice is often to collect individuals of various sizes, especially species targeted in the recreational fishery, to measure contaminant content in muscle and other tissues (https://www.ontario.ca/page/guide-eating-ontario-fish).
- While such harvest may have limited effects for populations of abundant species, the removal of healthy and reproductively viable adults from more marginal populations could contribute to their decline.
- Adjustments to current practices for assessing contaminants as they relate to sportfish guidelines for more marginal fishes may be prudent and could include: reducing the frequency of sampling events, using non-lethal sampling (e.g., muscle biopsy), and shifting the trophic level where contaminants are assessed (e.g., contaminants in forage fishes for harbour-resident species).
- From an AIS perspective, if AIS (e.g., Common Carp, Goldfish, Rudd) have contaminant levels that are found to be low, it would support easier targeted removal since contaminant-related concerns associated with disposal would be minimized.

8) Recommend continued fish community sampling in the harbour and Lake Ontario reference areas to support future assessments and provide baseline information for Hamilton Harbour AOC conditions.

- There are clear lake-wide changes occurring in Lake Ontario, including declines in pelagic production and the introduction and expansion of AIS.
- Continued tracking of the fish community in areas throughout the lake is thus important for interpreting the changes occurring within the Hamilton Harbour AOC.
- Continue monitoring Round Goby populations in the Hamilton Harbour AOC with minnow traps to maintain the time series, as no other fish community sampling approach effectively targets this species.
- Continue monitoring fish communities adjacent to WWTP outfalls, particularly the Woodward WWTP, to explore any fish community changes following WWTP upgrades and the relocation of its primary outfall.

9) Recommend continued invasive species management within the Hamilton Harbour AOC and review of fishway barrier effectiveness.

- The primary method for AIS management in the Hamilton Harbour AOC is the exclusion of Common Carp at the Cootes Paradise Fishway and targeted carp removals; Common Carp populations have since declined with these efforts.
- Continue use and maintenance of the fishway barrier to help keep Common Carp out of Cootes Paradise; this also presents an opportunity to actively remove other AIS (e.g., Goldfish and Rudd) that have been increasing in recent years.
- Explore refinements to open/closure times of the Cootes Paradise Fishway as acoustically tagged Common Carp were detected moving into Cootes Paradise when the fishway was open in the fall for spawning salmonids; a time which Common Carp were not thought to move into wetlands. A review of species phenology at the fishway could provide guidance on timing (e.g., Piczak et al. 2023b).
- Discuss the addition of a novel fishway at Grindstone Creek to further reduce AIS populations as telemetry studies have indicated Goldfish and Rudd may be using Grindstone Creek for spawning; this would allow the removal of multiple wetland-specific barriers in the Grindstone Creek Marshes and help restore the wetland complex.
- Since multiple agencies are implementing AIS management measures can consider regional coordination to address the sources and prevalence of AIS (e.g., Common Carp, Goldfish, Rudd) in natural waterways.

10) Recommend continuing the Hamilton Harbour AOC acoustic telemetry project to enhance the understanding of seasonal fish habitat use and movements.

- Tracking fishes has yielded information on their general habitat use, seasonal depth use, and residency within the harbour (Larocque et al. 2020; Larocque et al. 2024).
- This project has also yielded information on the behaviour of Common Carp both within the harbour (Bzonek et al. in review) and throughout Lake Ontario (Piczak et al. 2023a). From these works it is clear how far Common Carp are capable of moving and how a more regional approach for their population management may be necessary.
- Our understanding of species responses to hypoxia has also been expanded using telemetry (Brooks et al. 2022; Brooks et al. in review) and this can help to quantify habitat limitations during the stratified period.
- Next steps for this project include: 1) using existing data to develop more sophisticated models (after Brownscombe et al. 2021) to assess seasonal fish habitat associations for Northern Pike, Walleye, Largemouth Bass, and White Sucker; 2) comparing spatial and depth overlap among top predators to better understand seasonal foraging competition; and 3) tracking AIS (e.g., Goldfish and Rudd) to understand their spatial ecology within the system and ultimately to determine if active or passive management measures can be used to control their populations and habitat effects.

11) Recommend a review of fish population delisting criteria to assess their achievability given continued chronic and seasonal stressors.

- In this assessment, we have recommended continued monitoring (#8), quantification of fish population stressors (#2,#4,#5,#6,#7), and an evaluation of habitat supply (#1) or habitat use (#10).
- Results from these recommendations will be informative for assessing whether current delisting criteria are achievable in a reasonable time-frame given that some sources of stress (e.g., summer hypolimnetic anoxia) and habitat limitations will likely influence fish populations for the foreseeable future.
- It would be prudent to review delisting criteria once the necessary information is available and, if deemed unachievable, determine an appropriate course of action.

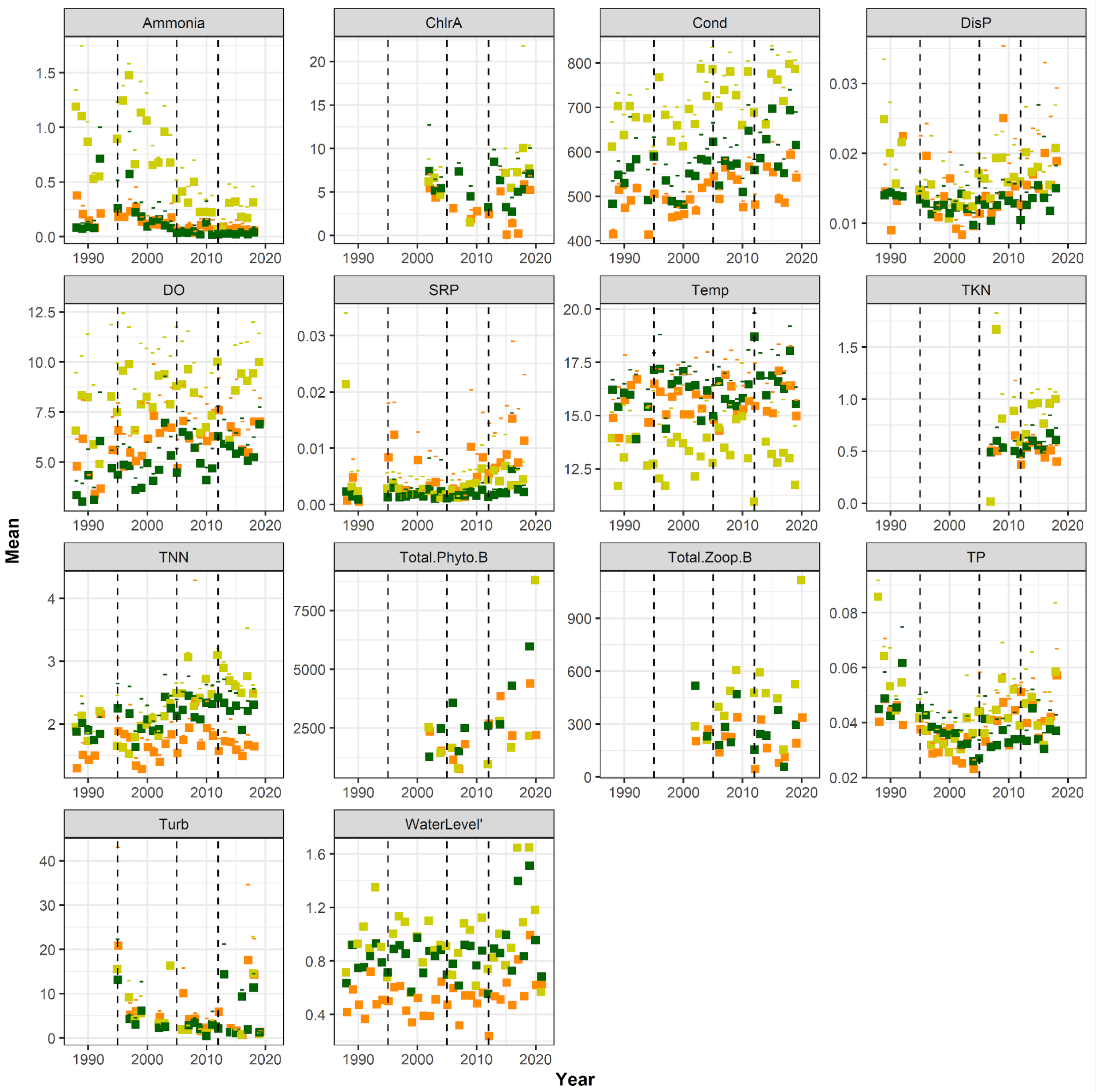

Figure 59. *Temporal trends in various environmental metrics. Data were compiled from D. Depew, unpublished data – unless specified. Values in yellow = spring, green = summer, and orange = fall; all data reflect the annual mean value at approximately 1-m depth. Ammonia = ammonia (mg/L); ChlA = Chlorophyll A (µg/L); DisP = total dissolved phosphorus (mg/L); DO = dissolved oxygen (mg/L); SRP = soluble reactive phosphorus (mg/L); Temp = temperature (°C); TKN = total Kjeldahl nitrogen (mg/L); TNN = total nitrate nitrite (mg/L); Total.Phyto.B = total phytoplankton biomass (mg/m^3; data source = M. Munawar, unpublished data); Total.Zoop.B = total zooplankton biomass (mg/m^3; data source = W. Currie, unpublished data); TP = total phosphorus (mg/L); Turb = turbidity (NTU); and WaterLevel = water levels (m, above chart datum at the Burlington water level station).*

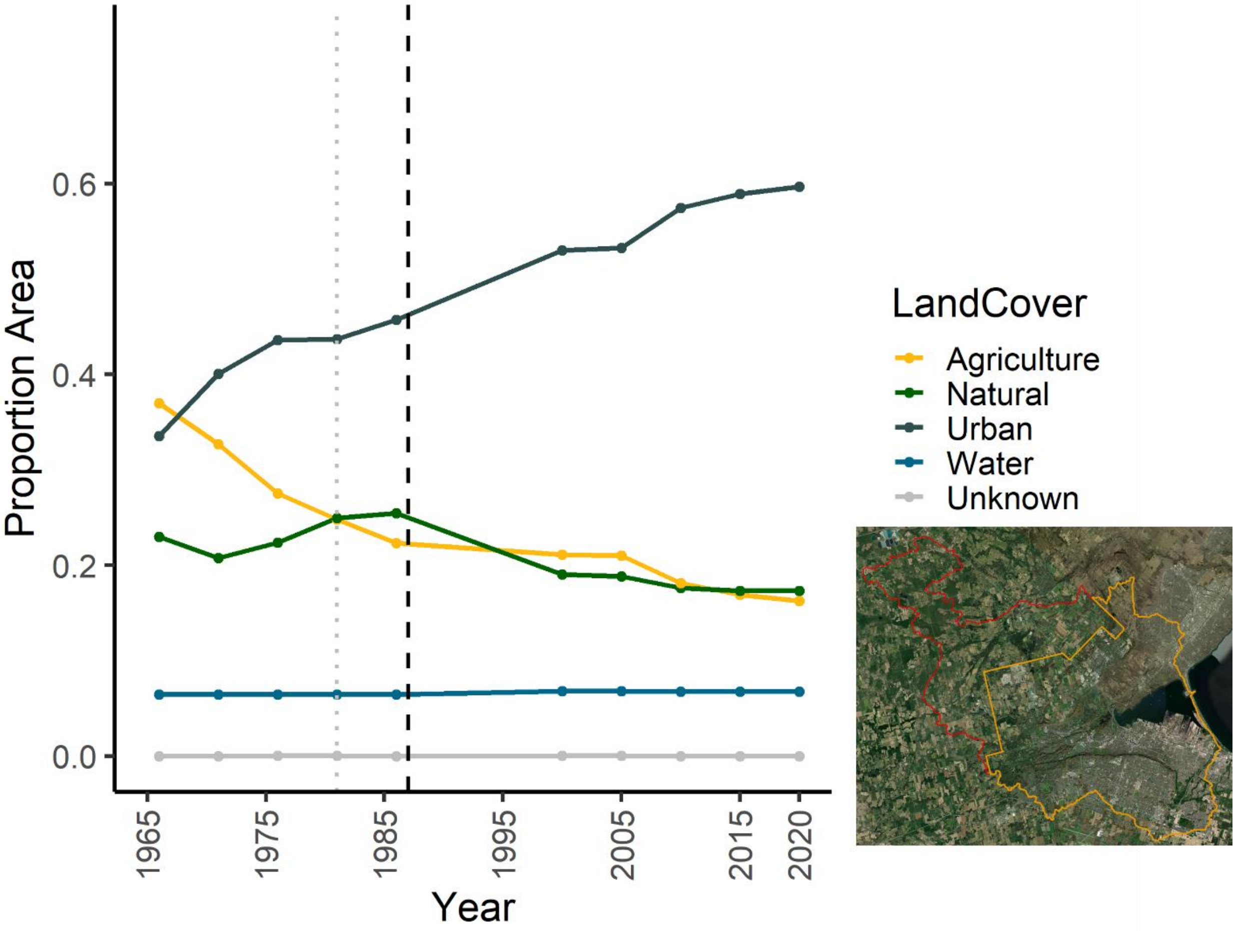

Figure 60. *Trends in general land cover types in the Hamilton Harbour watershed. Prior to 1990, land cover information was collected by the Canada Land Use Monitoring Program. This data was available solely within the boundaries of the City of Hamilton (delineated by the orange line in the inset map) and so all future land cover maps were clipped to this orange boundary instead of the entire Hamilton Harbour watershed (red line in inset map). As a result, the trends for agricultural cover are likely underestimates. After 1996, data were from the Ontario Land Cover Database. All land cover data were accessed via the Ontario GEoHub (https://geohub.lio.gov.on.ca/).*

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APPENDIX A: FISH SPECIES INFORMATION

Table A 1. *Assignments of species based on whether they are native (Yes) or non-native (No) to the Great Lakes, their tolerances to low dissolved oxygen (DO; low tolerance/sensitive = "S", meso-tolerant = "M", tolerant = "T", X = insufficient data to assess; from Tang et al. 2020), and their feeding/diet guild (from the Ontario Freshwater Fishes Life History Database website; www.ontariofishes.ca). Note that species may have different diets based on life stage.*

Family	**Scientific Name**	**Common Name**	**Native**	**DO Tolerance**	**Invertivore**	**Carnivore**	**Detritivore**	**Herbivore**	**Planktivore**
Amiidae	*Amia calva*	bowfin	Yes	M		X			
Anguillidae	*Anguilla rostrata*	american eel	Yes	M	X	X			
Atherinopsidae	*Labidesthes sicculus*	brook silverside	Yes	M	X				X
Catostomidae	*Catostomus catostomus*	longnose sucker	Yes	M	X				
Catostomidae	*Catostomus commersoni*	white sucker	Yes	T	X		X		
Catostomidae	*Hypentelium nigricans*	northern hog sucker	Yes	S	X			X	
Catostomidae	*Ictiobus cyprinellus*	bigmouth buffalo	Yes	M	X				
Catostomidae	*Moxostoma anisurum*	silver redhorse	Yes	M	X				
Catostomidae	*Moxostoma duquesnei*	black redhorse	Yes	S	X				
Catostomidae	*Moxostoma erythrurum*	golden redhorse	Yes	M	X				
Catostomidae	*Moxostoma macrolepidotum*	shorthead redhorse	Yes	M	X				
Catostomidae	*Moxostoma valenciennsi*	greater redhorse	Yes	S	X				
Centrarchidae	*Ambloplites rupestris*	rock bass	Yes	M	X	X			
Centrarchidae	*Lepomis cyanellus*	green sunfish	Yes	T	X	X			
Centrarchidae	*Lepomis gibbosus*	pumpkinseed	Yes	M	X	X			
Centrarchidae	*Lepomis macrochirus*	bluegill	Yes	T	X				
Centrarchidae	*Lepomis megalotis*	longear sunfish	Yes	X					
Centrarchidae	*Micropterus dolomieu*	smallmouth bass	Yes	M	X	X			
Centrarchidae	*Micropterus salmoides*	largemouth bass	Yes	M	X	X			
Centrarchidae	*Pomoxis annularis*	white crappie	Yes	T	X	X			
Centrarchidae	*Pomoxis nigromaculatus*	black crappie	Yes	M	X	X			
Clupeidae	*Alosa pseudoharengus*	alewife	No	M					X
Clupeidae	*Dorosoma cepedianum*	gizzard shad	Yes	T			X	X	X
Cottidae	*Cottus bairdii*	mottled sculpin	Yes	X	X				
Cyprinidae	*Carassius auratus*	goldfish	No	T	X			X	
Cyprinidae	*Chrosomus eos*	northern redbelly dace	Yes	X	X				X
Cyprinidae	*Chrosomus neogaeus*	finescale dace	Yes	M	X				X
Cyprinidae	*Clinostomus elongatus*	redside dace	Yes	S	X				
Cyprinidae	*Couesius plumbeus*	lake chub	Yes	M	X				X
Cyprinidae	*Cyprinella spiloptera*	spotfin shiner	Yes	M	X			X	
Cyprinidae	*Cyprinus carpio*	common carp	No	T	X		X		

Family	Scientific Name	Common Name	Native	DO Tolerance	Invertivore	Carnivore	Detritivore	Herbivore	Planktivore
Cyprinidae	*Hybognathus hankinsoni*	brassy minnow	Yes	M			X		X
Cyprinidae	*Luxilus chrysocephalus*	striped shiner	Yes	M	X				
Cyprinidae	*Luxilus cornutus*	common shiner	Yes	M	X				
Cyprinidae	*Margariscus nactriebi*	northern pearl dace	Yes	X	X	X			
Cyprinidae	*Nocomis biguttatus*	hornyhead chub	Yes	M	X			X	
Cyprinidae	*Nocomis micropogon*	river chub	Yes	S	X				X
Cyprinidae	*Notemigonus crysoleucas*	golden shiner	Yes	T	X			X	
Cyprinidae	*Notropis atherinoides*	emerald shiner	Yes	M					X
Cyprinidae	*Notropis heterodon*	blackchin shiner	Yes	S	X				
Cyprinidae	*Notropis heterolepis*	blacknose shiner	Yes	S	X			X	
Cyprinidae	*Notropis hudsonius*	spottail shiner	Yes	M	X				X
Cyprinidae	*Notropis photogenis*	silver shiner	Yes	S	X				X
Cyprinidae	*Notropis rubellus*	rosyface shiner	Yes	S	X		X	X	
Cyprinidae	*Notropis stramineus*	sand shiner	Yes	M	X		X		
Cyprinidae	*Notropis volucellus*	mimic shiner	Yes	M	X			X	
Cyprinidae	*Pimephales notatus*	bluntnose minnow	Yes	M			X		
Cyprinidae	*Pimephales promelas*	fathead minnow	Yes	T	X		X		
Cyprinidae	*Rhinichthys cataractae*	longnose dace	Yes	M	X				
Cyprinidae	*Rhinichthys obtusus*	western blacknose dace	Yes	X	X				
Cyprinidae	*Scardinius erythrophthalmus*	rudd	No	T	X			X	
Cyprinidae	*Semotilus atromaculatus*	creek chub	Yes	M	X	X			
Esocidae	*Esox lucius*	northern pike	Yes	M		X			
Esocidae	*Esox masquinongy*	muskellunge	Yes	M		X			
Gasterosteidae	*Culaea inconstans*	brook stickleback	Yes	M	X				X
Gasterosteidae	*Gasterosteus aculeatus*	threespine stickleback	Yes	M	X				
Gobiidae	*Neogobius melanostomus*	round goby	No	M	X				
Gobiidae	*Proterorhinus marmoratus*	tubenose goby	No	X	X				
Ictaluridae	*Ameiurus melas*	black bullhead	Yes	M	X	X			
Ictaluridae	*Ameiurus nebulosus*	brown bullhead	Yes	T	X	X		X	
Ictaluridae	*Ictalurus punctatus*	channel catfish	Yes	M	X	X			
Ictaluridae	*Noturus flavus*	stonecat	Yes	X	X	X			
Ictaluridae	*Noturus gyrinus*	tadpole madtom	Yes	M	X				X
Lepisosteidae	*Lepisosteus oculatus*	spotted gar	Yes	M		X			
Lepisosteidae	*Lepisosteus osseus*	longnose gar	Yes	T		X			
Moronidae	*Morone americana*	white perch	No	M	X	X			
Moronidae	*Morone chrysops*	white bass	Yes	T	X	X			
Osmeridae	*Osmerus mordax*	rainbow smelt	No	M	X	X			
Percidae	*Etheostoma caeruleum*	rainbow darter	Yes	S	X				
Percidae	*Etheostoma exile*	iowa darter	Yes	M	X				
Percidae	*Etheostoma flabellare*	fantail darter	Yes	S	X				

Family	Scientific Name	Common Name	Native	DO Tolerance	Invertivore	Carnivore	Detritivore	Herbivore	Planktivore
Percidae	*Etheostoma nigrum*	johnny darter	Yes	T	X				
Percidae	*Perca flavescens*	yellow perch	Yes	M	X	X			
Percidae	*Percina caprodes*	logperch	Yes	S	X				
Percidae	*Percina maculata*	blackside darter	Yes	M	X				
Percidae	*Percina shumardi*	river darter	Yes	M	X				
Percidae	*Sander vitreus*	walleye	Yes	M	X	X			
Percopsidae	*Percopsis omiscomaycus*	trout-perch	Yes	M	X	X			
Petromyzontidae	*Ichthyomyzon fossor*	northern brook lamprey	Yes	S				X	
Petromyzontidae	*Ichthyomyzon unicuspis*	silver lamprey	Yes	M		X		X	
Petromyzontidae	*Lethenteron appendix*	american brook lamprey	Yes	S				X	
Petromyzontidae	*Petromyzon marinus*	sea lamprey	No	M		X	X	X	
Salmonidae	*Coregonus artedi*	cisco	Yes	S	X				X
Salmonidae	*Oncorhynchus kisutch*	coho salmon	No	M	X	X			
Salmonidae	*Oncorhynchus mykiss*	rainbow trout	No	M	X	X			
Salmonidae	*Oncorhynchus tshawytscha*	chinook salmon	No	M	X	X			
Salmonidae	*Salmo salar*	Atlantic salmon	Yes	M	X	X			
Salmonidae	*Salmo trutta*	brown trout	No	M	X	X			
Salmonidae	*Salvelinus fontinalis*	brook trout	Yes	S	X	X			
Salmonidae	*Salvelinus namaycush*	lake trout	Yes	M	X	X			
Sciaenidae	*Aplodinotus grunniens*	freshwater drum	Yes	T	X	X			
Umbridae	*Umbra limi*	central mudminnow	Yes	X	X				

APPENDIX B: DETAILED MODEL OUTPUT FOR SECTION FP-1A

Temporal trend in species specific catch and catchability were evaluated using zero-inflated generalized linear mixed model (hurdle model) with Time Stanza and Location (Hamilton-Overall [HH], Hamilton-zones [West, North, East], Bay of Quinte [Ref.E], Frenchman Bay and Jordan Harbour [Ref.W]) as fixed effects and transect and sampling time period (day or night) included as random effects. When fixed effects were significant, least square means were used to examine pairwise differences between Time Stanza, Location, or their interaction. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. These works are presented in more detail in Turner et al. (in review).

Table B 1. *Results from the post-hoc assessment of differences in species catch among the Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] reference areas based on least-square means. For each combination of Stanza and Zone estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2 (overall W).*

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
Non-Natives								
Alewife	Overall	P1: pre 1994	HH	34.88	6.71	20.64	58.93	d
	Overall	P1: pre 1994	Ref.E	6.41	1.94	2.795	14.68	ab
	Overall	P2: 1995-2005	HH	21.76	4.08	13.040	36.32	cd
	Overall	P2: 1995-2005	Ref.E	3.49	1.09	1.482	8.23	ab
	Overall	P3: 2006-2012	HH	6.29	1.45	3.345	11.84	ab
	Overall	P3: 2006-2012	Ref.E	8.94	2.82	3.785	21.13	bc
	Overall	P3: 2006-2012	Ref.W	6.84	1.986	3.06	15.31	ab
	Overall	P4: 2013-2021	HH	3.86	0.92	2.014	7.39	ab
	Overall	P4: 2013-2021	Ref.E	1.39	0.71	0.342	5.65	a
	Overall	P4: 2013-2021	Ref.W	12.00	4.860	3.86	37.29	bcd
	Zonal	P1: pre 1994	East	24.08	5.94	11.637	49.83	efg
	Zonal	P1: pre 1994	North	37.80	10.8	16.206	88.15	g
	Zonal	P1: pre 1994	Ref.E	6.54	1.89	2.795	15.33	ab
	Zonal	P1: pre 1994	West	47.03	12.1	22.094	100.10	g
	Zonal	P2: 1995-2005	East	21.10	5.11	10.336	43.09	bcdefg
	Zonal	P2: 1995-2005	North	23.14	5.93	10.865	49.26	cdefg
	Zonal	P2: 1995-2005	Ref.E	3.60	1.07	1.491	8.68	a
	Zonal	P2: 1995-2005	West	21.90	4.74	11.574	41.46	dfg
	Zonal	P3: 2006-2012	East	7.67	2.88	2.539	23.16	abcdef
	Zonal	P3: 2006-2012	North	3.81	1.41	1.282	11.35	a
	Zonal	P3: 2006-2012	Ref.E	9.49	2.87	3.892	23.15	abcdef
	Zonal	P3: 2006-2012	West	7.72	2.09	3.475	17.13	abce

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P3: 2006-2012	Ref.W	7.09	1.933	3.139	15.99	abce
	Zonal	P4: 2013-2021	East	4.45	1.99	1.192	16.58	abcd
	Zonal	P4: 2013-2021	North	3.72	1.58	1.063	13.05	a
	Zonal	P4: 2013-2021	Ref.E	1.47	0.74	0.333	6.48	a
	Zonal	P4: 2013-2021	West	4.03	1.058	1.844	8.82	a
	Zonal	P4: 2013-2021	Ref.W	11.44	4.501	3.581	37.01	abcdefg
Common Carp	Overall	P1: pre 1994	HH	3.288	0.34	2.462	4.39	c
	Overall	P1: pre 1994	Ref.E	1.630	0.33	0.938	2.83	ab
	Overall	P2: 1995-2005	HH	2.946	0.26	2.314	3.75	bc
	Overall	P2: 1995-2005	Ref.E	0.929	0.36	0.323	2.68	ab
	Overall	P3: 2006-2012	HH	2.450	0.26	1.823	3.29	bc
	Overall	P3: 2006-2012	Ref.E	1.043	0.19	0.624	1.74	a
	Overall	P3: 2006-2012	Ref.W	2.432	0.558	1.279	4.62	abc
	Overall	P4: 2013-2021	HH	1.580	0.15	1.212	2.06	a
	Overall	P4: 2013-2021	Ref.E	1.221	0.23	0.728	2.05	a
	Overall	P4: 2013-2021	Ref.W	2.114	0.411	1.227	3.64	abc
	Zonal	P1: pre 1994	East	2.825	0.46	1.737	4.60	cde
	Zonal	P1: pre 1994	North	3.309	0.50	2.115	5.18	de
	Zonal	P1: pre 1994	Ref.E	1.614	0.31	0.908	2.87	abcd
	Zonal	P1: pre 1994	West	3.667	0.55	2.351	5.72	de
	Zonal	P2: 1995-2005	East	2.054	0.26	1.407	3.00	abcd
	Zonal	P2: 1995-2005	North	3.025	0.38	2.074	4.41	de
	Zonal	P2: 1995-2005	Ref.E	0.932	0.353	0.305	2.84	abcde
	Zonal	P2: 1995-2005	West	3.486	0.359	2.572	4.72	e
	Zonal	P3: 2006-2012	East	2.436	0.326	1.642	3.61	bcde
	Zonal	P3: 2006-2012	North	1.637	0.485	0.683	3.92	abcde
	Zonal	P3: 2006-2012	Ref.E	1.026	0.187	0.600	1.75	a
	Zonal	P3: 2006-2012	West	2.611	0.375	1.711	3.99	cde

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P3: 2006-2012	Ref.W	2.417	0.536	1.248	4.68	abcde
	Zonal	P4: 2013-2021	East	1.653	0.183	1.192	2.29	abc
	Zonal	P4: 2013-2021	North	1.520	0.413	0.683	3.38	abcde
	Zonal	P4: 2013-2021	Ref.E	1.199	0.220	0.698	2.06	ab
	Zonal	P4: 2013-2021	West	1.439	0.190	0.976	2.12	abc
	Zonal	P4: 2013-2021	Ref.W	2.119	0.398	1.210	3.71	abcde
White Perch	Overall	P1: pre 1994	HH	4.97	1.364	2.350	10.50	b
	Overall	P1: pre 1994	Ref.E	4.25	1.483	1.641	11.01	ab
	Overall	P2: 1995-2005	HH	3.97	1.040	1.947	8.11	b
	Overall	P2: 1995-2005	Ref.E	2.04	0.947	0.574	7.23	ab
	Overall	P3: 2006-2012	HH	3.35	0.918	1.584	7.07	ab
	Overall	P3: 2006-2012	Ref.E	1.87	0.607	0.774	4.53	a
	Overall	P4: 2013-2021	HH	2.31	0.627	1.103	4.84	a
	Overall	P4: 2013-2021	Ref.E	12.56	4.098	5.162	30.58	c
	Zonal	P1: pre 1994	East	4.76	1.468	1.920	11.81	abcd
	Zonal	P1: pre 1994	North	5.29	1.857	1.880	14.89	abcd
	Zonal	P1: pre 1994	Ref.E	4.39	1.452	1.658	11.64	abcd
	Zonal	P1: pre 1994	West	5.06	1.548	2.052	12.46	bcd
	Zonal	P2: 1995-2005	East	5.23	1.443	2.319	11.80	cd
	Zonal	P2: 1995-2005	North	3.86	1.106	1.660	8.98	abc
	Zonal	P2: 1995-2005	Ref.E	2.14	0.958	0.569	8.01	abc
	Zonal	P2: 1995-2005	West	3.32	0.897	1.495	7.36	abc
	Zonal	P3: 2006-2012	East	3.74	1.167	1.487	9.38	abc
	Zonal	P3: 2006-2012	North	4.56	1.398	1.845	11.26	abc
	Zonal	P3: 2006-2012	Ref.E	1.95	0.594	0.792	4.79	a
	Zonal	P3: 2006-2012	West	1.89	0.600	0.744	4.82	ab
	Zonal	P4: 2013-2021	East	2.35	0.724	0.947	5.83	abc
	Zonal	P4: 2013-2021	North	2.36	0.821	0.847	6.58	abc

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	Ref.E	13.10	4.033	5.282	32.47	d
	Zonal	P4: 2013-2021	West	2.30	0.642	1.010	5.24	abc
Natives								
Brown Bullhead	Overall	P1: pre 1994	HH	9.96	1.416	6.76	14.68	e
	Overall	P1: pre 1994	Ref.E	2.67	0.466	1.66	4.30	abcd
	Overall	P2: 1995-2005	HH	5.02	0.524	3.77	6.67	d
	Overall	P2: 1995-2005	Ref.E	2.60	0.316	1.87	3.62	abc
	Overall	P3: 2006-2012	HH	3.58	0.421	2.60	4.93	bcd
	Overall	P3: 2006-2012	Ref.E	2.49	0.303	1.78	3.46	abc
	Overall	P3: 2006-2012	Ref.W	3.12	0.683	1.69	5.76	abcd
	Overall	P4: 2013-2021	HH	2.40	0.282	1.74	3.31	a
	Overall	P4: 2013-2021	Ref.E	1.92	0.319	1.22	3.02	ab
	Overall	P4: 2013-2021	Ref.W	5.91	1.480	2.93	11.92	cde
	Zonal	P1: pre 1994	East	7.38	2.130	3.155	17.28	cdefgh
	Zonal	P1: pre 1994	North	14.44	2.943	7.919	26.33	h
	Zonal	P1: pre 1994	Ref.E	2.66	0.436	1.644	4.32	abcd
	Zonal	P1: pre 1994	West	8.88	1.817	4.859	16.23	gh
	Zonal	P2: 1995-2005	East	2.18	0.456	1.181	4.04	ab
	Zonal	P2: 1995-2005	North	7.17	1.173	4.429	11.61	fgh
	Zonal	P2: 1995-2005	Ref.E	2.69	0.303	1.933	3.75	Abc
	Zonal	P2: 1995-2005	West	5.79	0.702	4.053	8.28	efg
	Zonal	P3: 2006-2012	East	1.25	0.321	0.584	2.66	a
	Zonal	P3: 2006-2012	North	3.26	0.612	1.87	5.67	abcde
	Zonal	P3: 2006-2012	Ref.E	2.51	0.280	1.804	3.48	ab
	Zonal	P3: 2006-2012	West	5.45	0.754	3.622	8.19	cde
	Zonal	P3: 2006-2012	Ref.W	3.18	0.649	1.731	5.85	abcdef
	Zonal	P4: 2013-2021	East	1.33	0.334	0.634	2.78	a
	Zonal	P4: 2013-2021	North	2.48	0.451	1.453	4.24	abcd

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	Ref.E	1.94	0.306	1.216	3.08	a
	Zonal	P4: 2013-2021	West	3.35	0.476	2.206	5.10	abcd
	Zonal	P4: 2013-2021	Ref.W	5.98	1.411	2.955	12.09	bcdefgh
Gizzard Shad	Overall	P1: pre 1994	HH	1.29	0.312	0.665	2.49	a
	Overall	P1: pre 1994	Ref.E	7.77	3.620	2.183	27.68	cd
	Overall	P2: 1995-2005	HH	3.21	0.734	1.723	5.99	bcd
	Overall	P2: 1995-2005	Ref.E	3.29	1.094	1.331	8.15	abcd
	Overall	P3: 2006-2012	HH	2.35	0.487	1.332	4.13	abc
	Overall	P3: 2006-2012	Ref.E	1.91	1.120	0.385	9.46	abcd
	Overall	P3: 2006-2012	Ref.W	2.35	0.881	0.882	6.71	abcd
	Overall	P4: 2013-2021	HH	4.66	0.830	2.865	7.57	d
	Overall	P4: 2013-2021	Ref.E	1.14	0.389	0.446	2.89	ab
	Overall	P4: 2013-2021	Ref.W	6.91	2.256	2.757	17.30	d
	Zonal	P1: pre 1994	East	1.44	0.575	0.446	4.67	abcde
	Zonal	P1: pre 1994	North	1.07	0.458	0.303	3.78	abcd
	Zonal	P1: pre 1994	Ref.E	8.30	3.815	2.139	32.18	cdef
	Zonal	P1: pre 1994	West	1.42	0.437	0.574	3.52	abcd
	Zonal	P2: 1995-2005	East	1.88	0.606	0.730	4.86	abcde
	Zonal	P2: 1995-2005	North	1.88	0.684	0.642	5.50	abcdef
	Zonal	P2: 1995-2005	Ref.E	3.56	1.166	1.359	9.35	abcdef
	Zonal	P2: 1995-2005	West	5.99	1.798	2.475	14.51	ef
	Zonal	P3: 2006-2012	East	1.48	0.441	0.617	3.57	ac
	Zonal	P3: 2006-2012	North	3.73	1.332	1.302	10.69	abcdef
	Zonal	P3: 2006-2012	Ref.E	2.01	1.109	0.396	10.22	abcdef
	Zonal	P3: 2006-2012	West	2.60	0.656	1.239	5.47	abcde
	Zonal	P3: 2006-2012	Ref.W	2.42	0.869	0.827	7.06	abcdef
	Zonal	P4: 2013-2021	East	3.70	0.880	1.835	7.46	bdef
	Zonal	P4: 2013-2021	North	2.95	0.810	1.316	6.63	abcdef

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	Ref.E	1.12	0.364	0.430	2.92	ab
	Zonal	P4: 2013-2021	West	6.55	1.361	3.547	12.08	f
	Zonal	P4: 2013-2021	Ref.W	7.03	2.225	2.733	18.08	ef
Native Minnows	Overall	P1: pre 1994	HH	4.38	0.721	2.79	6.86	abc
	Overall	P1: pre 1994	Ref.E	3.90	0.763	2.29	6.65	abc
	Overall	P2: 1995-2005	HH	7.04	0.999	4.78	10.36	c
	Overall	P2: 1995-2005	Ref.E	6.57	1.014	4.31	10.01	bc
	Overall	P3: 2006-2012	HH	4.38	0.638	2.95	6.52	ab
	Overall	P3: 2006-2012	Ref.E	6.93	0.945	4.77	10.05	bc
	Overall	P3: 2006-2012	Ref.W	20.72	5.804	9.46	45.39	d
	Overall	P4: 2013-2021	HH	4.74	0.756	3.07	7.32	bc
	Overall	P4: 2013-2021	Ref.E	2.31	0.371	1.49	3.58	a
	Overall	P4: 2013-2021	Ref.W	1.94	0.850	0.572	6.61	abc
	Zonal	P1: pre 1994	East	3.34	0.838	1.59	7.00	ab
	Zonal	P1: pre 1994	North	7.00	2.04	2.97	16.53	abcde
	Zonal	P1: pre 1994	Ref.E	3.59	0..67	2.07	6.22	ab
	Zonal	P1: pre 1994	West	4.94	1.281	2.30	10.61	abcd
	Zonal	P2: 1995-2005	East	12.04	3.069	5.68	25.52	bcde
	Zonal	P2: 1995-2005	North	6.00	1.194	3.33	10.79	abcd
	Zonal	P2: 1995-2005	Ref.E	5.60	0.835	3.61	8.69	bcd
	Zonal	P2: 1995-2005	West	6.00	1.194	3.33	10.79	abcd
	Zonal	P3: 2006-2012	East	4.90	1.140	2.47	9.73	abcd
	Zonal	P3: 2006-2012	North	4.82	1.188	2.33	9.97	abc
	Zonal	P3: 2006-2012	Ref.E	4.77	0.685	3.12	7.29	abcd
	Zonal	P3: 2006-2012	West	3.67	0.815	1.9	7.06	abc
	Zonal	P3: 2006-2012	Ref,W	20.85	5.477	9.13	45.45	e
	Zonal	P4: 2013-2021	East	2.91	0.801	1.29	6.55	ab
	Zonal	P4: 2013-2021	North	2.37	0.708	0.98	5.72	ab

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	Ref.E	2.28	0.381	1.39	3.73	a
	Zonal	P4: 2013-2021	West	11.07	2.435	5.79	21.17	de
	Zonal	P4: 2013-2021	Ref.W	1.95	0.824	0.555	6.88	ab
Spottail Shiner	Zonal HH	P1: pre 1994	East	1.82	0.582	0.727	4.54	a
	Zonal HH	P1: pre 1994	North	3.49	1.168	1.341	9.08	ab
	Zonal HH	P1: pre 1994	West	4.06	1.561	1.353	12.19	ab
	Zonal HH	P2: 1995-2005	East	2.94	0.796	0.345	6.37	ab
	Zonal HH	P2: 1995-2005	North	8.41	2.335	3.805	18.60	b
	Zonal HH	P2: 1995-2005	West	2.75	0.612	1.455	5.19	a
	Zonal HH	P3: 2006-2012	East	2.40	0.716	1.026	5.63	ab
	Zonal HH	P3: 2006-2012	North	3.77	1.073	1.670	8.50	ab
	Zonal HH	P3: 2006-2012	West	1.91	0.591	0.787	4.63	a
	Zonal HH	P4: 2013-2021	East	3.97	1.218	1.313	9.48	sb
	Zonal HH	P4: 2013-2021	North	2.61	0.881	0.996	6.85	a
	Zonal HH	P4: 2013-2021	West	1.80	0.557	0.745	4.36	a
	HH	P1: pre 1994	HH	2.82	0.710	1.51	5.28	a
	HH	P2: 1995-2005	HH	3.93	0.793	2.38	6.50	a
	HH	P3: 2006-2012	HH	2.68	0.619	1.32	4.60	a
	HH	P4: 2013-2021	HH	2.47	0.617	1.32	4.60	a
Emerald Shiner	Zonal HH	P1: pre 1994	East	2.69	0.695	1.289	5.63	a
	Zonal HH	P1: pre 1994	North	6.94	2.22	2.783	17.33	abc
	Zonal HH	P1: pre 1994	West	4.10	1.172	1.813	9.28	ab
	Zonal HH	P2: 1995-2005	East	7.42	1.864	3.616	15.21	abc
	Zonal HH	P2: 1995-2005	North	9.43	2.722	4.123	21.51	bc
	Zonal HH	P2: 1995-2005	West	7.27	1.635	3.826	13.83	abc
	Zonal HH	P3: 2006-2012	East	7.69	1.195	2.267	9.72	abc
	Zonal HH	P3: 2006-2012	North	3.46	0.942	1.588	7.54	ab

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal HH	P3: 2006-2012	West	3.12	0.730	7.596	6.09	ab
	Zonal HH	P4: 2013-2021	East	2.32	0.752	0.918	5.86	a
	Zonal HH	P4: 2013-2021	North	1.77	0.689	0.585	5.38	a
	Zonal HH	P4: 2013-2021	West	13.29	3.340	6.479	27.26	c
	HH	P1: pre 1994	HH	4.33	0.812	2.72	6.91	ab
	HH	P2: 1995-2005	HH	8.17	1.390	5.35	12.48	c
	HH	P3: 2006-2012	HH	3.9	0.697	2.5	6.09	a
	HH	P4: 2013-2021	HH	7.37	1.486	4.46	12.18	bc
Native Sunfishes	Overall	P1: pre 1994	HH	3.27	0.742	1.76	6.07	bc
	Overall	P1: pre 1994	Ref.E	3.92	0.776	2.28	6.73	B
	Overall	P2: 1995-2005	HH	6.83	1.31	4.051	11.52	de
	Overall	P2: 1995-2005	Ref.E	12.93	2.297	7.964	20.99	e
	Overall	P3: 2006-2012	HH	2.25	0.462	1.281	3.94	ab
	Overall	P3: 2006-2012	Ref.E	9.63	1.789	5.802	15.98	cd
	Overall	P3: 2006-2012	Ref.W	2.16	0.595	1.003	4.67	abc
	Overall	P4: 2013-2021	HH	1.51	0.328	0.837	2.73	a
	Overall	P4: 2013-2021	Ref.E	8.33	1.572	4.979	13.93	cde
	Overall	P4: 2013-2021	Ref.W	1.30	0.359	0.601	2.81	ab
	Zonal	P1: pre 1994	East	1.44	0.544	0.469	4.39	abcd
	Zonal	P1: pre 1994	North	3.57	1.185	1.341	9.50	bcdef
	Zonal	P1: pre 1994	Ref.E	3.95	0.726	2.295	6.79	abc
	Zonal	P1: pre 1994	West	4.23	1.11	1.94	9.18	abcd
	Zonal	P2: 1995-2005	East	4.81	1.120	2.42	9.56	cde
	Zonal	P2: 1995-2005	North	2.74	0.746	1.228	6.11	abcd
	Zonal	P2: 1995-2005	Ref.E	13.10	2.133	8.11	21.17	ef
	Zonal	P2: 1995-2005	West	12.96	2.684	7.039	23.87	f
	Zonal	P3: 2006-2012	East	1.57	0.479	0.640	3.86	ab
	Zonal	P3: 2006-2012	North	1.51	0.452	0.628	3.65	a

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P3: 2006-2012	Ref.E	9.96	1.701	6.016	16.47	d
	Zonal	P3: 2006-2012	West	3.91	0.897	1.99	7.69	abc
	Zonal	P3: 2006-2012	Ref.W	2.20	0.572	1.014	4.78	abcd
	Zonal	P4: 2013-2021	East	1.16	0.441	0.380	3.55	abcd
	Zonal	P4: 2013-2021	North	1.15	0.506	0.313	4.21	abcd
	Zonal	P4: 2013-2021	Ref.E	8.81	1.551	5.245	14.81	de
	Zonal	P4: 2013-2021	West	2.50	0.569	1.274	4.86	abc
	Zonal	P4: 2013-2021	Ref.W	1.29	0.339	0.588	2.83	ab
Pumpkinseed	Overall	P1: pre 1994	HH	3.267	0.721	1.790	5.96	b
	Overall	P1: pre 1994	Ref.E	3.256	0.633	1.934	5.48	b
	Overall	P2: 1995-2005	HH	7.272	1.300	4.467	11.84	cd
	Overall	P2: 1995-2005	Ref.E	8.141	1.303	5.263	12.59	d
	Overall	P3: 2006-2012	HH	1.471	0.327	0.803	2.70	a
	Overall	P3: 2006-2012	Ref.E	4.159	0.716	2.601	6.65	bc
	Overall	P3: 2006-2012	Ref.W	1.930	0.601	0.808	4.61	ab
	Overall	P4: 2013-2021	HH	0.934	0.257	0.442	1.98	a
	Overall	P4: 2013-2021	Ref.E	3.657	0.709	2.155	6.21	b
	Overall	P4: 2013-2021	Ref.W	1.326	0.483	0.479	3.67	ab
Bluegill	Overall	P1: pre 1994	HH	1.04	0.593	0.220	4.92	a
	Overall	P1: pre 1994	Ref.E	1.20	0.703	0.240	5.94	ab
	Overall	P2: 1995-2005	HH	2.04	0.503	1.039	4.00	a
	Overall	P2: 1995-2005	Ref.E	5.73	1.166	3.292	9.98	b
	Overall	P3: 2006-2012	HH	2.09	0.515	1.070	4.09	a
	Overall	P3: 2006-2012	Ref.E	5.65	1.166	3.216	9.92	b
	Overall	P4: 2013-2021	HH	1.76	0.451	0.874	3.54	a
	Overall	P4: 2013-2021	Ref.E	5.78	1.205	3.270	10.21	b
White Sucker	Overall	P1: pre 1994	HH	1.70	0.219	1.198	2.42	b

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Overall	P1: pre 1994	Ref.E	1.74	0.255	1.167	2.59	ab
	Overall	P2: 1995-2005	HH	1.49	0.143	1.147	1.94	ab
	Overall	P2: 1995-2005	Ref.E	1.16	0.285	0.592	2.27	ab
	Overall	P3: 2006-2012	HH	1.68	0.192	1.228	2.29	ab
	Overall	P3: 2006-2012	Ref.E	1.57	0.246	1.022	2.41	ab
	Overall	P3: 2006-2012	Ref.W	1.09	0.195	0.659	1.80	a
	Overall	P4: 2013-2021	HH	1.01	0.148	0.676	1.51	a
	Overall	P4: 2013-2021	Ref.E	1.09	0.239	0.592	2.02	a
	Overall	P4: 2013-2021	Ref.W	1.55	0.414	0.731	3.27	a
	Zonal	P1: pre 1994	East	2.188	0.356	1.355	3.53	b
	Zonal	P1: pre 1994	North	1.377	0.254	0.800	2.37	ab
	Zonal	P1: pre 1994	Ref.E	1.794	0.248	1.194	2.70	ab
	Zonal	P1: pre 1994	West	1.144	0.338	0.479	2.73	ab
	Zonal	P2: 1995-2005	East	1.748	0.277	1.095	2.79	ab
	Zonal	P2: 1995-2005	North	1.189	0.176	0.769	1.84	ab
	Zonal	P2: 1995-2005	Ref.E	1.131	0.258	0.577	2.22	ab
	Zonal	P2: 1995-2005	West	1.631	0.220	1.096	2.43	ab
	Zonal	P3: 2006-2012	East	1.355	0.261	0.768	2.39	ab
	Zonal	P3: 2006-2012	North	2.402	0.399	1.473	3.92	b
	Zonal	P3: 2006-2012	Ref.E	1.590	0.230	1.037	2.44	ab
	Zonal	P3: 2006-2012	West	1.096	0.197	0.645	1.86	ab
	Zonal	P3: 2006-2012	Ref.W	1.101	0.183	0.670	1.81	ab
	Zonal	P4: 2013-2021	East	1.437	0.348	0.704	2.94	ab
	Zonal	P4: 2013-2021	North	0.782	0.231	0.327	1.87	ab
	Zonal	P4: 2013-2021	West	1.091	0.227	0.591	2.01	a
	Zonal	P4: 2013-2021	Ref.E	0.933	0.151	0.579	1.51	ab
	Zonal	P4: 2013-2021	Ref.W	1.539	0.381	0.735	3.22	ab
Yellow Perch	Overall	P1: pre 1994	HH	1.67	0.506	0.733	3.82	ab

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Overall	P1: pre 1994	Ref.E	14.43	3.204	7.878	26.44	d
	Overall	P2: 1995-2005	HH	3.16	0.703	1.726	5.80	ab
	Overall	P2: 1995-2005	Ref.E	13.82	2.822	7.915	24.11	d
	Overall	P3: 2006-2012	HH	3.09	0.678	1.698	5.62	bc
	Overall	P3: 2006-2012	Ref.E	12.12	2.481	6.835	21.50	d
	Overall	P3: 2006-2012	Ref.W	3.19	1.118	1.194	8.51	abc
	Overall	P4: 2013-2021	HH	1.47	0.351	0.765	2.82	a
	Overall	P4: 2013-2021	Ref.E	5.51	1.131	3.145	9.64	c
	Overall	P4: 2013-2021	Ref.W	3.74	1.333	1.377	10.15	abc
	Zonal	P1: pre 1994	East	4.769	3.442	0.568	40.04	abcdef
	Zonal	P1: pre 1994	North	1.340	0.563	0.389	4.62	abc
	Zonal	P1: pre 1994	Ref.E	14.318	3.245	7.341	27.93	f
	Zonal	P1: pre 1994	West	1.297	0.561	0.363	4.64	abcd
	Zonal	P2: 1995-2005	East	1.402	0.521	0.469	4.19	abc
	Zonal	P2: 1995-2005	North	2.392	0.847	0.843	6.79	abcd
	Zonal	P2: 1995-2005	Ref.E	1.402	0.521	0.469	4.19	f
	Zonal	P2: 1995-2005	West	4.303	1.171	1.929	9.59	cd
	Zonal	P3: 2006-2012	East	3.064	0.977	1.197	7.84	bcd
	Zonal	P3: 2006-2012	North	3.073	1.007	1.170	8.07	abcd
	Zonal	P3: 2006-2012	Ref.E	11.686	2.538	6.162	22.16	ef
	Zonal	P3: 2006-2012	West	3.011	0.892	1.258	7.21	abcd
	Zonal	P3: 2006-2012	Ref.W	3.150	1.106	1.107	8.98	abcd
	Zonal	P4: 2013-2021	East	0.863	0.350	0.261	2.85	a
	Zonal	P4: 2013-2021	North	1.749	0.695	0.542	5.64	abcd
	Zonal	P4: 2013-2021	Ref.E	5.461	1.150	2.935	10.16	d
	Zonal	P4: 2013-2021	West	1.679	0.503	0.694	4.06	ab
	Zonal	P4: 2013-2021	Ref.W	3.765	1.343	1.299	10.91	abcde
Piscivore								

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
Largemouth Bass	Overall	P1: pre 1994	HH	1.22	0.262	0.684	2.19	a
	Overall	P1: pre 1994	Ref.E	2.66	0.629	1.397	5.07	abcdef
	Overall	P2: 1995-2005	HH	4.43	0.506	3.246	6.05	df
	Overall	P2: 1995-2005	Ref.E	2.76	0.297	2.057	3.70	bcd
	Overall	P3: 2006-2012	HH	2.90	0.351	2.087	4.04	ce
	Overall	P3: 2006-2012	Ref.E	4.41	0.469	3.300	5.89	ef
	Overall	P3: 2006-2012	Ref.W	2.20	0.936	0.671	7.24	abcdef
	Overall	P4: 2013-2021	HH	1.84	0.243	1.284	2.64	ab
	Overall	P4: 2013-2021	Ref.E	2.82	0.332	2.047	3.89	bcd
	Overall	P4: 2013-2021	Ref.W	2.03	0.601	0.885	4.65	abcdef
	Zonal	P1: pre 1994	East	1.199	0.916	0.126	11.42	abcd
	Zonal	P1: pre 1994	North	1.551	0.511	0.587	4.10	abc
	Zonal	P1: pre 1994	Ref.E	2.653	0.613	1.343	5.24	abcd
	Zonal	P1: pre 1994	West	0.961	0.270	0.420	2.20	a
	Zonal	P2: 1995-2005	East	1.570	0.421	0.712	3.46	ab
	Zonal	P2: 1995-2005	North	3.366	0.734	1.770	6.40	bcd
	Zonal	P2: 1995-2005	Ref.E	2.762	0.293	2.020	3.78	b
	Zonal	P2: 1995-2005	West	5.787	0.790	3.870	8.65	d
	Zonal	P3: 2006-2012	East	3.420	0.799	1.717	6.81	bcd
	Zonal	P3: 2006-2012	North	1.689	0.520	0.681	4.19	abc
	Zonal	P3: 2006-2012	Ref.E	4.411	0.461	3.241	6.00	cd
	Zonal	P3: 2006-2012	Ref.W	2.243	0.925	0.655	7.68	Abcd
	Zonal	P3: 2006-2012	West	3.253	0.472	2.120	4.99	bc
	Zonal	P4: 2013-2021	East	1.224	0.416	0.450	3.33	ab
	Zonal	P4: 2013-2021	North	0.836	0.331	0.260	2.69	ab
	Zonal	P4: 2013-2021	Ref.E	2.812	0.326	1.997	3.96	bc
	Zonal	P4: 2013-2021	Ref.W	2.048	0.589	0.868	4.83	abcd
	Zonal	P4: 2013-2021	West	2.266	0.330	1.474	3.48	a

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
Northern Pike	Overall	P1: pre 1994	HH	1.086	0.229	0.611	1.93	a
	Overall	P1: pre 1994	Ref.E	1.443	0.134	1.120	1.86	a
	Overall	P2: 1995-2005	HH	1.054	0.132	0.748	1.48	a
	Overall	P2: 1995-2005	Ref.E	1.341	0.117	1.057	1.70	a
	Overall	P3: 2006-2012	HH	1.071	0.138	0.754	1.52	a
	Overall	P3: 2006-2012	Ref.E	1.095	0.116	0.819	1.46	a
	Overall	P4: 2013-2021	HH	0.973	0.172	0.601	1.57	a
	Overall	P4: 2013-2021	Ref.E	1.241	0.206	0.790	1.95	a
Walleye	Ref.E	P1: pre 1994	Ref.E	2.477	0.846	1.09	5.63	b
	Ref.E	P2: 1995-2005	Ref.E	0.928	0.344	0.368	2.34	a
	Ref.E	P3: 2006-2012	Ref.E	1.373	0.471	0.585	3.23	a
	Ref.E	P4: 2013-2021	Ref.E	0.262	0.445	0.524	3.04	a

Table B 2. *Results from the post-hoc assessment of differences in species catchability among the Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] reference areas based on least-square means. For each combination of Stanza and Zone estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
Non-Natives								
Alewife	Overall	P1: pre 1994	HH	0.7872	0.0378	0.667	0.873	a
	Overall	P1: pre 1994	Ref.E	0.3512	0.0573	0.214	0.518	cde
	Overall	P2: 1995-2005	HH	0.4905	0.0315	0.406	0.576	bc
	Overall	P2: 1995-2005	Ref.E	0.1620	0.0332	0.090	0.273	ef
	Overall	P3: 2006-2012	HH	0.2914	0.0330	0.210	0.389	de
	Overall	P3: 2006-2012	Ref.E	0.2010	0.0384	0.116	0.326	def
	Overall	P3: 2006-2012	Ref.W	0.7979	0.0707	0.5363	0.931	ab
	Overall	P4: 2013-2021	HH	0.1302	0.0188	0.087	0.191	f
	Overall	P4: 2013-2021	Ref.E	0.192	0.0267	0.0218	0.192	f
	Overall	P4: 2013-2021	Ref.W	0.764	0.1047	0.2367	0.764	abcd
	Zonal	P1: pre 1994	East	0.7214	0.0633	0.506	0.867	abc
	Zonal	P1: pre 1994	North	0.7830	0.0727	0.950	0.927	abc
	Zonal	P1: pre 1994	Ref.E	0.3502	0.0573	0.204	0.530	defgh
	Zonal	P1: pre 1994	West	0.8851	0.0541	0.616	0.973	a
	Zonal	P2: 1995-2005	East	0.4123	0.0526	0.270	0.571	cdef
	Zonal	P2: 1995-2005	North	0.6177	0.0621	0.427	0.778	abcd
	Zonal	P2: 1995-2005	Ref.E	0.1629	0.0333	0.086	0.285	ghij
	Zonal	P2: 1995-2005	West	0.4765	0.0472	0.343	0.613	bcde
	Zonal	P3: 2006-2012	East	0.2156	0.0529	0.099	0.408	efghij
	Zonal	P3: 2006-2012	North	0.2872	0.0671	0.133	0.514	defghi
	Zonal	P3: 2006-2012	Ref.E	0.2027	0.0386	0.113	0.339	fghij
	Zonal	P3: 2006-2012	West	0.3502	0.0523	0.215	0.514	defgh

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P3: 2006-2012	Ref.W	0.937	0.0703	0.5191	0.937	Ab
	Zonal	P4: 2013-2021	East	0.0643	0.0225	0.022	0.171	j
	Zonal	P4: 2013-2021	North	0.1283	0.0384	0.051	0.288	hij
	Zonal	P4: 2013-2021	Ref.E	0.0679	0.0267	0.021	0.202	ij
	Zonal	P4: 2013-2021	West	0.1860	0.0333	0.107	0.304	ghij
	Zonal	P4: 2013-2021	Ref.W	0.5019	0.1047	0.2241	0.779	abcdefg
Common Carp	Overall	P1: pre 1994	HH	0.5220	0.0457	0.399	0.643	a
	Overall	P1: pre 1994	Ref.E	0.1782	0.0466	0.084	0.340	cd
	Overall	P2: 1995-2005	HH	0.5132	0.0314	0.428	0.598	a
	Overall	P2: 1995-2005	Ref.E	0.0209	0.0120	0.004	0.095	e
	Overall	P3: 2006-2012	HH	0.2969	0.0328	0.216	0.393	bc
	Overall	P3: 2006-2012	Ref.E	0.1045	0.0269	0.051	0.204	de
	Overall	P3: 2006-2012	Ref.W	0.3052	0.0827	0.1284	0.567	abcd
	Overall	P4: 2013-2021	HH	0.2693	0.0250	0.207	0.343	bc
	Overall	P4: 2013-2021	Ref.E	0.1337	0.0337	0.065	0.254	cde
	Overall	P3: 2006-2012	Ref.W	0.5496	0.1043	0.2726	0.799	ab
	Zonal	P1: pre 1994	East	0.3559	0.0672	0.189	0.567	abcde
	Zonal	P1: pre 1994	North	0.6761	0.0813	0.411	0.862	a
	Zonal	P1: pre 1994	Ref.E	0.1789	0.0467	0.079	0.357	cdef
	Zonal	P1: pre 1994	West	0.6225	0.0808	0.375	0.820	ab
	Zonal	P2: 1995-2005	East	0.3885	0.0527	0.248	0.550	abcd
	Zonal	P2: 1995-2005	North	0.5792	0.0618	0.395	0.744	a
	Zonal	P2: 1995-2005	Ref.E	0.0206	0.0118	0.004	0.105	g
	Zonal	P2: 1995-2005	West	0.5787	0.0463	0.440	0.706	a
	Zonal	P3: 2006-2012	East	0.4595	0.0634	0.286	0.643	abc
	Zonal	P3: 2006-2012	North	0.1012	0.0431	0.027	0.313	defg
	Zonal	P3: 2006-2012	Ref.E	0.1028	0.0266	0.047	0.211	fg

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P3: 2006-2012	West	0.2842	0.0487	0.163	0.446	bcdef
	Zonal	P3: 2006-2012	Ref.W	0.3018	0.0825	0.1184	0.582	abcdef
	Zonal	P4: 2013-2021	East	0.4543	0.0484	0.319	0.597	ab
	Zonal	P4: 2013-2021	North	0.0808	0.0317	0.024	0.236	fg
	Zonal	P4: 2013-2021	Ref.E	0.1322	0.0333	0.061	0.264	efg
	Zonal	P4: 2013-2021	West	0.2271	0.0360	0.138	0.350	cdef
	Zonal	P4: 2013-2021	Ref.W	0.5473	0.1045	0.2557	0.810	abc
White Perch	Overall	P1: pre 1994	HH	0.4608	0.0456	0.341	0.585	a
	Overall	P1: pre 1994	Ref.E	0.2111	0.0487	0.108	0.373	b
	Overall	P2: 1995-2005	HH	0.4303	0.0310	0.349	0.516	a
	Overall	P2: 1995-2005	Ref.E	0.0481	0.0191	0.016	0.136	c
	Overall	P3: 2006-2012	HH	0.3263	0.0340	0.241	0.425	ab
	Overall	P3: 2006-2012	Ref.E	0.2046	0.0382	0.119	0.328	b
	Overall	P4: 2013-2021	HH	0.2066	0.0227	0.151	0.275	b
	Overall	P4: 2013-2021	Ref.E	0.2170	0.0429	0.122	0.356	b
	Zonal	P1: pre 1994	East	0.3918	0.0679	0.218	0.599	abcd
	Zonal	P1: pre 1994	North	0.3851	0.0848	0.179	0.643	abcd
	Zonal	P1: pre 1994	Ref.E	0.2109	0.0487	0.101	0.388	bcde
	Zonal	P1: pre 1994	West	0.6302	0.0812	0.379	0.826	a
	Zonal	P2: 1995-2005	East	0.4438	0.0530	0.298	0.601	abc
	Zonal	P2: 1995-2005	North	0.5154	0.0629	0.336	0.691	a
	Zonal	P2: 1995-2005	Ref.E	0.0481	0.0192	0.015	0.148	e
	Zonal	P2: 1995-2005	West	0.3712	0.0451	0.250	0.511	abcd
	Zonal	P3: 2006-2012	East	0.3451	0.0608	0.193	0.538	abcd
	Zonal	P3: 2006-2012	North	0.5216	0.0731	0.315	0.721	ab
	Zonal	P3: 2006-2012	Ref.E	0.2051	0.0383	0.114	0.340	de
	Zonal	P3: 2006-2012	West	0.2043	0.0442	0.103	0.364	cde
	Zonal	P4: 2013-2021	East	0.1897	0.0373	0.103	0.324	de

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	North	0.1709	0.0435	0.077	0.338	de
	Zonal	P4: 2013-2021	Ref.E	0.2174	0.0429	0.117	0.369	cd
	Zonal	P4: 2013-2021	West	0.2395	0.0366	0.148	0.363	cd
Natives								
Brown Bullhead	Overall	P1: pre 1994	HH	0.528	0.0459	0.404	0.649	a
	Overall	P1: pre 1994	Ref.E	0.462	0.0604	0.307	0.625	ab
	Overall	P2: 1995-2005	HH	0.603	0.0306	0.518	0.683	a
	Overall	P2: 1995-2005	Ref.E	0.551	0.0442	0.430	0.666	a
	Overall	P3: 2006-2012	HH	0.518	0.0362	0.420	0.615	a
	Overall	P3: 2006-2012	Ref.E	0.601	0.0462	0.471	0.718	a
	Overall	P3: 2006-2012	Ref.W	0.667	0.0881	0.397	0.859	a
	Overall	P4: 2013-2021	HH	0.337	0.0268	0.268	0.413	b
	Overall	P4: 2013-2021	Ref.E	0.299	0.0457	0.191	0.436	b
	Overall	P4: 2013-2021	Ref.W	0.631	0.1021	0.34	0.631	ab
	Zonal	P1: pre 1994	East	0.239	0.0603	0.106	0.455	efg
	Zonal	P1: pre 1994	North	0.771	0.0724	0.501	0.918	abc
	Zonal	P1: pre 1994	Ref.E	0.463	0.0605	0.296	0.638	bcdef
	Zonal	P1: pre 1994	West	0.711	0.0750	0.456	0.878	abc
	Zonal	P2: 1995-2005	East	0.256	0.0480	0.141	0.419	efg
	Zonal	P2: 1995-2005	North	0.741	0.0535	0.557	0.866	ab
	Zonal	P2: 1995-2005	Ref.E	0.549	0.0443	0.418	0.674	bc
	Zonal	P2: 1995-2005	West	0.782	0.0379	0.650	0.873	a
	Zonal	P3: 2006-2012	East	0.200	0.0502	0.091	0.386	fg
	Zonal	P3: 2006-2012	North	0.712	0.0673	0.484	0.866	abc
	Zonal	P3: 2006-2012	Ref.E	0.600	0.0464	0.459	0.725	abc
	Zonal	P3: 2006-2012	West	0.649	0.0524	0.484	0.784	abc
	Zonal	P3: 2006-2012	Ref.W	0.667	0.0884	0.3719	0.868	Abcd

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	East	0.142	0.0342	0.068	0.274	g
	Zonal	P4: 2013-2021	North	0.464	0.0588	0.302	0.635	bcdef
	Zonal	P4: 2013-2021	Ref.E	0.298	0.0456	0.183	0.447	defg
	Zonal	P4: 2013-2021	West	0.298	0.0456	0.183	0.447	cdef
	Zonal	P4: 2013-2021	Ref.W	0.631	0.1023	0.3154	0.863	abcde
Gizzard Shad	Overall	P1: pre 1994	HH	0.2302	0.0389	0.141	0.352	bc
	Overall	P1: pre 1994	Ref.E	0.1353	0.0419	0.056	0.293	bcd
	Overall	P2: 1995-2005	HH	0.1834	0.0245	0.126	0.260	bc
	Overall	P2: 1995-2005	Ref.E	0.1281	0.0281	0.069	0.226	cd
	Overall	P3: 2006-2012	HH	0.2923	0.0326	0.212	0.388	b
	Overall	P3: 2006-2012	Ref.E	0.0278	0.0138	0.007	0.103	d
	Overall	P3: 2006-2012	Ref.W	0.4727	0.0909	0.2085	0.678	ab
	Overall	P4: 2013-2021	HH	0.5894	0.0280	0.512	0.663	a
	Overall	P4: 2013-2021	Ref.E	0.1101	0.0304	0.050	0.224	cd
	Overall	P4: 2013-2021	Ref.W	0.6772	0.0993	0.370	0.882	a
	Zonal	P1: pre 1994	East	0.139	0.0488	0.046	0.350	cde
	Zonal	P1: pre 1994	North	0.186	0.0686	0.057	0.465	bcde
	Zonal	P1: pre 1994	Ref.E	0.135	0.0419	0.052	0.310	cde
	Zonal	P1: pre 1994	West	0.401	0.0827	0.195	0.649	bc
	Zonal	P2: 1995-2005	East	0.170	0.0413	0.079	0.327	cde
	Zonal	P2: 1995-2005	North	0.169	0.0485	0.068	0.360	cde
	Zonal	P2: 1995-2005	Ref.E	0.129	0.0282	0.066	0.236	de
	Zonal	P2: 1995-2005	West	0.201	0.0383	0.111	0.337	cd
	Zonal	P3: 2006-2012	East	0.281	0.0567	0.146	0.472	bcd
	Zonal	P3: 2006-2012	North	0.242	0.0618	0.106	0.463	bcd
	Zonal	P3: 2006-2012	Ref.E	0.028	0.0139	0.006	0.115	e
	Zonal	P3: 2006-2012	West	0.330	0.0509	0.200	0.492	bc
	Zonal	P3: 2006-2012	Ref.W	0.428	0.0908	0.1982	0.694	abc

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	East	0.477	0.0488	0.338	0.618	b
	Zonal	P4: 2013-2021	North	0.486	0.0592	0.319	0.655	b
	Zonal	P4: 2013-2021	Ref.E	0.110	0.0305	0.047	0.236	de
	Zonal	P4: 2013-2021	West	0.733	0.0381	0.607	0.830	a
	Zonal	P4: 2013-2021	Ref.W	0.678	0.0992	0.3515	0.891	ab
Native Minnows	Overall	P1: pre 1994	HH	0.493	0.0458	0.371	0.616	bc
	Overall	P1: pre 1994	Ref.E	0.527	0.0603	0.365	0.683	abc
	Overall	P2: 1995-2005	HH	0.425	0.0308	0.343	0.510	c
	Overall	P2: 1995-2005	Ref.E	0.538	0.0437	0.419	0.653	abc
	Overall	P3: 2006-2012	HH	0.503	0.0361	0.406	0.6	bc
	Overall	P3: 2006-2012	Ref.E	0.728	0.0360	0.620	0.814	a
	Overall	P3: 2006-2012	Ref.W	0.758	0.0763	0.494	0.909	ab
	Overall	P4: 2013-2021	HH	0.209	0.0229	0.154	0.278	d
	Overall	P4: 2013-2021	Ref.E	0.457	0.543	0.337	0.583	bc
	Overall	P4: 2013-2021	Ref.W	0.318	0.0984	0.116	0.624	bcd
	Zonal	P1: pre 1994	East	0.450	0.0693	0.349	0.736	abcd
	Zonal	P1: pre 1994	North	0.538	0.0873	0.234	0.707	abcd
	Zonal	P1: pre 1994	Ref.E	0.528	0.0603	0.305	0.646	abc
	Zonal	P1: pre 1994	West	0.518	0.0837	0.257	0.714	abcd
	Zonal	P2: 1995-2005	East	0.378	0.0514	0.463	0.757	cd
	Zonal	P2: 1995-2005	North	0.454	0.546	0.364	0.716	bcd
	Zonal	P2: 1995-2005	Ref.E	0.538	0.0438	0.339	0.591	abc
	Zonal	P2: 1995-2005	West	0.449	0.0466	0.413	0.681	bcd
	Zonal	P3: 2006-2012	East	0.378	0.0514	0.463	0.757	abcd
	Zonal	P3: 2006-2012	North	0.454	0.546	0.364	0.716	ab
	Zonal	P3: 2006-2012	Ref.E	0.719	0.0406	0.178	0.414	a
	Zonal	P3: 2006-2012	West	0.395	0.0534	0.442	0.747	bcd

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P3: 2006-2012	Ref.W	0.760	0.0760	0.4771	0.916	ab
	Zonal	P4: 2013-2021	East	0.155	0.0342	0.716	0.921	e
	Zonal	P4: 2013-2021	North	0.211	0.0473	0.618	0.896	de
	Zonal	P4: 2013-2021	Ref.E	0.489	0.0511	0.364	0.656	bc
	Zonal	P4: 2013-2021	West	0.262	0.0377	0.613	0.833	de
	Zonal	P3: 2006-2012	Ref.W	0.319	0.0986	0.1077	0.644	abcde
Spottail Shiner	Zonal HH	P1: pre 1994	East	0.2117	0.0567	0.0923	0.415	abcd
	Zonal HH	P1: pre 1994	North	0.3030	0.0800	0.1284	0.562	abc
	Zonal HH	P1: pre 1994	West	0.1667	0.0621	0.0528	0.418	abcd
	Zonal HH	P2: 1995-2005	East	0.1783	0.0406	0.0895	0.324	bcd
	Zonal HH	P2: 1995-2005	North	0.3085	0.0577	0.1708	0.491	ab
	Zonal HH	P2: 1995-2005	West	0.2676	0.0413	0.1669	0.2676	ab
	Zonal HH	P3: 2006-2012	East	0.2091	0.0518	0.0974	0.393	abcd
	Zonal HH	P3: 2006-2012	North	0.4670	0.0733	0.2740	0.670	a
	Zonal HH	P3: 2006-2012	West	0.1290	0.0365	0.0553	0.272	bcd
	Zonal HH	P4: 2013-2021	East	0.0643	0.0235	0.0220	0.174	d
	Zonal HH	P4: 2013-2021	North	0.1350	0.0397	0.0558	0.292	bcd
	Zonal HH	P4: 2013-2021	West	0.0881	0.0243	0.0391	0.187	cd
	HH	P1: pre 1994	HH	0.2233	0.0379	0.1430	0.331	a
	HH	P2: 1995-2005	HH	0.2484	0.0266	0.1881	0.320	a
	HH	P3: 2006-2012	HH	0.2356	0.0310	0.1672	0.321	a
	HH	P4: 2013-2021	HH	0.0908	0.0161	0.0579	0.140	b
Emerald Shiner	Zonal HH	P1: pre 1994	East	0.3920	0.0695	0.2188	0.597	ab
	Zonal HH	P1: pre 1994	North	0.3885	0.0867	0.1830	0.643	ab
	Zonal HH	P1: pre 1994	West	0.4369	0.0842	0.2258	0.674	ab
	Zonal HH	P2: 1995-2005	East	0.2733	0.0468	0.1608	0.425	abc

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
Native Sunfishes	Zonal HH	P2: 1995-2005	North	0.2544	0.0534	0.1324	0.433	abcd
	Zonal HH	P2: 1995-2005	West	0.2755	0.0417	0.1731	0.409	abc
	Zonal HH	P3: 2006-2012	East	0.4227	0.0644	0.2560	0.609	ab
	Zonal HH	P3: 2006-2012	North	0.5364	0.0741	0.3306	0.5364	a
	Zonal HH	P3: 2006-2012	West	0.3613	0.0541	0.2245	0.525	ab
	Zonal HH	P4: 2013-2021	East	0.0893	0.0263	0.0375	0.198	d
	Zonal HH	P4: 2013-2021	North	0.1001	0.0346	0.0358	0.250	cd
	Zonal HH	P4: 2013-2021	West	0.2125	0.0359	0.1275	0.333	bcd
	HH	P1: pre 1994	HH	0.405	0.0456	0.298	0.522	a
	HH	P2: 1995-2005	HH	0.272	0.0274	0.209	0.345	b
	HH	P3: 2006-2012	HH	0.422	0.0368	0.334	0.515	a
	HH	P4: 2013-2021	HH	0.143	0.0199	0.1	0.2	c
	Overall	P1: pre 1994	HH	0.341	0.6587	0.235	0.467	ef
	Overall	P1: pre 1994	Ref.E	0.853	0.1473	0.695	0.936	bc
	Overall	P2: 1995-2005	HH	0.620	0.0305	0.534	0.699	cd
	Overall	P2: 1995-2005	Ref.E	0.971	0.0142	0.894	0.993	a
	Overall	P3: 2006-2012	HH	0.381	0.0351	0.291	0.480	e
	Overall	P3: 2006-2012	Ref.E	0.923	0.0772	0.828	0.967	a
	Overall	P3: 2006-2012	Ref.W	0.1467	0.0319	0.0776	0.259	def
	Overall	P4: 2013-2021	HH	0.182	0.0216	0.130	0.248	f
	Overall	P4: 2013-2021	Ref.E	0.794	0.0407	0.661	0.883	ab
	Overall	P4: 2013-2021	Ref.W	0.304	0.0390	0.0827	0.304	cde
	Zonal	P1: pre 1994	East	0.1470	0.8530	0.0523	0.350	hi
	Zonal	P1: pre 1994	North	0.4165	0.5835	0.2011	0.669	efgh
	Zonal	P1: pre 1994	Ref.E	0.8515	0.1485	0.6764	0.940	bcd
	Zonal	P1: pre 1994	West	0.5468	0.4532	0.3090	0.765	cdef
	Zonal	P2: 1995-2005	East	0.5246	0.0537	0.3690	0.676	ef

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P2: 1995-2005	North	0.4407	0.0623	0.2722	0.624	fgh
	Zonal	P2: 1995-2005	Ref.E	0.9721	0.0138	0.8858	0.994	a
	Zonal	P2: 1995-2005	West	0.7845	0.0390	0.6485	0.878	bc
	Zonal	P3: 2006-2012	East	0.2137	0.7863	0.0976	0.406	ghi
	Zonal	P3: 2006-2012	North	0.3486	0.0701	0.1772	0.571	fgh
	Zonal	P3: 2006-2012	Ref.E	0.7253	0.0747	0.8225	0.9253	a
	Zonal	P3: 2006-2012	West	0.5249	0.4751	0.3676	0.677	cde
	Zonal	P3: 2006-2012	Ref.W	0.1471	0.032	0.0745	0.269	defgh
	Zonal	P4: 2013-2021	East	0.0658	0.0237	0.0240	0.180	i
	Zonal	P4: 2013-2021	North	0.0655	0.0284	0.0175	0.216	i
	Zonal	P4: 2013-2021	Ref.E	0.7978	0.0401	0.6547	0.891	ab
	Zonal	P4: 2013-2021	West	0.3358	0.0406	0.2282	0.464	fg
	Zonal	P4: 2013-2021	Ref.W	0.166	0.0392	0.0791	0.3171	cdefg
Pumpkinseed	Overall	P1: pre 1994	HH	0.3186	0.0425	0.215	0.443	de
	Overall	P1: pre 1994	Ref.E	0.6637	0.0571	0.496	0.798	bc
	Overall	P2: 1995-2005	HH	0.5680	0.0313	0.481	0.650	c
	Overall	P2: 1995-2005	Ref.E	0.9123	0.0244	0.819	0.959	a
	Overall	P3: 2006-2012	HH	0.1927	0.0285	0.126	0.282	e
	Overall	P3: 2006-2012	Ref.E	0.7699	0.0386	0.649	0.858	ab
	Overall	P3: 2006-2012	Ref.W	0.4525	0.0896	0.2310	0.695	cde
	Overall	P4: 2013-2021	HH	0.0526	0.0125	0.027	0.098	f
	Overall	P4: 2013-2021	Ref.E	0.4875	0.0513	0.352	0.624	cd
	Overall	P4: 2013-2021	Ref.W	0.3487	0.0996	0.1356	0.646	cde
Bluegill	Overall	P1: pre 1994	HH	0.0168	0.0118	0.8932	0.998	d
	Overall	P1: pre 1994	Ref.E	0.0295	0.0205	0.8231	0.996	bcd
	Overall	P2: 1995-2005	HH	0.1412	0.0219	0.7881	0.909	bc
	Overall	P2: 1995-2005	Ref.E	0.6605	0.0422	0.2353	0.462	a
	Overall	P3: 2006-2012	HH	0.2031	0.0289	0.7068	0.865	b

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Overall	P3: 2006-2012	Ref.E	0.8284	0.0356	0.0947	0.291	a
	Overall	P4: 2013-2021	HH	0.0979	0.0167	0.8461	0.939	cd
	Overall	P4: 2013-2021	Ref.E	0.7057	0.0472	0.1832	0.437	a
White Sucker	Overall	P1: pre 1994	HH	0.1546	0.0320	0.0846	0.263	a
	Overall	P1: pre 1994	Ref.E	0.1930	0.0461	0.096	0.349	ab
	Overall	P2: 1995-2005	HH	0.1158	0.0190	0.073	0.178	ab
	Overall	P2: 1995-2005	Ref.E	0.0431	0.0189	0.013	0.136	bc
	Overall	P3: 2006-2012	HH	0.1340	0.0252	0.079	0.218	ab
	Overall	P3: 2006-2012	Ref.E	0.1387	0.0356	0.067	0.266	abc
	Overall	P3: 2006-2012	Ref.W	0.2988	0.0946	0.1075	0.6013	a
	Overall	P4: 2013-2021	HH	0.0469	0.0113	0.024	0.089	c
	Overall	P4: 2013-2021	Ref.E	0.0770	0.0301	0.026	0.209	abc
	Overall	P4: 2013-2021	Ref.W	0.2009	0.0887	0.0508	0.5415	abc
	Zonal	P1: pre 1994	East	0.1854	0.0532	0.075	0.391	abc
	Zonal	P1: pre 1994	North	0.2060	0.0692	0.069	0.475	abc
	Zonal	P1: pre 1994	Ref.E	0.1917	0.0460	0.090	0.362	ab
	Zonal	P1: pre 1994	West	0.0645	0.0371	0.011	0.296	abc
	Zonal	P2: 1995-2005	East	0.0883	0.0267	0.035	0.205	abc
	Zonal	P2: 1995-2005	North	0.1272	0.0379	0.051	0.285	abc
	Zonal	P2: 1995-2005	Ref.E	0.0431	0.0189	0.012	0.148	bc
	Zonal	P2: 1995-2005	West	0.1266	0.0291	0.062	0.240	abc
	Zonal	P3: 2006-2012	East	0.1177	0.0420	0.039	0.306	abc
	Zonal	P3: 2006-2012	North	0.773	0.0639	0.091	0.462	ab
	Zonal	P3: 2006-2012	Ref.E	0.1400	0.0359	0.063	0.282	abc
	Zonal	P3: 2006-2012	Ref.W	0.2991	0.0955	0.09886	0.624	a
	Zonal	P3: 2006-2012	West	0.0962	0.0326	0.034	0.243	abc
	Zonal	P4: 2013-2021	East	0.0307	0.0138	0.008	0.111	c
	Zonal	P4: 2013-2021	North	0.0285	0.0169	0.005	0.151	bc

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	Ref.E	0.0777	0.0303	0.024	0.227	abc
	Zonal	P4: 2013-2021	West	0.0716	0.0211	0.029	0.164	abc
	Zonal	P4: 2013-2021	Ref.W	0.2019	0.0891	0.0463	0.568	abc
Yellow Perch	Overall	P1: pre 1994	HH	0.150	0.0326	0.081	0.261	d
	Overall	P1: pre 1994	Ref.E	0.870	0.0404	0.717	0.946	a
	Overall	P2: 1995-2005	HH	0.369	0.0303	0.290	0.454	c
	Overall	P2: 1995-2005	Ref.E	0.856	0.0309	0.750	0.921	a
	Overall	P3: 2006-2012	HH	0.478	0.0360	0.382	0.5758	c
	Overall	P3: 2006-2012	Ref.E	0.950	0.0200	0.858	0.9836	a
	Overall	P3: 2006-2012	Ref.W	0.419	0.0887	0.205	0.666	C
	Overall	P4: 2013-2021	HH	0.157	0.8427	0.2213	0.9796	d
	Overall	P4: 2013-2021	Ref.E	0.814	0.1858	0.682	0.8998	ab
	Overall	P4: 2013-2021	Ref.W	0.521	0.1043	0.2521	0.778	bc
	Zonal	P1: pre 1994	East	0.0384	0.0267	0.005	0.251	ij
	Zonal	P1: pre 1994	North	0.2726	0.0776	0.106	0.542	efghij
	Zonal	P1: pre 1994	Ref.E	0.8695	0.0406	0.699	0.959	abc
	Zonal	P1: pre 1994	West	0.1943	0.0660	0.065	0.455	fghij
	Zonal	P2: 1995-2005	East	0.1553	0.0385	0.072	0.304	Ij
	Zonal	P2: 1995-2005	North	0.3073	0.0578	0.166	0.497	efghi
	Zonal	P2: 1995-2005	Ref.E	0.8573	0.0306	0.742	0.926	ab
	Zonal	P2: 1995-2005	West	0.5600	0.0466	0.422	0.689	de
	Zonal	P3: 2006-2012	East	0.4356	0.5644	0.266	0.621	def
	Zonal	P3: 2006-2012	North	0.7023	0.0668	0.479	0.858	bcd
	Zonal	P3: 2006-2012	Ref.E	0.9509	0.0197	0.848	0.985	a
	Zonal	P3: 2006-2012	West	0.3884	0.0530	0.248	0.550	defgh
	Zonal	P3: 2006-2012	Ref.W	0.4208	0.0889	0.1966	0.683	defgh
	Zonal	P4: 2013-2021	East	0.0825	0.0264	0.031	0.200	j
	Zonal	P4: 2013-2021	North	0.1486	0.0414	0.062	0.3139	ghij

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
	Zonal	P4: 2013-2021	Ref.E	0.8165	0.0394	0.0937	0.906	abc
	Zonal	P4: 2013-2021	West	0.2206	0.0356	0.133	0.3424	fghij
	Zonal	P4: 2013-2021	Ref.W	0.5234	0.1043	0.2398	0.793	cdefg
Piscivores								
Largemouth Bass	Overall	P1: pre 1994	HH	0.126	0.766	0.0636	0.234	d
	Overall	P1: pre 1994	Ref.E	0.177	0.0462	0.0827	0.338	cd
	Overall	P2: 1995-2005	HH	0.383	0.0305	0.3037	0.469	c
	Overall	P2: 1995-2005	Ref.E	0.607	0.0431	0.4851	0.716	b
	Overall	P3: 2006-2012	HH	0.377	0.0349	0.2874	0.476	c
	Overall	P3: 2006-2012	Ref.E	0.871	0.0314	0.7589	0.935	a
	Overall	P3: 2006-2012	Ref.W	0.124	0.0583	0.0303	0.389	cd
	Overall	P4: 2013-2021	HH	0.205	0.0227	0.1503	0.274	d
	Overall	P4: 2013-2021	Ref.E	0.581	0.0506	0.4403	0.710	b
	Overall	P4: 2013-2021	Ref.W	0.339	0.661	0.1308	0.687	bcd
	Zonal	P1: pre 1994	East	0.0195	0.0193	0.001	0.281	efg
	Zonal	P1: pre 1994	North	0.1836	0.0677	0.056	0.459	efg
	Zonal	P1: pre 1994	Ref.E	0.1759	0.0461	0.077	0.352	efg
	Zonal	P1: pre 1994	West	0.2249	0.0700	0.082	0.486	defg
	Zonal	P2: 1995-2005	East	0.1145	0.0342	0.046	0.259	fg
	Zonal	P2: 1995-2005	North	0.2999	0.0578	0.160	0.491	def
	Zonal	P2: 1995-2005	Ref.E	0.6094	0.0432	0.478	0.726	bc
	Zonal	P2: 1995-2005	West	0.6271	0.0453	0.487	0.758	b
	Zonal	P3: 2006-2012	East	0.2397	0.0541	0.116	0.430	efg
	Zonal	P3: 2006-2012	North	0.1466	0.0513	0.049	0.365	efg
	Zonal	P3: 2006-2012	Ref.E	0.8724	0.0311	0.750	0.939	a
	Zonal	P3: 2006-2012	West	0.6088	0.0531	0.446	0.750	bc
	Zonal	P3: 2006-2012	Ref.W	0.125	0.0588	0.0279	0.416	efg

	Comparison	Stanza	Location	Estimate	SE	Lower CI	Upper CI	Group
Northern Pike	Zonal	P4: 2013-2021	East	0.0560	0.0222	0.017	0.170	g
	Zonal	P4: 2013-2021	North	0.0542	0.264	0.012	0.207	fg
	Zonal	P4: 2013-2021	Ref.E	0.5840	0.0506	0.432	0.721	bcd
	Zonal	P4: 2013-2021	West	0.4049	0.0421	0.289	0.532	cde
	Zonal	P4: 2013-2021	Ref.W	0.3410	0.0986	0.1226	0.657	bcdef
	Overall	P1: pre 1994	HH	0.0232	0.0133	0.0047	0.1057	d
	Overall	P1: pre 1994	Ref.E	0.3674	0.0582	0.2268	0.5348	a
	Overall	P2: 1995-2005	HH	0.0365	0.0112	0.0155	0.0832	d
	Overall	P2: 1995-2005	Ref.E	0.2395	0.0388	0.1469	0.3605	ab
	Overall	P3: 2006-2012	HH	0.0530	0.0631	0.0225	0.1195	cd
	Overall	P3: 2006-2012	Ref.E	0.1535	0.0352	0.0796	0.2755	bc
	Overall	P4: 2013-2021	HH	0.0118	0.0059	0.0029	0.0455	d
	Overall	P4: 2013-2021	Ref.E	0.0554	0.0241	0.0163	0.1716	cd
Walleye	Ref.E only	P1: pre 1994	Ref.E	0.651	0.0647	0.479	0.791	a
	Ref.E only	P2: 1995-2005	Ref.E	0.226	0.0156	0.123	0.379	b
	Ref.E only	P3: 2006-2012	Ref.E	0.403	0.0517	0.283	0.535	b
	Ref.E only	P4: 2013-2021	Ref.E	0.317	0.0561	0.196	0.470	b

Table B 3. *Mean catch per transect across all three HH zones, HH combined, Ref.E, and Ref.W*

Species	Comparison	Stanza	Location	Average catch/transect
Goldfish	Overall	P1: pre 1994	HH	0.13
	Overall	P1: pre 1994	Ref.E	0.00
	Overall	P2: 1995-2005	HH	0.03
	Overall	P2: 1995-2005	Ref.E	0.00
	Overall	P3: 2006-2012	HH	0.30
	Overall	P3: 2006-2012	Ref.E	0.00
	Overall	P3: 2006-2012	Ref.W	0.03
	Overall	P4: 2013-2021	HH	0.70
	Overall	P4: 2013-2021	Ref.E	0.00
	Overall	P4: 2013-2021	Ref.W	0.10
	Zonal	P1: pre 1994	East	0.35
	Zonal	P1: pre 1994	North	0.40
	Zonal	P1: pre 1994	West	0.11
	Zonal	P2: 1995-2005	East	0.01
	Zonal	P2: 1995-2005	North	0.03
	Zonal	P2: 1995-2005	West	0.03
	Zonal	P3: 2006-2012	East	0.09
	Zonal	P3: 2006-2012	North	0.20
	Zonal	P3: 2006-2012	West	0.50
	Zonal	P4: 2013-2021	East	0.09
	Zonal	P4: 2013-2021	North	0.70
	Zonal	P4: 2013-2021	West	1.20
Rudd	Overall	P1: pre 1994	HH	0.00
	Overall	P1: pre 1994	Ref.E	0.00
	Overall	P2: 1995-2005	HH	0.00
	Overall	P2: 1995-2005	Ref.E	0.00
	Overall	P3: 2006-2012	HH	0.00
	Overall	P3: 2006-2012	Ref.E	0.00
	Overall	P3: 2006-2012	Ref.W	0.06
	Overall	P4: 2013-2021	HH	0.06
	Overall	P4: 2013-2021	Ref.E	0.00

Species	Comparison	Stanza	Location	Average catch/transect
	Overall	P4: 2013-2021	Ref.W	0.06
	Zonal	P1: pre 1994	East	0.00
	Zonal	P1: pre 1994	North	0.00
	Zonal	P1: pre 1994	West	0.00
	Zonal	P2: 1995-2005	East	0.00
	Zonal	P2: 1995-2005	North	0.00
	Zonal	P2: 1995-2005	West	0.00
	Zonal	P3: 2006-2012	East	0.00
	Zonal	P3: 2006-2012	North	0.00
	Zonal	P3: 2006-2012	West	0.00
	Zonal	P4: 2013-2021	East	0.01
	Zonal	P4: 2013-2021	North	0.01
	Zonal	P4: 2013-2021	West	0.10
Walleye	Overall	P1: pre 1994	HH	0.00
	Overall	P1: pre 1994	Ref.E	2.63
	Overall	P2: 1995-2005	HH	0.003
	Overall	P2: 1995-2005	Ref.E	0.50
	Overall	P3: 2006-2012	HH	0.00
	Overall	P3: 2006-2012	Ref.E	0.60
	Overall	P3: 2006-2012	Ref.W	0.00
	Overall	P4: 2013-2021	HH	0.11
	Overall	P4: 2013-2021	Ref.E	0.42
	Overall	P4: 2013-2021	Ref.W	0.00
	Zonal	P1: pre 1994	East	0.00
	Zonal	P1: pre 1994	North	0.00
	Zonal	P1: pre 1994	West	0.00
	Zonal	P2: 1995-2005	East	0.01
	Zonal	P2: 1995-2005	North	0.00
	Zonal	P2: 1995-2005	West	0.00
	Zonal	P3: 2006-2012	East	0.00
	Zonal	P3: 2006-2012	North	0.00
	Zonal	P3: 2006-2012	West	0.00
	Zonal	P4: 2013-2021	East	0.05

Species	Comparison	Stanza	Location	Average catch/transect
	Zonal	P4: 2013-2021	North	0.10
	Zonal	P4: 2013-2021	West	0.20
Smallmouth Bass	Overall	P1: pre 1994	HH	0.17
	Overall	P1: pre 1994	Ref.E	0.79
	Overall	P2: 1995-2005	HH	0.03
	Overall	P2: 1995-2005	Ref.E	0.15
	Overall	P3: 2006-2012	HH	0.03
	Overall	P3: 2006-2012	Ref.E	0.22
	Overall	P3: 2006-2012	Ref.W	0.31
	Overall	P4: 2013-2021	HH	0.00
	Overall	P4: 2013-2021	Ref.E	0.02
	Overall	P4: 2013-2021	Ref.W	0.00
	Zonal	P1: pre 1994	East	0.00
	Zonal	P1: pre 1994	North	0.10
	Zonal	P1: pre 1994	West	0.50
	Zonal	P2: 1995-2005	East	0.03
	Zonal	P2: 1995-2005	North	0.00
	Zonal	P2: 1995-2005	West	0.04
	Zonal	P3: 2006-2012	East	0.02
	Zonal	P3: 2006-2012	North	0.00
	Zonal	P3: 2006-2012	West	0.59
	Zonal	P4: 2013-2021	East	0.00
	Zonal	P4: 2013-2021	North	0.00
	Zonal	P4: 2013-2021	West	0.00

APPENDIX C: DETAILED MODEL OUTPUT FOR SECTION FP-2A

Temporal trends in fish community metrics were evaluated using repeated measure ANOVA with Time Stanza and Location (Hamilton-overall, Hamilton-zones [West, North, East], east [Ref.E], and west [Ref.W] and reference areas) as fixed effects and transect and sampling time period (day or night) included as random effects. When fixed effects were significant, least square means were used to examine pairwise differences between Time Stanza, Location, or their interaction. These works are presented in more detail in Turner et al. (in review).

HABITAT PRODUCTIVITY INDEX (HPI)

Table C 1. *Results from the post-hoc assessment of differences in Habitat Productivity Index values among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	1.68	0.15	-5.96	9.33	a
Overall	P2: 1995-2005	HamH	1.64	0.14	-9.12	12.40	ab
Overall	P3: 2006-2012	HamH	1.32	0.15	-8.35	10.99	c
Overall	P4: 2013-2021	HamH	1.32	0.14	-10.06	12.70	c
Overall	P1: pre 1994	Ref.E	1.62	0.15	-3.99	7.22	abd
Overall	P2: 1995-2005	Ref.E	1.43	0.15	-7.66	10.52	bcd
Overall	P3: 2006-2012	Ref.E	1.55	0.15	-6.46	9.55	abd
Overall	P4: 2013-2021	Ref.E	1.37	0.15	-6.59	9.34	cd
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	1.28	0.17	-0.86	3.42	cd
Overall	P4: 2013-2021	Ref.W	1.85	0.17	0.00	3.69	a
Zonal	P4: 2013-2021	North	1.10	0.15	-4.46	6.65	a
Zonal	P3: 2006-2012	East	1.18	0.15	-4.49	6.86	ab
Zonal	P4: 2013-2021	East	1.23	0.15	-7.38	9.84	abc
Zonal	P3: 2006-2012	North	1.24	0.16	-2.66	5.14	abcd
Zonal	P3: 2006-2012	Ref.W	1.29	0.16	-1.68	4.27	abcde
Zonal	P4: 2013-2021	Ref.E	1.38	0.15	-10.72	13.48	abcde
Zonal	P2: 1995-2005	East	1.39	0.15	-6.13	8.90	abcde
Zonal	P1: pre 1994	East	1.40	0.16	-3.41	6.22	abcdef
Zonal	P2: 1995-2005	Ref.E	1.43	0.14	-13.20	16.07	bcde
Zonal	P3: 2006-2012	West	1.47	0.15	-6.56	9.51	bcdef
Zonal	P4: 2013-2021	West	1.51	0.15	-9.47	12.48	cdef
Zonal	P3: 2006-2012	Ref.E	1.56	0.15	-11.36	14.48	defg
Zonal	P1: pre 1994	Ref.E	1.63	0.15	-6.81	10.06	efgh
Zonal	P2: 1995-2005	North	1.68	0.16	-3.36	6.73	efgh
Zonal	P1: pre 1994	North	1.74	0.17	-1.08	4.56	efgh
Zonal	P2: 1995-2005	West	1.81	0.15	-8.13	11.75	gh
Zonal	P4: 2013-2021	Ref.W	1.85	0.17	-0.51	4.20	fgh
Zonal	P1: pre 1994	West	1.92	0.16	-1.59	5.43	h
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

HABITAT PRODUCTIVITY INDEX - ADJUSTED (HPI_{ADJ})

Table C 2. *Results from the post-hoc assessment of differences in adjusted (no offshore fishes) Habitat Productivity Index values among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	1.39	0.13	-2.12	4.90	ab
Overall	P2: 1995-2005	HamH	1.42	0.13	-4.06	6.91	a
Overall	P3: 2006-2012	HamH	1.22	0.13	-3.53	5.97	b
Overall	P4: 2013-2021	HamH	0.93	0.13	-5.01	6.86	c
Overall	P1: pre 1994	Ref.E	1.50	0.14	-1.01	4.00	ab
Overall	P2: 1995-2005	Ref.E	1.38	0.13	-3.18	5.94	ab
Overall	P3: 2006-2012	Ref.E	1.49	0.13	-2.33	5.31	a
Overall	P4: 2013-2021	Ref.E	1.30	0.13	-2.60	5.20	ab
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	1.16	0.16	0.12	2.19	abc
Overall	P4: 2013-2021	Ref.W	1.62	0.17	0.66	2.57	ab
Zonal	P4: 2013-2021	North	0.74	0.15	-0.97	2.44	a
Zonal	P4: 2013-2021	East	0.91	0.14	-1.75	3.58	ab
Zonal	P4: 2013-2021	West	1.03	0.13	-2.62	4.69	abc
Zonal	P1: pre 1994	East	1.04	0.15	-0.61	2.70	abcd
Zonal	P2: 1995-2005	East	1.06	0.14	-1.31	3.42	abcd
Zonal	P3: 2006-2012	East	1.07	0.14	-0.80	2.95	abcde
Zonal	P3: 2006-2012	North	1.12	0.15	-0.23	2.47	bcd f
Zonal	P3: 2006-2012	Ref.W	1.16	0.16	-0.07	2.39	abcdefg
Zonal	P4: 2013-2021	Ref.E	1.30	0.13	-4.22	6.83	cdefg
Zonal	P2: 1995-2005	Ref.E	1.38	0.13	-5.37	8.13	defgh
Zonal	P3: 2006-2012	West	1.38	0.14	-1.30	4.06	defg
Zonal	P3: 2006-2012	Ref.E	1.49	0.13	-4.08	7.07	fgh
Zonal	P1: pre 1994	Ref.E	1.50	0.13	-1.89	4.89	fgh
Zonal	P2: 1995-2005	North	1.52	0.15	-0.07	3.12	e gh
Zonal	P1: pre 1994	North	1.59	0.16	0.47	2.72	gh
Zonal	P1: pre 1994	West	1.60	0.15	0.23	2.97	fgh
Zonal	P4: 2013-2021	Ref.W	1.62	0.16	0.52	2.71	fgh
Zonal	P2: 1995-2005	West	1.66	0.13	-1.64	4.95	h
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

INDEX OF BIOTIC INTEGRITY (IBI)

Table C 3. *Results from the post-hoc assessment of differences in Index of Biotic Integrity scores among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	5.31	0.44	2.26	8.36	a
Overall	P1: pre 1994	Ref.E	7.70	0.45	5.10	10.30	cd
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	HamH	5.76	0.42	2.10	9.42	ab
Overall	P2: 1995-2005	Ref.E	8.08	0.43	4.79	11.38	c
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	HamH	5.87	0.43	2.42	9.32	ab
Overall	P3: 2006-2012	Ref.E	8.17	0.44	5.06	11.27	c
Overall	P3: 2006-2012	Ref.W	6.49	0.51	4.69	8.29	abd
Overall	P4: 2013-2021	HamH	5.49	0.42	1.71	9.27	ab
Overall	P4: 2013-2021	Ref.E	7.64	0.44	4.58	10.70	cd
Overall	P4: 2013-2021	Ref.W	6.66	0.53	4.95	8.37	bd
Zonal	P1: pre 1994	East	4.81	0.46	2.44	7.17	df
Zonal	P1: pre 1994	North	5.24	0.49	3.28	7.19	bcdef
Zonal	P1: pre 1994	Ref.E	7.72	0.45	4.96	10.49	gh
Zonal	P1: pre 1994	Ref.W					
Zonal	P1: pre 1994	West	5.58	0.48	3.53	7.62	abcdef
Zonal	P2: 1995-2005	East	5.35	0.44	2.43	8.27	cde
Zonal	P2: 1995-2005	North	5.29	0.45	2.76	7.82	cdef
Zonal	P2: 1995-2005	Ref.E	8.09	0.43	4.56	11.63	g
Zonal	P2: 1995-2005	Ref.W					
Zonal	P2: 1995-2005	West	6.33	0.43	3.09	9.57	ab
Zonal	P3: 2006-2012	East	4.67	0.45	2.12	7.21	df
Zonal	P3: 2006-2012	North	6.19	0.47	3.95	8.43	abce
Zonal	P3: 2006-2012	Ref.E	8.23	0.43	4.85	11.60	g
Zonal	P3: 2006-2012	Ref.W	6.48	0.50	4.56	8.41	abce
Zonal	P3: 2006-2012	West	6.60	0.44	3.68	9.51	a
Zonal	P4: 2013-2021	East	4.46	0.44	1.33	7.59	f
Zonal	P4: 2013-2021	North	5.25	0.45	2.58	7.91	cdf
Zonal	P4: 2013-2021	Ref.E	7.66	0.43	4.48	10.83	gh
Zonal	P4: 2013-2021	Ref.W	6.67	0.52	4.91	8.43	abeh
Zonal	P4: 2013-2021	West	6.42	0.43	3.00	9.84	a

INDEX OF BIOTIC INTEGRITY - ADJUSTED (IBI$_{ADJ}$)

Table C 4. *Results from the post-hoc assessment of differences in adjusted (no offshore fishes) Index of Biotic Integrity scores among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	3.81	0.31	1.36	6.27	ab
Overall	P2: 1995-2005	HamH	4.56	0.28	0.75	8.37	c
Overall	P3: 2006-2012	HamH	4.99	0.29	1.74	8.24	c
Overall	P4: 2013-2021	HamH	3.40	0.28	-0.80	7.61	a
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	5.72	0.44	4.18	7.25	cd
Overall	P4: 2013-2021	Ref.W	5.14	0.46	3.60	6.69	bc
Overall	P1: pre 1994	Ref.E	6.67	0.33	4.72	8.63	de
Overall	P2: 1995-2005	Ref.E	7.69	0.29	4.56	10.82	f
Overall	P3: 2006-2012	Ref.E	7.74	0.30	5.09	10.39	f
Overall	P4: 2013-2021	Ref.E	7.10	0.30	4.39	9.81	ef
Zonal	P4: 2013-2021	East	2.68	0.32	0.34	5.01	a
Zonal	P1: pre 1994	East	2.99	0.37	1.21	4.77	abc
Zonal	P4: 2013-2021	North	3.19	0.36	1.33	5.05	ab
Zonal	P2: 1995-2005	East	3.59	0.33	1.45	5.73	bcd
Zonal	P3: 2006-2012	East	3.72	0.36	1.84	5.59	bcd
Zonal	P1: pre 1994	West	4.02	0.40	2.35	5.70	abcdef
Zonal	P4: 2013-2021	West	4.08	0.31	1.16	6.99	bcde
Zonal	P1: pre 1994	North	4.26	0.43	2.61	5.91	bcdefgh
Zonal	P2: 1995-2005	North	4.31	0.37	2.51	6.11	cdefg
Zonal	P4: 2013-2021	Ref.W	5.15	0.45	3.50	6.79	defghi
Zonal	P3: 2006-2012	North	5.27	0.39	3.57	6.98	efgh
Zonal	P2: 1995-2005	West	5.44	0.31	2.80	8.08	gh
Zonal	P3: 2006-2012	Ref.W	5.68	0.42	4.03	7.34	fghi
Zonal	P3: 2006-2012	West	5.79	0.33	3.54	8.03	hi
Zonal	P1: pre 1994	Ref.E	6.69	0.32	4.31	9.06	ij
Zonal	P4: 2013-2021	Ref.E	7.11	0.30	3.66	10.56	jk
Zonal	P2: 1995-2005	Ref.E	7.69	0.28	3.22	12.16	k
Zonal	P3: 2006-2012	Ref.E	7.79	0.29	4.09	11.48	k
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

TOTAL CATCH

Table C 5. *Results from the post-hoc assessment of differences in total catch among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	3.31	0.42	-32.40	39.00	ab
Overall	P2: 1995-2005	HamH	3.25	0.42	-38.80	45.30	ab
Overall	P3: 2006-2012	HamH	2.30	0.42	-37.70	42.30	c
Overall	P4: 2013-2021	HamH	1.88	0.42	-41.30	45.00	d
Overall	P1: pre 1994	Ref.E	3.21	0.43	-28.00	34.50	ab
Overall	P2: 1995-2005	Ref.E	3.38	0.42	-37.20	44.00	a
Overall	P3: 2006-2012	Ref.E	3.29	0.42	-34.40	41.00	ab
Overall	P4: 2013-2021	Ref.E	2.87	0.42	-35.90	41.60	b
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	3.03	0.45	-11.60	17.70	ab
Overall	P4: 2013-2021	Ref.W	3.12	0.46	-10.30	16.50	ab
Zonal	P4: 2013-2021	East	1.37	0.42	-52.50	55.30	a
Zonal	P4: 2013-2021	North	1.59	0.43	-40.00	43.20	a
Zonal	P3: 2006-2012	East	1.86	0.43	-39.80	43.50	ab
Zonal	P4: 2013-2021	West	2.42	0.42	-59.00	63.80	bc
Zonal	P3: 2006-2012	North	2.42	0.43	-29.90	34.70	bc
Zonal	P3: 2006-2012	West	2.57	0.42	-48.80	54.00	cd
Zonal	P1: pre 1994	East	2.58	0.43	-34.70	39.90	cd
Zonal	P2: 1995-2005	East	2.71	0.42	-47.00	52.50	cde
Zonal	P4: 2013-2021	Ref.E	2.90	0.42	-60.10	65.90	cde
Zonal	P3: 2006-2012	Ref.W	3.00	0.44	-22.60	28.60	cdef
Zonal	P4: 2013-2021	Ref.W	3.12	0.45	-17.30	23.60	cdefg
Zonal	P2: 1995-2005	North	3.20	0.43	-35.80	42.20	defg
Zonal	P1: pre 1994	Ref.E	3.25	0.42	-48.80	55.20	efg
Zonal	P3: 2006-2012	Ref.E	3.37	0.42	-62.20	68.90	fg
Zonal	P2: 1995-2005	Ref.E	3.39	0.42	-66.30	73.00	fg
Zonal	P1: pre 1994	North	3.47	0.44	-21.30	28.20	efg
Zonal	P2: 1995-2005	West	3.68	0.42	-54.30	61.70	fg
Zonal	P1: pre 1994	West	3.87	0.44	-25.50	33.20	g
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

TOTAL CATCH – NATIVE SPECIES

Table C 6. *Results from the post-hoc assessment of differences in total catch of native fishes among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	2.03	0.36	-19.22	23.28	a
Overall	P2: 1995-2005	HamH	2.54	0.35	-23.86	28.93	b
Overall	P3: 2006-2012	HamH	1.98	0.36	-22.74	26.70	a
Overall	P4: 2013-2021	HamH	1.59	0.35	-25.73	28.91	c
Overall	P1: pre 1994	Ref.E	3.07	0.36	-15.57	21.71	bde
Overall	P2: 1995-2005	Ref.E	3.32	0.35	-23.26	29.90	d
Overall	P3: 2006-2012	Ref.E	3.19	0.36	-20.67	27.05	de
Overall	P4: 2013-2021	Ref.E	2.75	0.35	-22.69	28.20	be
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	2.71	0.40	-4.46	9.88	abde
Overall	P4: 2013-2021	Ref.W	2.69	0.40	-4.09	9.48	abde
Zonal	P4: 2013-2021	East	0.99	0.36	-28.52	30.50	a
Zonal	P1: pre 1994	East	1.25	0.37	-17.63	20.10	a
Zonal	P4: 2013-2021	North	1.29	0.37	-19.10	21.70	ab
Zonal	P3: 2006-2012	East	1.40	0.37	-20.14	22.90	abc
Zonal	P2: 1995-2005	East	1.84	0.36	-24.87	28.60	bcd
Zonal	P3: 2006-2012	North	2.17	0.38	-13.13	17.50	cdef
Zonal	P4: 2013-2021	West	2.21	0.35	-33.88	38.30	de
Zonal	P1: pre 1994	North	2.30	0.39	-9.18	13.80	def
Zonal	P3: 2006-2012	West	2.32	0.36	-26.43	31.10	def
Zonal	P2: 1995-2005	North	2.36	0.37	-16.54	21.30	def
Zonal	P1: pre 1994	West	2.47	0.38	-12.18	17.10	defg
Zonal	P4: 2013-2021	Ref.W	2.70	0.39	-7.48	12.90	efghi
Zonal	P3: 2006-2012	Ref.W	2.72	0.38	-9.86	15.30	efghi
Zonal	P4: 2013-2021	Ref.E	2.78	0.35	-38.98	44.50	fgh
Zonal	P1: pre 1994	Ref.E	3.11	0.36	-28.50	34.70	ghi
Zonal	P2: 1995-2005	West	3.16	0.36	-30.39	36.70	hi
Zonal	P3: 2006-2012	Ref.E	3.28	0.35	-39.66	46.20	i
Zonal	P2: 1995-2005	Ref.E	3.33	0.35	-43.85	50.50	i
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

TOTAL CATCH NON-NATIVE SPECIES

Table C 7. *Results from the post-hoc assessment of differences in total catch of non-native fishes among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	2.70	0.39	-33.32	38.70	a
Overall	P2: 1995-2005	HamH	2.01	0.39	-44.20	48.20	b
Overall	P3: 2006-2012	HamH	1.11	0.39	-41.64	43.90	cd
Overall	P4: 2013-2021	HamH	0.78	0.39	-47.31	48.90	ef
Overall	P1: pre 1994	Ref.E	0.85	0.40	-25.85	27.50	cef
Overall	P2: 1995-2005	Ref.E	0.27	0.39	-37.41	38.00	g
Overall	P3: 2006-2012	Ref.E	0.49	0.39	-35.12	36.10	eg
Overall	P4: 2013-2021	Ref.E	0.48	0.40	-32.06	33.00	eg
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	1.37	0.43	-11.76	14.50	bcdf
Overall	P4: 2013-2021	Ref.W	1.70	0.44	-8.16	11.60	b d
Zonal	P2: 1995-2005	Ref.E	0.28	0.39	-59.30	59.80	a
Zonal	P4: 2013-2021	Ref.E	0.48	0.39	-49.40	50.40	ab
Zonal	P3: 2006-2012	Ref.E	0.50	0.39	-55.70	56.70	ab
Zonal	P4: 2013-2021	North	0.65	0.39	-41.50	42.80	abc
Zonal	P4: 2013-2021	East	0.66	0.39	-53.40	54.80	abc
Zonal	P1: pre 1994	Ref.E	0.85	0.40	-39.50	41.20	bcd
Zonal	P4: 2013-2021	West	0.94	0.39	-59.70	61.50	bcd
Zonal	P3: 2006-2012	West	1.10	0.39	-45.60	47.80	cd
Zonal	P3: 2006-2012	East	1.11	0.40	-36.00	38.20	cd
Zonal	P3: 2006-2012	North	1.13	0.40	-27.90	30.20	cd
Zonal	P3: 2006-2012	Ref.W	1.36	0.42	-17.10	19.80	cde
Zonal	P4: 2013-2021	Ref.W	1.70	0.43	-11.30	14.70	def
Zonal	P2: 1995-2005	East	1.78	0.39	-46.30	49.90	ef
Zonal	P2: 1995-2005	West	2.04	0.39	-53.80	57.90	ef
Zonal	P1: pre 1994	East	2.22	0.40	-29.70	34.10	fg
Zonal	P2: 1995-2005	North	2.24	0.40	-36.00	40.50	fg
Zonal	P1: pre 1994	North	2.77	0.42	-17.30	22.90	gh
Zonal	P1: pre 1994	West	3.30	0.41	-18.80	25.40	h
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

TOTAL CATCH – OFFSHORE SPECIES

Table C 8. *Results from the post-hoc assessment of differences in total catch of predominantly offshore fishes among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	2.53	0.52	-47.10	52.20	a
Overall	P2: 1995-2005	HamH	2.11	0.51	-56.30	60.50	b
Overall	P3: 2006-2012	HamH	1.12	0.51	-54.50	56.80	cde
Overall	P4: 2013-2021	HamH	1.18	0.51	-58.80	61.10	cd
Overall	P1: pre 1994	Ref.E	1.57	0.52	-40.30	43.50	bc
Overall	P2: 1995-2005	Ref.E	0.72	0.52	-52.90	54.40	e
Overall	P3: 2006-2012	Ref.E	0.75	0.52	-49.80	51.30	de
Overall	P4: 2013-2021	Ref.E	0.89	0.52	-49.20	51.00	de
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	1.50	0.55	-20.30	23.30	bcde
Overall	P4: 2013-2021	Ref.W	2.24	0.56	-16.50	21.00	ab
Zonal	P2: 1995-2005	Ref.E	0.72	0.51	-85.60	87.10	a
Zonal	P3: 2006-2012	Ref.E	0.75	0.51	-80.30	81.80	a
Zonal	P4: 2013-2021	East	0.81	0.52	-61.30	62.90	a
Zonal	P4: 2013-2021	Ref.E	0.90	0.51	-78.70	80.50	a
Zonal	P3: 2006-2012	East	0.91	0.53	-48.40	50.20	ab
Zonal	P4: 2013-2021	North	0.99	0.53	-46.20	48.20	ab
Zonal	P3: 2006-2012	West	1.12	0.52	-60.00	62.20	ab
Zonal	P3: 2006-2012	North	1.43	0.54	-36.30	39.10	abcd
Zonal	P3: 2006-2012	Ref.W	1.50	0.54	-30.70	33.70	abcde
Zonal	P4: 2013-2021	West	1.57	0.52	-70.10	73.20	bc
Zonal	P1: pre 1994	Ref.E	1.58	0.52	-64.00	67.20	bcd
Zonal	P1: pre 1994	East	2.07	0.53	-42.60	46.70	cde
Zonal	P2: 1995-2005	West	2.09	0.52	-66.00	70.20	de
Zonal	P2: 1995-2005	North	2.11	0.53	-42.40	46.60	cde
Zonal	P2: 1995-2005	East	2.11	0.52	-55.70	59.90	cde
Zonal	P4: 2013-2021	Ref.W	2.24	0.55	-24.60	29.10	cdef
Zonal	P1: pre 1994	North	2.51	0.55	-27.20	32.20	ef
Zonal	P1: pre 1994	West	3.10	0.54	-33.40	39.60	f
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

SPECIES RICHNESS

Table C 9. *Results from the post-hoc assessment of differences in species richness among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	0.73	0.10	-8.57	10.02	ab
Overall	P2: 1995-2005	HamH	0.76	0.10	-9.86	11.37	ac
Overall	P3: 2006-2012	HamH	0.67	0.10	-9.53	10.87	b
Overall	P4: 2013-2021	HamH	0.53	0.10	-10.31	11.36	d
Overall	P1: pre 1994	Ref.E	0.83	0.10	-7.55	9.22	ace
Overall	P2: 1995-2005	Ref.E	0.84	0.10	-9.56	11.24	ce
Overall	P3: 2006-2012	Ref.E	0.87	0.10	-8.92	10.66	e
Overall	P4: 2013-2021	Ref.E	0.79	0.10	-9.26	10.83	ace
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	0.74	0.11	-3.57	5.05	abce
Overall	P4: 2013-2021	Ref.W	0.81	0.11	-3.21	4.82	abce
Zonal	P4: 2013-2021	East	0.42	0.10	-12.95	13.78	a
Zonal	P4: 2013-2021	North	0.47	0.10	-10.12	11.05	ab
Zonal	P3: 2006-2012	East	0.55	0.10	-10.35	11.45	bc
Zonal	P1: pre 1994	East	0.59	0.10	-9.38	10.55	bcd
Zonal	P2: 1995-2005	East	0.63	0.10	-11.92	13.18	cdef
Zonal	P4: 2013-2021	West	0.65	0.10	-14.46	15.75	cdeg
Zonal	P3: 2006-2012	North	0.71	0.10	-7.88	9.31	defghi
Zonal	P3: 2006-2012	Ref.W	0.73	0.10	-6.66	8.12	defghi
Zonal	P1: pre 1994	North	0.74	0.10	-6.16	7.64	defghij
Zonal	P3: 2006-2012	West	0.75	0.10	-12.39	13.88	f h
Zonal	P2: 1995-2005	North	0.75	0.10	-9.24	10.74	efghij
Zonal	P4: 2013-2021	Ref.E	0.79	0.10	-15.62	17.19	hij
Zonal	P4: 2013-2021	Ref.W	0.81	0.10	-5.43	7.05	ghij
Zonal	P1: pre 1994	Ref.E	0.84	0.10	-13.06	14.73	hij
Zonal	P1: pre 1994	West	0.84	0.10	-7.46	9.14	hij
Zonal	P2: 1995-2005	Ref.E	0.84	0.10	-16.76	18.45	hij
Zonal	P2: 1995-2005	West	0.86	0.10	-13.59	15.31	ij
Zonal	P3: 2006-2012	Ref.E	0.88	0.10	-15.80	17.57	j
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

SPECIES RICHNESS – NATIVE SPECIES

Table C 10. *Results from the post-hoc assessment of differences in native species richness among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	0.53	0.09	-5.72	6.79	a
Overall	P2: 1995-2005	HamH	0.62	0.09	-6.83	8.07	b
Overall	P3: 2006-2012	HamH	0.58	0.09	-6.49	7.64	ab
Overall	P4: 2013-2021	HamH	0.42	0.09	-7.24	8.08	c
Overall	P1: pre 1994	Ref.E	0.79	0.09	-4.83	6.41	def
Overall	P2: 1995-2005	Ref.E	0.83	0.09	-6.67	8.33	de
Overall	P3: 2006-2012	Ref.E	0.85	0.09	-6.03	7.73	d
Overall	P4: 2013-2021	Ref.E	0.77	0.09	-6.48	8.01	def
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	0.65	0.09	-1.74	3.04	abf
Overall	P4: 2013-2021	Ref.W	0.68	0.09	-1.58	2.95	abef
Zonal	P4: 2013-2021	East	0.28	0.09	-8.30	8.87	a
Zonal	P1: pre 1994	East	0.36	0.09	-5.56	6.29	abc
Zonal	P4: 2013-2021	North	0.38	0.09	-5.88	6.64	ab
Zonal	P3: 2006-2012	East	0.43	0.09	-6.20	7.05	bcd
Zonal	P2: 1995-2005	East	0.47	0.09	-7.44	8.39	bcde
Zonal	P1: pre 1994	North	0.54	0.09	-3.22	4.31	cdefg
Zonal	P4: 2013-2021	West	0.56	0.09	-9.64	10.75	def
Zonal	P2: 1995-2005	North	0.59	0.09	-5.25	6.42	defg
Zonal	P3: 2006-2012	North	0.64	0.09	-4.23	5.51	fghi
Zonal	P3: 2006-2012	Ref.W	0.64	0.09	-3.54	4.82	efghi
Zonal	P3: 2006-2012	West	0.66	0.09	-7.84	9.15	gh
Zonal	P1: pre 1994	West	0.67	0.09	-4.12	5.45	fghi
Zonal	P4: 2013-2021	Ref.W	0.69	0.09	-2.79	4.16	fghij
Zonal	P2: 1995-2005	West	0.75	0.09	-8.87	10.36	hij
Zonal	P4: 2013-2021	Ref.E	0.77	0.08	-11.07	12.62	hijk
Zonal	P1: pre 1994	Ref.E	0.79	0.09	-8.61	10.20	ijk
Zonal	P2: 1995-2005	Ref.E	0.83	0.08	-12.15	13.81	jk
Zonal	P3: 2006-2012	Ref.E	0.86	0.08	-11.16	12.88	k
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

SPECIES RICHNESS – NON-NATIVE SPECIES

Table C 11. *Results from the post-hoc assessment of differences in non-native species richness among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	0.45	0.07	-6.38	7.28	a
Overall	P2: 1995-2005	HamH	0.38	0.07	-8.13	8.88	b
Overall	P3: 2006-2012	HamH	0.28	0.07	-7.67	8.23	c
Overall	P4: 2013-2021	HamH	0.22	0.07	-8.59	9.03	d
Overall	P1: pre 1994	Ref.E	0.19	0.07	-5.08	5.46	de
Overall	P2: 1995-2005	Ref.E	0.06	0.07	-7.12	7.25	f
Overall	P3: 2006-2012	Ref.E	0.13	0.07	-6.67	6.92	ef
Overall	P4: 2013-2021	Ref.E	0.09	0.07	-6.28	6.45	f
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	0.29	0.08	-2.38	2.96	bcd
Overall	P4: 2013-2021	Ref.W	0.38	0.08	-1.69	2.46	abc
Zonal	P2: 1995-2005	Ref.E	0.06	0.07	-11.38	11.51	a
Zonal	P4: 2013-2021	Ref.E	0.09	0.07	-9.85	10.03	ab
Zonal	P3: 2006-2012	Ref.E	0.13	0.07	-10.65	10.90	abc
Zonal	P4: 2013-2021	North	0.17	0.07	-7.36	7.70	bcd
Zonal	P1: pre 1994	Ref.E	0.19	0.07	-7.90	8.28	cde
Zonal	P4: 2013-2021	East	0.21	0.07	-9.42	9.84	cde
Zonal	P4: 2013-2021	West	0.26	0.07	-10.63	11.15	def
Zonal	P3: 2006-2012	North	0.26	0.08	-5.18	5.70	def
Zonal	P3: 2006-2012	East	0.27	0.07	-6.71	7.26	def
Zonal	P3: 2006-2012	Ref.W	0.29	0.08	-3.52	4.10	defgh
Zonal	P3: 2006-2012	West	0.29	0.07	-8.43	9.01	efg
Zonal	P2: 1995-2005	East	0.34	0.07	-8.38	9.05	fghi
Zonal	P4: 2013-2021	Ref.W	0.38	0.08	-2.45	3.22	fghij
Zonal	P2: 1995-2005	West	0.38	0.07	-9.76	10.53	hij
Zonal	P1: pre 1994	East	0.40	0.07	-5.71	6.51	ghij
Zonal	P2: 1995-2005	North	0.42	0.07	-6.45	7.29	hij
Zonal	P1: pre 1994	North	0.45	0.08	-3.48	4.39	ij
Zonal	P1: pre 1994	West	0.50	0.08	-3.97	4.97	j
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

SPECIES RICHNESS – CENTRARCHIDS

Table C 12. *Results from the post-hoc assessment of differences in Centrarchidae species richness among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	0.21	0.05	-0.58	0.99	a
Overall	P2: 1995-2005	HamH	0.31	0.04	-0.74	1.35	bc
Overall	P3: 2006-2012	HamH	0.23	0.04	-0.72	1.18	a
Overall	P4: 2013-2021	HamH	0.11	0.04	-0.99	1.21	d
Overall	P1: pre 1994	Ref.E	0.39	0.05	-0.35	1.12	be
Overall	P2: 1995-2005	Ref.E	0.55	0.04	-0.68	1.78	f
Overall	P3: 2006-2012	Ref.E	0.57	0.04	-0.46	1.59	f
Overall	P4: 2013-2021	Ref.E	0.44	0.04	-0.77	1.64	e
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	0.23	0.06	-0.08	0.53	acd
Overall	P4: 2013-2021	Ref.W	0.28	0.06	-0.03	0.58	abc
Zonal	P4: 2013-2021	North	0.03	0.05	-0.37	0.42	a
Zonal	P4: 2013-2021	East	0.03	0.05	-0.53	0.59	ab
Zonal	P1: pre 1994	East	0.06	0.05	-0.36	0.49	abc
Zonal	P3: 2006-2012	East	0.13	0.05	-0.33	0.58	abcd
Zonal	P3: 2006-2012	North	0.15	0.05	-0.20	0.50	bcde
Zonal	P1: pre 1994	North	0.18	0.06	-0.14	0.51	bcdef
Zonal	P2: 1995-2005	North	0.21	0.05	-0.17	0.59	bcdef
Zonal	P4: 2013-2021	West	0.21	0.05	-0.54	0.96	cd
Zonal	P3: 2006-2012	Ref.W	0.22	0.05	-0.15	0.59	cdef
Zonal	P2: 1995-2005	East	0.22	0.05	-0.30	0.75	def
Zonal	P4: 2013-2021	Ref.W	0.28	0.05	-0.08	0.63	defg
Zonal	P1: pre 1994	West	0.34	0.05	-0.05	0.74	efgh
Zonal	P3: 2006-2012	West	0.35	0.05	-0.27	0.97	fgh
Zonal	P1: pre 1994	Ref.E	0.38	0.04	-0.65	1.42	gh
Zonal	P2: 1995-2005	West	0.43	0.05	-0.28	1.13	gh
Zonal	P4: 2013-2021	Ref.E	0.44	0.04	-1.33	2.21	h
Zonal	P2: 1995-2005	Ref.E	0.55	0.04	-1.40	2.50	i
Zonal	P3: 2006-2012	Ref.E	0.57	0.04	-1.02	2.16	i
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

SPECIES RICHNESS – CYPRINIDS

Table C 13. *Results from the post-hoc assessment of differences in Cyprinid species richness among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	0.18	0.04	-1.46	1.81	a
Overall	P2: 1995-2005	HamH	0.15	0.04	-2.61	2.90	a
Overall	P3: 2006-2012	HamH	0.17	0.04	-2.16	2.49	a
Overall	P4: 2013-2021	HamH	0.08	0.04	-2.94	3.11	b
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	0.24	0.05	-0.18	0.65	ac
Overall	P4: 2013-2021	Ref.W	0.15	0.05	-0.20	0.50	abc
Overall	P1: pre 1994	Ref.E	0.17	0.04	-0.85	1.18	a
Overall	P2: 1995-2005	Ref.E	0.21	0.04	-1.69	2.11	ac
Overall	P3: 2006-2012	Ref.E	0.26	0.04	-1.38	1.91	c
Overall	P4: 2013-2021	Ref.E	0.15	0.04	-1.35	1.64	ab
Zonal	P4: 2013-2021	East	0.05	0.04	-1.49	1.58	a
Zonal	P4: 2013-2021	North	0.07	0.05	-0.89	1.02	ab
Zonal	P4: 2013-2021	West	0.11	0.04	-1.95	2.18	abc
Zonal	P3: 2006-2012	West	0.13	0.04	-1.25	1.51	abcd
Zonal	P2: 1995-2005	East	0.13	0.04	-1.17	1.43	abcd
Zonal	P4: 2013-2021	Ref.W	0.15	0.05	-0.27	0.56	abcde
Zonal	P4: 2013-2021	Ref.E	0.15	0.04	-2.01	2.30	bcd
Zonal	P2: 1995-2005	West	0.15	0.04	-1.65	1.96	bcd
Zonal	P2: 1995-2005	North	0.16	0.05	-0.69	1.01	abcde
Zonal	P3: 2006-2012	East	0.16	0.05	-0.78	1.10	bcde
Zonal	P1: pre 1994	West	0.17	0.05	-0.41	0.74	abcde
Zonal	P1: pre 1994	Ref.E	0.17	0.04	-1.23	1.56	bcd
Zonal	P1: pre 1994	East	0.17	0.05	-0.62	0.96	bcde
Zonal	P1: pre 1994	North	0.19	0.05	-0.30	0.68	abcde
Zonal	P2: 1995-2005	Ref.E	0.21	0.04	-2.60	3.03	de
Zonal	P3: 2006-2012	Ref.W	0.24	0.05	-0.26	0.73	cde
Zonal	P3: 2006-2012	North	0.25	0.05	-0.40	0.90	de
Zonal	P3: 2006-2012	Ref.E	0.26	0.04	-2.13	2.66	e
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

NATIVE BIOMASS

Table C 14. *Results from the post-hoc assessment of differences in native species biomass among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	0.37	0.07	-1.49	2.22	a
Overall	P2: 1995-2005	HamH	0.37	0.07	-2.39	3.12	a
Overall	P3: 2006-2012	HamH	0.38	0.07	-2.05	2.81	a
Overall	P4: 2013-2021	HamH	0.43	0.07	-2.52	3.38	ab
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	0.26	0.09	-0.31	0.84	a
Overall	P4: 2013-2021	Ref.W	0.73	0.09	0.19	1.27	c
Overall	P1: pre 1994	Ref.E	0.62	0.07	-0.80	2.05	c
Overall	P2: 1995-2005	Ref.E	0.41	0.07	-2.12	2.94	a
Overall	P3: 2006-2012	Ref.E	0.56	0.07	-1.55	2.68	bc
Overall	P4: 2013-2021	Ref.E	0.46	0.07	-1.80	2.71	ab
Zonal	P3: 2006-2012	East	0.19	0.08	-1.05	1.43	a
Zonal	P1: pre 1994	East	0.23	0.08	-0.85	1.31	ab
Zonal	P2: 1995-2005	East	0.25	0.08	-1.34	1.85	ab
Zonal	P3: 2006-2012	Ref.W	0.28	0.09	-0.48	1.04	abc
Zonal	P4: 2013-2021	East	0.30	0.08	-1.52	2.11	abc
Zonal	P4: 2013-2021	North	0.31	0.08	-0.84	1.46	abc
Zonal	P3: 2006-2012	North	0.34	0.08	-0.54	1.21	abcd
Zonal	P1: pre 1994	North	0.40	0.09	-0.30	1.10	abcdefg
Zonal	P2: 1995-2005	North	0.41	0.08	-0.65	1.46	abcdef
Zonal	P2: 1995-2005	Ref.E	0.41	0.07	-3.85	4.68	bcd
Zonal	P2: 1995-2005	West	0.43	0.07	-1.79	2.66	bcde
Zonal	P1: pre 1994	West	0.44	0.08	-0.42	1.30	abcdefg
Zonal	P4: 2013-2021	Ref.E	0.46	0.07	-3.01	3.92	cdef
Zonal	P3: 2006-2012	West	0.54	0.08	-1.25	2.33	defgh
Zonal	P3: 2006-2012	Ref.E	0.57	0.07	-2.99	4.13	efgh
Zonal	P4: 2013-2021	West	0.60	0.07	-1.89	3.08	fgh
Zonal	P1: pre 1994	Ref.E	0.63	0.07	-1.54	2.80	gh
Zonal	P4: 2013-2021	Ref.W	0.73	0.09	0.07	1.40	h
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

PROPORTION PISCIVORE BIOMASS (PPB)

Table C 15. *Results from the post-hoc assessment of differences in percentage of biomass comprised of piscivorous species among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	5.44	2.57	-2.03	12.90	a
Overall	P2: 1995-2005	HamH	8.34	2.04	2.25	14.40	a
Overall	P3: 2006-2012	HamH	13.25	2.22	6.69	19.80	a
Overall	P4: 2013-2021	HamH	9.92	1.95	4.04	15.80	a
Overall	P1: pre 1994	Ref.E	32.41	3.06	23.60	41.20	bc
Overall	P2: 1995-2005	Ref.E	26.77	2.31	20.04	33.50	bd
Overall	P3: 2006-2012	Ref.E	42.04	2.57	34.53	49.50	c
Overall	P4: 2013-2021	Ref.E	39.23	2.60	31.64	46.80	c
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	11.19	4.80	-2.59	25.00	ad
Overall	P4: 2013-2021	Ref.W	13.54	5.10	-1.08	28.10	abd
Zonal	P4: 2013-2021	East	3.15	3.20	-6.81	13.10	a
Zonal	P1: pre 1994	East	3.53	3.95	-8.57	15.60	a
Zonal	P1: pre 1994	North	4.08	4.87	-10.77	18.90	ab
Zonal	P2: 1995-2005	North	5.19	3.98	-7.13	17.50	ab
Zonal	P3: 2006-2012	East	5.36	3.73	-6.10	16.80	ab
Zonal	P1: pre 1994	West	6.61	4.38	-6.67	19.90	ab
Zonal	P3: 2006-2012	North	7.09	4.35	-6.27	20.50	ab
Zonal	P2: 1995-2005	West	8.46	2.95	-0.70	17.60	a
Zonal	P4: 2013-2021	North	8.91	3.84	-3.04	20.90	ab
Zonal	P2: 1995-2005	East	10.29	3.36	-0.13	20.70	ab
Zonal	P3: 2006-2012	Ref.W	11.12	4.71	-3.16	25.40	abc
Zonal	P4: 2013-2021	Ref.W	13.56	5.04	-1.70	28.80	abcd
Zonal	P4: 2013-2021	West	15.77	2.83	6.93	24.60	abc
Zonal	P3: 2006-2012	West	22.49	3.23	12.56	32.40	bcd
Zonal	P2: 1995-2005	Ref.E	26.87	2.27	19.89	33.90	cd
Zonal	P1: pre 1994	Ref.E	32.63	3.01	23.46	41.80	de
Zonal	P4: 2013-2021	Ref.E	39.24	2.58	31.28	47.20	e
Zonal	P3: 2006-2012	Ref.E	42.21	2.52	34.43	50.00	e
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

PROPORTION OFFSHORE BIOMASS

Table C 16. *Results from the post-hoc assessment of differences in percentage of biomass comprised of offshore species among Hamilton Harbour (overall) or zones in Hamilton Harbour (zonal) and the east [Ref.E], and west [Ref.W] references areas based on least-squares means. For each combination of Stanza and Zone an estimate (modelled mean), standard error (SE), lower and upper confidence intervals (CI), and letter groupings are provided. Combinations that do not share the same letter groups are interpreted as significantly different based on α of <0.05. No data were available for the Ref.W in Time Stanza P1 and P2.*

Comparison	Stanza	Zone	Estimate	SE	Lower CI	Upper CI	Group
Overall	P1: pre 1994	HamH	28.49	4.82	-23.59	80.60	ab
Overall	P2: 1995-2005	HamH	21.13	4.40	-82.04	124.30	ac
Overall	P3: 2006-2012	HamH	17.20	4.53	-62.78	97.20	cd
Overall	P4: 2013-2021	HamH	37.67	4.33	-82.98	158.30	b
Overall	P1: pre 1994	Ref.E	20.40	5.30	-14.60	55.40	acd
Overall	P2: 1995-2005	Ref.E	8.65	4.68	-53.54	70.80	d
Overall	P3: 2006-2012	Ref.E	9.09	4.82	-43.70	61.90	cd
Overall	P4: 2013-2021	Ref.E	8.32	4.89	-39.98	56.60	d
Overall	P1: pre 1994	Ref.W					
Overall	P2: 1995-2005	Ref.W					
Overall	P3: 2006-2012	Ref.W	17.30	6.83	-8.11	42.70	acd
Overall	P4: 2013-2021	Ref.W	29.02	7.33	3.62	54.40	abcd
Zonal	P4: 2013-2021	Ref.E	8.33	4.91	-55.18	71.90	a
Zonal	P2: 1995-2005	Ref.E	8.69	4.71	-76.21	93.60	a
Zonal	P3: 2006-2012	Ref.E	9.14	4.84	-61.01	79.30	a
Zonal	P1: pre 1994	North	13.64	6.89	-14.39	41.70	abc
Zonal	P2: 1995-2005	West	14.60	5.10	-36.85	66.00	ab
Zonal	P3: 2006-2012	West	14.95	5.35	-27.14	57.00	ab
Zonal	P2: 1995-2005	North	16.15	5.93	-16.16	48.50	abc
Zonal	P3: 2006-2012	Ref.W	17.26	6.81	-10.86	45.40	abcd
Zonal	P3: 2006-2012	North	17.68	6.32	-11.95	47.30	abc
Zonal	P3: 2006-2012	East	19.74	5.78	-14.06	53.50	abcd
Zonal	P1: pre 1994	Ref.E	20.35	5.31	-22.80	63.50	abcd
Zonal	P1: pre 1994	West	28.09	6.51	-0.69	56.90	abcde
Zonal	P4: 2013-2021	Ref.W	29.08	7.30	1.37	56.80	abcde
Zonal	P4: 2013-2021	East	30.98	5.26	-14.06	76.00	bcde
Zonal	P2: 1995-2005	East	32.94	5.42	-7.30	73.20	bcde
Zonal	P4: 2013-2021	North	37.82	5.78	3.87	71.80	de
Zonal	P1: pre 1994	East	38.56	6.01	7.07	70.00	cde
Zonal	P4: 2013-2021	West	42.97	4.99	-15.09	101.00	e
Zonal	P1: pre 1994	Ref.W					
Zonal	P2: 1995-2005	Ref.W					

APPENDIX D: SPECIES-SPECIFIC TRAP NET CATCH INFORMATION

WALLEYE

Walleye restoration

Findings from the NSCIN surveys have historically shown very low abundance of Walleye in the Hamilton Harbour AOC relative to comparable sheltered embayments in Lake Ontario. Walleye are a predatory fish, and a healthy fish community should have a percentage of predators to balance the fish community (i.e., PPB > 20%). The Hamilton Harbour AOC has historically been below this target. Stocking Walleye in the Hamilton Harbour AOC not only supports efforts of the local RAP objectives to restore a healthy fish community, but it may also provide angling opportunities for urban anglers.

In the 1990s, there was an opportunistic stocking of adult and summer fingerling Walleye into Hamilton Harbour in low numbers and biomass. Starting in 2012, a more targeted effort was directed at Walleye stocking in Hamilton Harbour. The Lake Ontario Management Unit worked in conjunction with OMNRF’s White Lake Fish Culture Station to collect Bay of Quinte Walleye gametes (target of eight million eggs and 40 families) with the goal of stocking out Walleye of various life stages at different times of the year into Hamilton Harbour. In July 2018, a target was set at 100,000 3-month old (summer fingerling) Walleye stocked into Hamilton Harbour every other year (Ontario Ministry of Natural Resources and Forestry, 2020). In 2018, 2020, and 2022, 82,176, 26,394, and 63,031 3-month old Walleye were stocked respectively, along with a number of swim-up fry in 2018 and 2022 (Table D1). The low number of 3-month old Walleye stocked in 2020 was due to a hatchery production issue.

In 2021, three age classes, age nine, age five, and age three, were captured in the trap net survey (Table D2). These ages corresponded with stocking events in 2012, 2016, and 2018. Two thousand twenty one was the first year to detect Walleye presumably from the 2018 stocking event, but the age five and age nine Walleye corresponding with the 2012 and 2016 stocking had been detected in the survey starting in 2014 and 2018, respectively. These year classes provide evidence that multiple years of stocked Walleye survived and persisted within the Hamilton Harbour fish community and reached age of maturity. The outcomes of Walleye stocking will continue to be monitored in future surveys.

Walleye condition

Hamilton Harbour Walleye condition was evaluated using relative weight (Wr) and compared to the Bay of Quinte Walleye population (an unimpaired fish community with a highly productive Walleye population, Hoyle et al. 2017). Wr was selected as it serves not only as a common measure of fish condition but is a measure of fish health and has been correlated with prey abundance (Blackwell et al., 2000). Wr was calculated using the equation developed by Murphey et al. (1990) and biological data (length and weight) collected from existing OMNRF fisheries assessment programs. Biological data from the Bay of Quinte and Eastern Basin of Lake Ontario collected from OMNRF's community index gillnet survey (2006-2021; Ontario Ministry of Natural Resources and Forestry, 2022) was used to provide an accurate representation of the Bay of Quinte Walleye population (Hoyle et al. 2017). At the time of the gillnet survey, juvenile and young of year Walleye occupied the Bay of Quinte, whereas adults showed extremely low residency and migrated out into the Eastern Basin, Lake Ontario (Elliott et al. 2022, Hoyle and Bowlby 2011). As such, both sites were included to ensure the Bay of Quinte Walleye population was accurately represented. Acoustic telemetry data for Walleye in Hamilton Harbour indicated many Walleye (73%) leave Hamilton harbour during the summer while some stay resident (Brooks et al. 2019; Larocque et al. 2024). Biological data collected from OMNRFs Hamilton Harbour NSCIN trap net survey (2006-2021; Ontario Ministry of Natural Resources and Forestry, 2022) was the only information available at the time of this report and therefore was used to represent the Hamilton Walleye population.

Walleye Wr in Hamilton Harbour was higher when compared to the Bay of Quinte in the first time stanza and similar in the second time stanza (Figure D1; Table D3). Higher Walleye Wr in Hamilton in the first time stanza may be explained, in part, by the catches of predominantly large and older individuals that may have been adult remnants from the Bay of Quinte transplants that occurred in the 1990's (Table D3). The Bay of Quinte Walleye population is highly productive with high condition due in part to their eastern Lake Ontario migration and the availability of Alewife as a prey source (Hoyle et al., 2017). The observation that Hamilton Walleye Wr is comparable to that observed in the Bay of Quinte population suggests that Walleye in Hamilton Harbour are in good condition with adequate prey availability despite a degraded fish community and occurrences of hypoxia.

Table D 1. *Chronology of Walleye (Bay of Quinte strain, White Lake Fish Culture Station) stocked into the Hamilton Harbour Area of Concern 1993-2022. Adults in the 1990's were directly transplanted from the Bay of Quinte.*

Year	Month	Life-Stage	Number of Fish	Total Biomass (kg)
1993	Oct	Adult	185	111
1994	Oct	Adult	129	193.5
1997	Oct	Adult	130	117
1998	Sept	Adult	120	163.7
1998	July	Summer Fingerling	5,000	2.5
1999	July	Summer Fingerling	6,000	3.2
2012	July	Summer Fingerling	100,000	40.8
2012	Nov	Adult	74	77.7
2013	July	Summer Fingerling	10,000	5.1
2014	June	Swim-up Fry	950,000	-
2015	May	Swim-up Fry	1,017,625	-
2015	July	Summer Fingerling	52,963	15
2016	May	Swim-up Fry	168,000	-
2016	June	Summer Fingerling	115,722	52.1
2018	May	Swim-up Fry	1,000,000	-
2018	July	Summer Fingerling	82,176	49.4
2020	July	Summer Fingerling	26,394	13.2
2022	May	Swim-up Fry	1,073,870	-
2022	July	Summer Fingerling	63,031	29

Table D 2. *Ages (and proportion) of Walleye captured in trap nets annually. Total Walleye aged, mean round weight (g) and mean fork length (mm) is summarized.*

	Year								
Age	**2006**	**2008**	**2010**	**2014**	**2015**	**2016**	**2018**	**2019**	**2021**
1								1 (0.03)	
2				30 (1)	1 (0.03)		10 (0.42)		
3	6 (0.33)				29 (0.94)		2 (0.08)	15 (0.48)	9 (0.31)
4						31 (1)		4 (0.13)	
5	1 (0.06)								6 (0.21)
6							11 (0.46)		
7	2 (0.11)		1 (1)				1 (0.04)	10 (0.32)	
8	7 (0.39)								
9		2 (0.5)							14 (0.48)
10	1 (0.06)	2 (0.5)							
11	1 (0.06)								
12					1 (0.03)				
13								1 (0.03)	
Total aged	18	4	1	30	31	31	24	30	29
Mean weight	2806	3824	3737	697	1398	1770	1691	2185	2495
Mean length	581	658	650	417	492	527	557	579	610

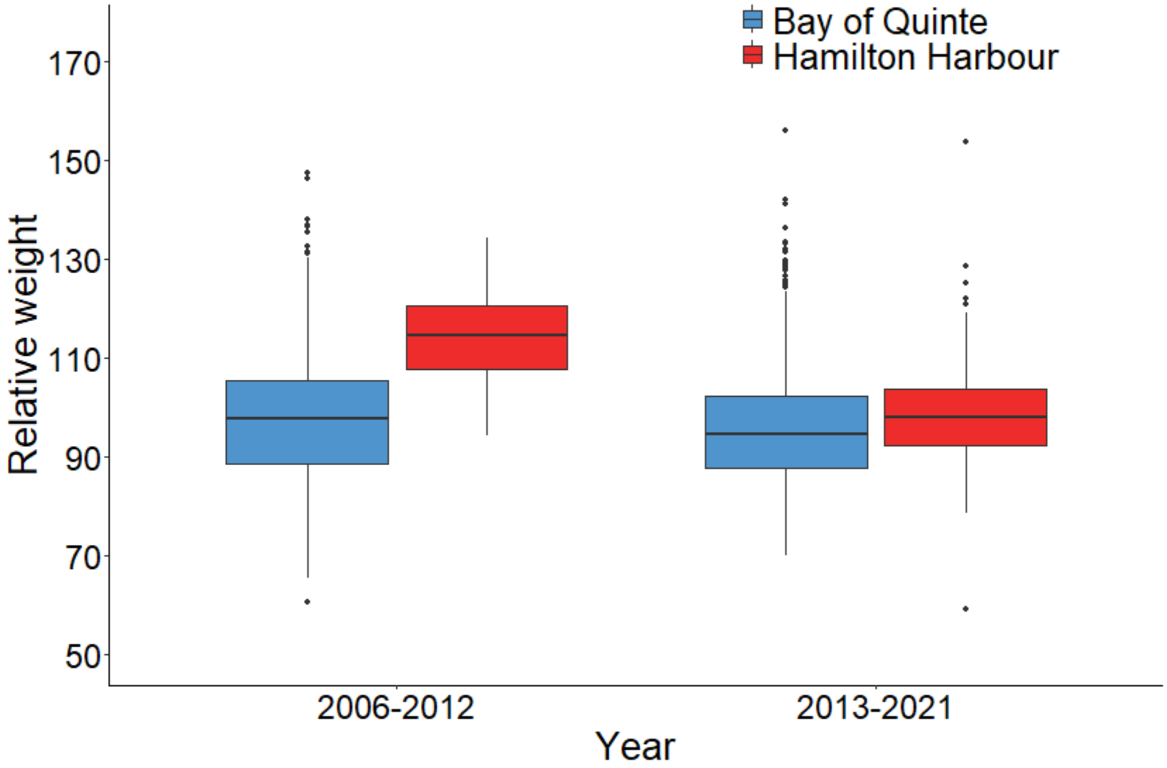

Figure D 1. *Relative weight (Wr) of Walleye from Hamilton Harbour (red) and the Bay of Quinte (blue) in two time stanzas.*

Table D 3. *Annual average relative weight (Wr) and standard deviation of Walleye in Hamilton Harbour and the Bay of Quinte.*

Year	Bay of Quinte	Hamilton Harbour
2006	96.16 (10.7)	114.36 (10.4)
2007	94.09 (9.6)	-
2008	96.14 (10.1)	110.73 (4)
2009	95.62 (10.9)	-
2010	100.2 (13.3)	114.62 (0)
2011	99.23 (12.2)	-
2012	100.01 (11.4)	-
2013	93.08 (11.1)	-
2014	96.46 (10.1)	94.78 (6.4)
2015	96.61 (12.2)	98.99 (9.1)
2016	95.84 (13.1)	102.38 (11.7)
2017	95.94 (11.5)	-
2018	96.24 (9.8)	95.7 (9.2)
2019	95.3 (9.5)	102.41 (13.6)
2020	94.24 (9.5)	-
2021	92.99 (9.1)	95.69 (10.9)

NORTHERN PIKE

Biological data was taken from Northern Pike sampled during the NSCIN trap netting program run by the Lake Ontario Management Unit (OMNRF) between 2006-2021. A total of 130 individuals were sampled for biological information from Hamilton Harbour with 108 sampled lethally over 10 sampling events (a total of 137 fish caught in all years). Ages and proportion of ages within a year were summarized annually for Hamilton Harbour. Length-weight regressions were also calculated for Hamilton Harbour and reference sheltered embayments in two timeframes. The relationship was modelled using the equation, where RWT = weight (g) and FLEN = fork length (mm):

$$log\ [RWT] = slope * log\ [FLEN]\ + intercept$$

Ages of Northern Pike sampled in trap nets between 2006-2021 ranged from 0 to 8 with a broad range of age classes observed in most years (Table D4). NSCIN trap nets do not target smaller fish with elongated body shapes (Stirling 1999) and therefore are not a robust indicator of age-0 Northern Pike. The length weight regression model showed an increased slope for Hamilton Harbour compared to other sheltered embayments in the first time stanza but not the second (Figure D2). At large fork lengths, individuals generally weighed more in Hamilton than other sheltered embayments, however, sample sizes were smaller for Hamilton potentially explaining the similar slopes.

Table D 4. *Annual ages and proportion of ages of Northern Pike captured in trap nets in Hamilton Harbour.*

	Year									
Age	**2008**	**2010**	**2012**	**2014**	**2015**	**2016**	**2018**	**2019**	**2021**	
0		1 (0.05)								
1	4 (0.19)		1 (0.06)	1 (0.14)	1 (0.17)		2 (0.17)	1 (0.14)	1 (0.06)	1 (0.11)
2	3 (0.14)	2 (0.1)	12 (0.67)	2 (0.29)		5 (0.45)	2 (0.17)		3 (0.19)	2 (0.22)
3	8 (0.38)	2 (0.1)	3 (0.17)	1 (0.14)	1 (0.17)	3 (0.27)	4 (0.33)	3 (0.43)	5 (0.31)	
4	5 (0.24)	3 (0.14)	1 (0.06)	3 (0.43)	1 (0.17)	2 (0.18)	3 (0.25)		4 (0.25)	1 (0.11)
5	1 (0.05)	6 (0.29)	1 (0.06)		1 (0.17)		1 (0.08)	1 (0.14)	1 (0.06)	1 (0.11)
6		3 (0.14)				1 (0.09)		2 (0.29)	2 (0.12)	3 (0.33)
7		3 (0.14)			2 (0.33)					1 (0.11)
8		1 (0.05)								
Total aged	21	21	18	7	6	11	12	7	16	9

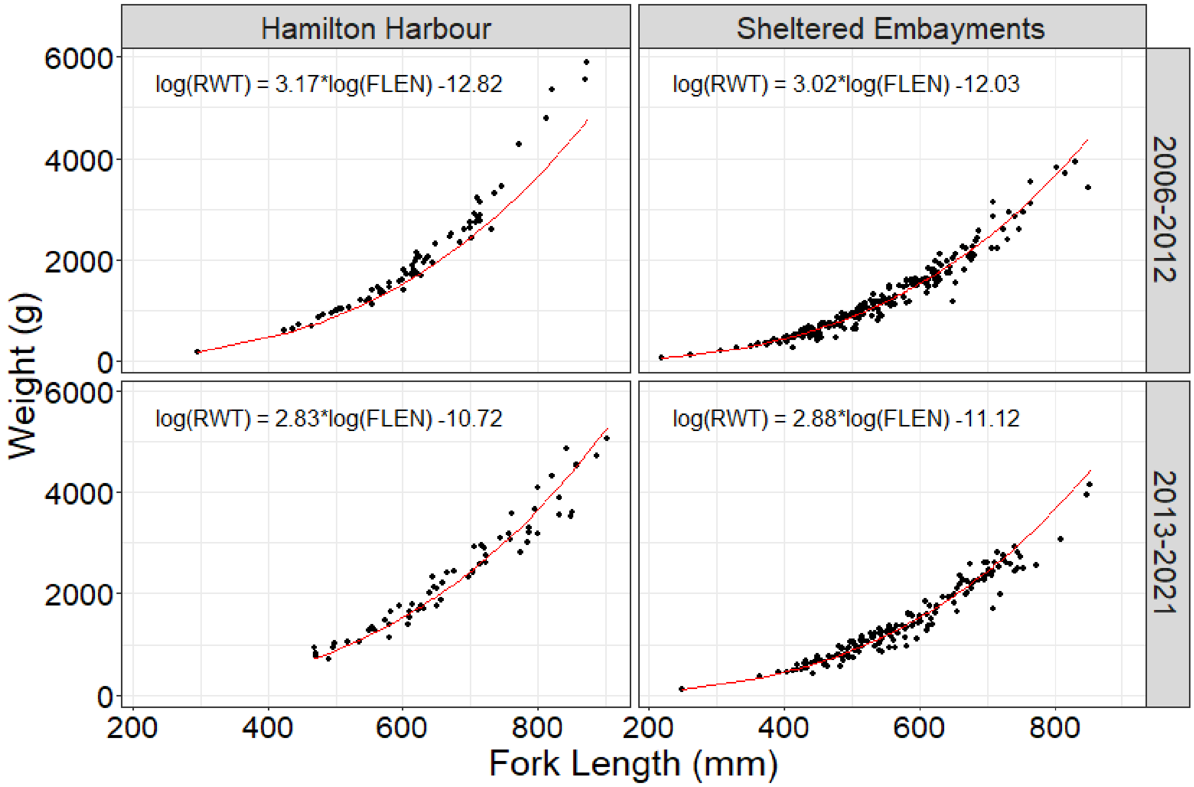

Figure D 2. *Length weight regression for Northern Pike in Hamilton Harbour compared to reference sheltered embayments (East Lake, West Lake, Weller's Bay, Upper and Middle Bay of Quinte) in two time stanzas (2006-2012, 2013-2021).*

LARGEMOUTH BASS

Biological data was taken from Largemouth Bass sampled during the NSCIN trap netting program run by the Lake Ontario Management Unit (OMNRF) between 2006-2021. Age and proportion of ages within a year were summarized annually for Hamilton Harbour. Length weight regressions were also calculated for Hamilton Harbour and reference sheltered embayments in two timeframes. The relationship was modelled using the equation, where RWT = weight (g) and FLEN = fork length (mm):

$$log\,[RWT] = slope * \quad log\,[FLEN]\; + intercept$$

Ages of Largemouth Bass sampled in trap nets between 2006-2021 ranged from 0 to 10 (Table D5). The range and distribution of ages were generally inconsistent across years. The length weight regression model indicated similar slopes for Hamilton Harbour and other sheltered embayments in the first time stanza but less similar in the second time stanza (Figure D3). Individuals generally had heavier weights at large fork lengths in Hamilton compared to other sheltered embayments, potentially influenced by substantially smaller sample sizes in Hamilton.

Table D 5. *Annual ages and proportion of ages of Largemouth Bass captured in trap nets in Hamilton Harbour.*

				Year				
Age	**2006**	**2008**	**2014**	**2015**	**2016**	**2018**	**2019**	**2021**
0						1 (0.11)		12 (0.71)
1	1 (0.2)				2 (0.5)	1 (0.11)		1 (0.06)
2	2 (0.4)		1 (0.33)					1 (0.06)
3			1 (0.33)			1 (0.11)		
4		2 (0.5)	1 (0.33)		1 (0.25)	1 (0.11)		
5	1 (0.2)			1 (1)		2 (0.22)		
6		2 (0.5)			1 (0.25)	2 (0.22)		
7						1 (0.11)		1 (0.06)
8							1 (0.5)	1 (0.06)
9	1 (0.2)							
10							1 (0.5)	1 (0.06)
Total aged	5	4	3	1	5	9	2	17

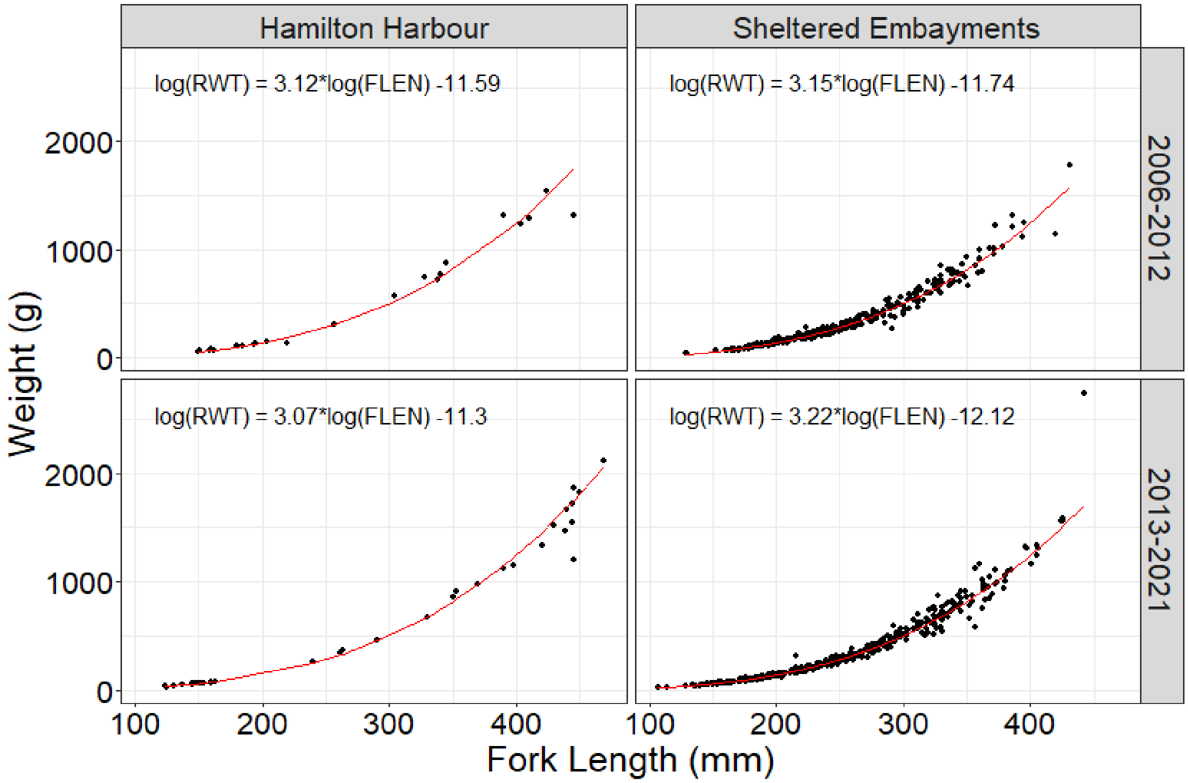

Figure D 3. *Length weight regression for Largemouth Bass in Hamilton Harbour compared to reference sheltered embayments (East Lake, West Lake, Weller's Bay, Upper and Middle Bay of Quinte) in two time stanzas (2006-2012, 2013-2021).*

BLUEGILL

Biological data were taken from Bluegill sampled during the NSCIN trap netting program run by the Lake Ontario Management Unit (OMNRF) between 2006-2021. Age and proportion of ages within a year were summarized annually for Hamilton Harbour (Table D6). Length weight regressions were also calculated for Hamilton Harbour and reference sheltered embayments in two timeframes (Figure D4). The relationship was modelled using the equation, where RWT = weight (g) and FLEN = fork length (mm):

$$log\,[RWT] = slope * log\,[FLEN]\; + intercept$$

Table D 6. *Annual ages and proportion of ages of Bluegill captured in trap nets in Hamilton Harbour.*

	Year						
Age	**2008**	**2014**	**2015**	**2016**	**2018**	**2019**	**2021**
1	1 (0.03)			6 (0.2)	1 (0.03)		10 (0.32)
2	3 (0.1)	11 (0.37)	6 (0.21)	13 (0.43)	12 (0.31)		8 (0.26)
3	17 (0.57)	5 (0.17)	13 (0.45)	4 (0.13)	18 (0.46)	1 (0.33)	6 (0.19)
4	8 (0.27)	9 (0.3)	8 (0.28)	5 (0.17)	8 (0.21)	2 (0.67)	5 (0.16)
5	1 (0.03)	4 (0.13)	2 (0.07)	1 (0.03)			1 (0.03)
6		1 (0.03)		1 (0.03)			1 (0.03)
Total aged	30	30	29	30	39	3	28

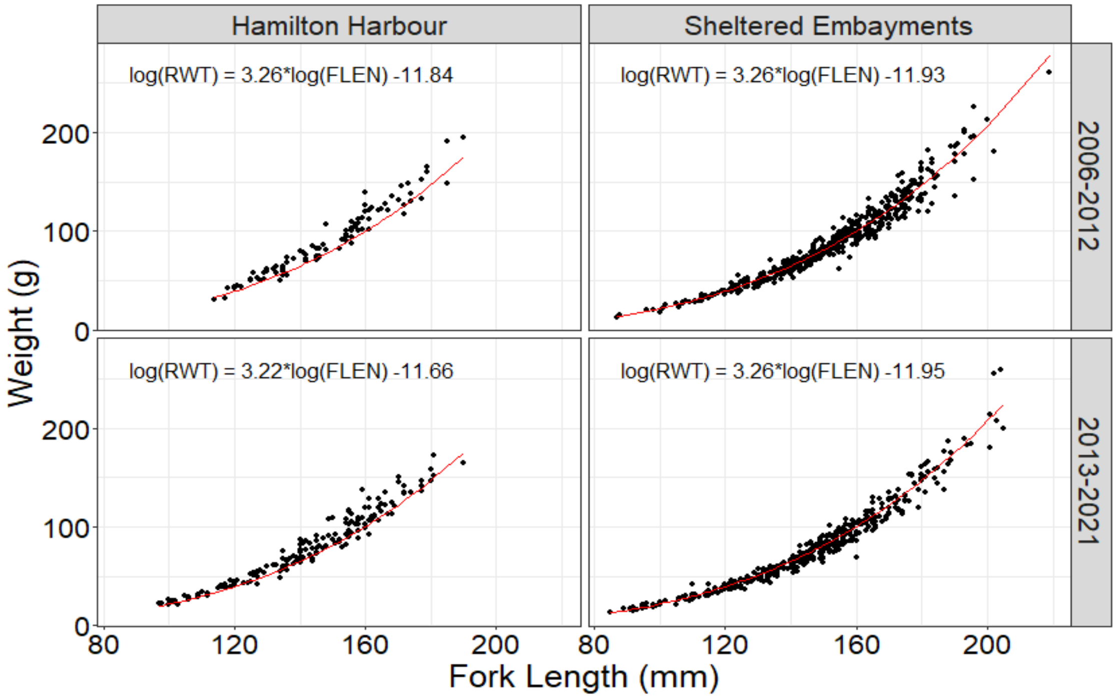

Figure D 4. *Length weight regression for Bluegill in Hamilton Harbour compared to reference sheltered embayments (East Lake, West Lake, Weller's Bay, Upper and Middle Bay of Quinte) in two time stanzas (2006-2012, 2013-2021).*

PUMPKINSEED

Biological data was taken from Pumpkinseed sampled during the NSCIN trap netting program run by the Lake Ontario Management Unit (OMNRF) between 2006-2021. Age and proportion of ages within a year were summarized annually for Hamilton Harbour (Table D7). Length weight regressions were also calculated for Hamilton Harbour and reference sheltered embayments in two timeframes (Figure D5). The relationship was modelled using the equation, where RWT = weight (g) and FLEN = fork length (mm):

$$log\ [RWT] = slope * log\ [FLEN] + intercept$$

Table D 7. *Annual ages and proportion of ages of Pumpkinseed captured in trap nets in Hamilton Harbour.*

	Year					
Age	**2008**	**2014**	**2016**	**2018**	**2019**	**2021**
1	2 (0.08)	5 (0.25)				19 (0.63)
2	10 (0.38)	6 (0.3)	11 (0.73)	20 (1)		11 (0.37)
3	9 (0.35)	5 (0.25)	3 (0.2)		1 (0.5)	
4	5 (0.19)	3 (0.15)	1 (0.07)		1 (0.5)	
5		1 (0.05)				
Total aged	27	20	15	20	2	30

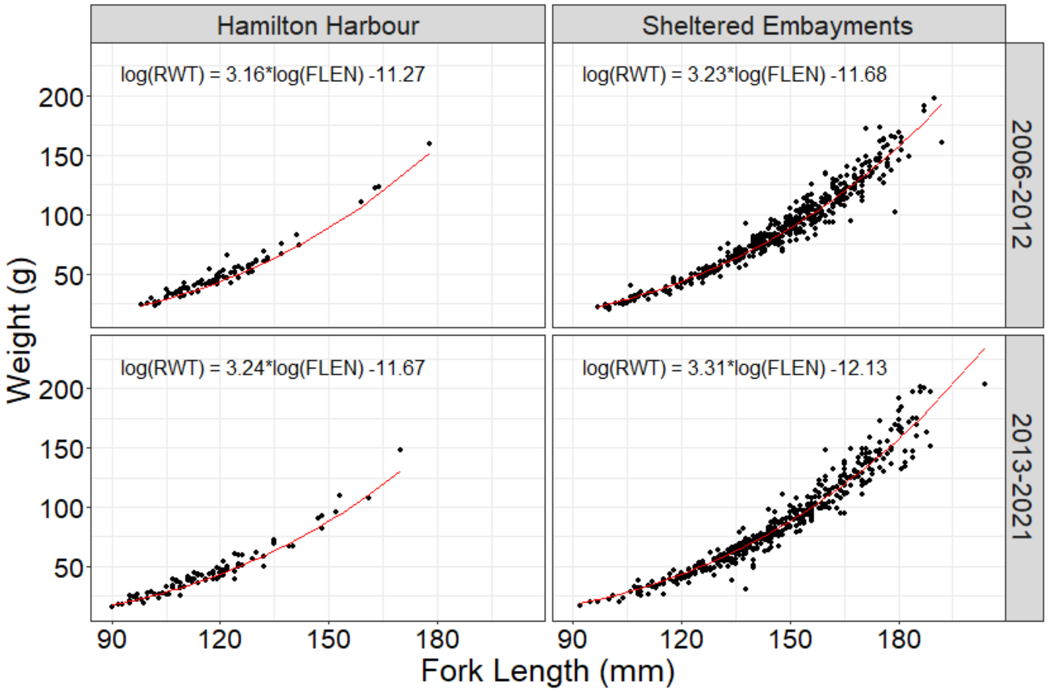

Figure D 5. *Length weight regression for Pumpkinseed in Hamilton Harbour compared to reference sheltered embayments (East Lake, West Lake, Weller's Bay, Upper and Middle Bay of Quinte) in two time stanzas (2006-2012, 2013-2021).*

APPENDIX E: SUMMARY OF ROUND GOBY POPULATION MONITORING (2002-2022) IN HAMILTON HARBOUR

SUMMARY

The round goby (*Neogobius melanostomus*) is a small benthic fish that rapidly invaded the Laurentian Great Lakes over 30 years ago. This fish has had deleterious impacts on the ecosystem stemming from competition with native species and contaminant transfer in food webs. Despite the important reverberating impacts caused by this invasive species, the dynamics of this invasion remain vastly understudied. The Aquatic Behavioural Ecology Laboratory (ABEL) at McMaster University, has continuously monitored round goby populations for over 20 years (2002 – 2022) in Hamilton Harbour, an International Joint Commission Area of Concern. We show that the abundance of this invasive fish species has declined, but that the decline appears to level off and the population appears to have stabilized since 2014. Fish body size (mass and length) also appears to have declined over the years, whereas body condition has increased. Gonadal (GSI) and liver (HSI) investment appear to have remained stable across the years. Within the harbour, four sampling sites represent areas of low sediment contamination and two sites are in areas of high sediment contamination. We found lower liver investment (HSI) in sites of high contamination and fish were smaller (mass and length) compared to sites of low contamination. Research of this kind, focused on how populations change over time, highlights the importance of long-term population monitoring of invasive species. Having good demographic data of a robust and disruptive invader in heavily contaminated areas (e.g., Hamilton Harbour) will be critical for the management, remediation, and protection of the harbour and for aquatic environments and resources worldwide.

KEY MESSAGES

The population of the invasive round goby has been continuously monitored since 2002 in Hamilton Harbour. Such long-term time series data on species invasion and establishment in an ecosystem are rare. The abundance of round goby declined from the high levels observed during the initial sampling years. However, this decline did not continue, and the population has been relatively stable since 2014. In sites with high sediment contamination, smaller round goby were found and appeared to invest more in reproduction (as measured by GSI, the gonadal somatic index) compared to goby caught in sites of relatively lower contamination. Round goby from highly contaminated sites also appeared to have lower energetic reserves (as measured by hepatosomatic index HSI) when compared to round goby in relatively less contaminated sites. Understanding the role of round goby in Hamilton Harbour’s ecosystem is of vital importance and will be especially helpful to present and future remediation efforts.

REMAINING CONCERNS AND UNCERTAINTY

Despite the considerable amount of research focused on round goby biology, there still remains a plethora of unanswered questions about the trajectory and impacts of its invasion. We need to statistically confirm whether the round goby population in Hamilton Harbour has indeed stabilized or if continued declines are likely. Further, if the population has stabilized, it remains unclear why and what caused the initial decline and what stemmed the decline. Researchers at ABEL are currently investigating several different hypotheses for the decline (e.g., inter- and intraspecific competition, changes in water quality, and the incorporation of round goby into the diet of native fishes and piscivorous birds). It also remains unclear how the continuous remediation efforts being implemented in Hamilton Harbour will affect the population of round goby. The round goby is tolerant to a wide variety of environmental conditions and is highly resilient to environmental perturbations, thereby, making their decline in Hamilton Harbour all the more puzzling (McCallum et al. 2017a). If this robust species is in decline, then other more sensitive species may also be in peril. This unique, large-scale (~18,000 fish), longitudinal fish population time series of a robust invasive species can provide important sentinel information about Hamilton Harbour's changing environmental conditions. The data and the monitoring program will help address questions about the long-term health of the Harbour and its biota.

FUTURE MONITORING Round goby populations in Hamilton Harbour should continue to be monitored annually ideally using the methods described below to provide data to explore recovery following the recent remediation to Hamilton Harbour (the capping of Randal Reef and implementation of tertiary treatment at Woodward Wastewater Treatment Plant). To date, the majority of the work on round goby biology has focused on adults and/or their reproduction. Understanding the role of early life stages in the invasion success and range expansion would be valuable as it would provide a more comprehensive assessment of the impact of invasive species on ecosystem function. It would also be useful to run telemetry studies to ascertain the extent to which round goby move around the harbour and use different habitats within it. Continued monitoring will ensure the integrity and increase the value of this unique long-term dataset, thereby, giving us the ability to ask and answer questions about the invasion dynamics of round goby in the Great Lakes.

RECOMMENDED ACTIONS

The invasion dynamics of round goby in Hamilton Harbour should continue to be studied. The time series created is a unique and extremely rich dataset that provides a detailed temporal view (2002-2022) of the early stages and establishment phases of the round goby invasion in Hamilton Harbour. Providing continued support for such monitoring efforts would ensure its integrity as an uninterrupted time series on invasive species population dynamics while maximizing the knowledge learned from Hamilton Harbour and how it may apply to the Great Lakes and beyond.

BACKGROUND

Round goby are a small, benthic, invasive fish species, native to the Ponto-Caspian region of Europe, that are now widespread throughout the Laurentian Great Lakes and the waterways of Western Europe (Corkum et al., 2004; Kornis et al., 2012). Many life history, physiological, and behavioural factors have contributed to their success as an invasive species, such as their tolerance for a wide-range of environmental conditions (Charlebois et al., 1997; Moskal'kova, 1996), generalist diet (Brush et al., 2012; French & Jude, 2001; Johnson et al., 2008), rapid reproductive rates with multiple spawns each season (Corkum et al., 1998; Johnson et al., 2005; Macinnis & Corkum, 2000), and aggressive nature (Balshine et al., 2005; Bergstrom & Mensinger, 2009; McCallum et al 2016, 2017b; Capelle et al. 2015). However, without regular estimates of the population size, there is no way of tracking the invasion success and the population dynamics of any organism. ABEL has created a detailed time series for the round goby population in Hamilton Harbour spanning 20 years (2002 – 2020), with sampling every other week for six months of the year. Understanding the dynamics of an invasive species, like the round goby, is particularly important for the management of an ecosystem under remediation as it allows scientists and managers to better understand the impacts of invasive species on native species.

Round goby occupy and prefer rocky, sheltered habitats in the littoral zone (Young et al., 2010) and make use of these rocky spaces to hide from avian and fish predators (Reyjol et al., 2010; Somers et al., 2003). Round goby also use rocky shelters as breeding areas in which they reproduce and care for their offspring (Corkum et al., 1998; Macinnis & Corkum, 2000). Round goby monopolization of these often-limited shelters, is thought to be linked with declines of small native fish species that occupy the same types of habitats, such as johnny darter (*Etheostoma nigrum*) and mottled sculpin (*Cottus bairdii*; Janssen and Jude, 2001; Lauer et al., 2004). Understanding the density, reproductive, and aggregation capacity of round goby will better help us understand their possibly competitive impacts on native fish and prey species in Hamilton and the Great Lakes.

METHODS

Round goby were sampled between 2002 to 2022 in Hamilton Harbour. Sampling occurred twice a month between April and November. Sampling took place along 6 sites in Hamilton Harbour: Desjardins Canal, Grindstone Creek, LaSalle, Fisherman's Pier, Pier 27, and Sherman Inlet (Figure E1). These sites represent areas of relatively low contamination (Desjardins Canal, Grindstone Creek, LaSalle, Fisherman's Pier) and areas of relatively high contamination (Pier 27, and Sherman Inlet). Multiple minnow traps (4-10 per site) were deployed at 1 m depth and 10 meters apart at each site. Data is presented as fish per trap to account for differences in effort and trap loss. For detailed methodology, see Young et al. (2010), McCallum et al. (2014) and McLean et al. in prep.

RESULTS

Abundance

A total of 18,109 round goby have been sampled and analyzed (2002-2022; Table E1). Round goby population abundance appears to have stabilized after a steep decline in abundance. From 2002 to 2012, round goby population in Hamilton Harbour appeared to decline from ~6-8 round goby per trap to ~2-4 round goby per trap (Figure E2A). The decline in round goby abundance appears to be more dramatic in males (Figure E2B), whereas female abundance seems to have been more stable over the years (Figure E2C).

Morphometrics

Body size (mass and standard length) of round goby seemingly also declined over the years (Figure E3A and Figure E3B); in contrast, body condition seems to have increased over the years (Figure E3C). Body mass and standard length appear to be higher in fish from areas of low contamination, whereas body condition appears to be fairly similar across sites of low and high contamination (Figure E3). Body condition in round goby from Hamilton Harbour declines during the breeding period (April to August), then increases from September to November prior to the winter (Figure E4). Investment in gonads (GSI) and liver tissue (HSI) for both male and female round goby does not appear to have changed across the years sampled (Figure E5A and Figure E5B). Male gonadal investment (GSI) appears to be greater in highly contaminated sites, whereas female GSI does not appear to differ between fish collected from areas of high and low contamination (Figure E5A and Figure E5B). Both male and female gonadal investment is highest during the breeding season (April to August) and decreases from September to November (Figure E5C and Figure E5D). Male liver investment (HSI) appears to be lower in highly contaminated sites, whereas female HSI does not appear to differ between sites according to contamination levels (Figure E6A and Figure E6B). Seasonally, both male and female liver investment (HSI) is lowest during the breeding season (April to August) and increases from September to November (Figure E6C and Figure E6D).

DISCUSSION

Trends across years

In Hamilton Harbour, round goby abundance and body size declined initially (over the first decade) but appears to be stabilizing over the last decade. It is possible that when round goby first invaded, their population size increased beyond the carrying capacity of the Harbour (Velez-Espino et al., 2010). The stability in abundance over the last years could be the result of the round goby reaching an equilibrium with the resources available in the Harbour. Intra- and interspecific competition may also have caused the initial reduction in abundance and selected for slower growth (Peters 1983; Blanckenhorn 2000). Further, a rapid decline in abundance and the overall reduction in body size observed after the initial sightings of round goby in the Harbour may represent a predation response. Initially, bird and fish predators (e.g., double crested cormorants, largemouth and smallmouth bass, northern pike, and walleye) may have not recognized or viewed the round goby as prey. Over time, these predators may have learned that round goby were a reliable prey source in Hamilton Harbour and how to hunt them, incorporating them into their diets (Sommers et al., 2003; Reyjol et al. 2010; Taraborelli et al. 2010; Dietrich et al. 2006; Truemper and Lauer 2005).

Trends between sites of low and high contamination

Round goby are tolerant of a wide variety of water conditions and are considered to be a pollution tolerant species (Pinchuk et al. 2003; McCallum et al., 2017c). It is currently unclear whether round goby are more abundant in cleaner vs more contaminated sites and further statistical modelling is needed to determine how abundance differs with contamination load. Round goby in sites with high contamination certainly appear to be smaller and to have higher reproductive investment. Further, previous ABEL research has shown that round goby from sites with high contamination were younger (when aged using otoliths; Marentette et al., 2010). Collectively, these results indicate that round goby at sites with high contamination may be adopting a “live fast and die young” fitness trade-off strategy, whereby reaching sexual maturity and reproducing earlier in life provides a higher pay-off than for fish in sites with lower contamination, where the costs of foraging, growth, and somatic maintenance may be lower (Promislow & Harvey 1990, Amundsen et al 2012, Crespi et al 2013). Current work at McMaster University’s Aquatic Behavioural Ecology Laboratory is assessing this hypothesis.

Table E 1. *Total number of round goby collected and partitioned by sex, site, and year. “-“ indicates years where round goby were not collected at particular sites. DC = Desjardins Canal, GC = Grindstone Creek, LS = LaSalle Marina, FP = Fisherman’s Pier, P27 = Pier 27, and SI = Sherman Inlet – see Figure E1 for locations.*

	DC		**GC**		**LS**		**FP**		**P27**		**SI**	
Year	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**
2002	226	128	90	64	185	88	287	118	–	–	–	–
2003	53	15	17	16	62	27	82	14	–	–	–	–
2004	77	72	46	58	51	26	90	57	–	–	–	–
2005	162	67	77	30	227	73	135	74	–	–	–	–
2006	180	56	59	24	193	98	116	64	9	6	38	45
2007	119	59	20	19	161	58	98	48	159	102	88	92
2008	96	40	22	6	133	56	68	34	89	26	79	67
2009	42	31	13	10	68	40	32	19	–	–	–	–
2010	43	15	30	7	226	102	152	47	207	72	73	63
2011	98	68	25	10	197	85	137	80	153	103	219	169
2012	88	64	32	10	136	48	161	78	202	109	108	64
2013	74	50	24	11	126	58	112	63	105	79	120	60
2014	49	61	13	9	77	46	35	16	47	40	104	69
2015	33	45	11	14	94	81	32	47	128	112	73	62
2016	58	36	21	6	163	125	103	66	127	110	83	54
2017	40	34	26	17	114	110	114	71	123	113	78	96
2018	41	35	6	6	67	80	77	58	43	46	63	65
2019	91	70	42	16	123	75	89	67	136	146	58	55
2020	166	90	81	45	109	85	46	46	40	37	64	62
2021	142	97	12	14	135	71	135	56	44	58	115	65
2022	121	100	9	15	109	135	85	97	86	98	66	100

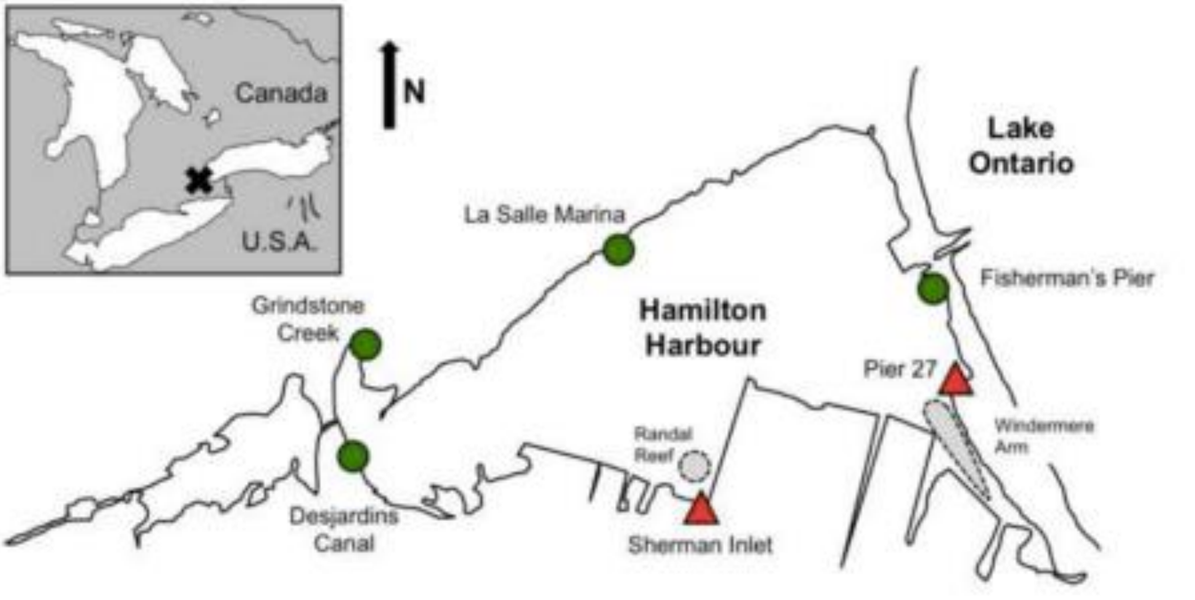

Figure E 1. *A map of Hamilton Harbour, ON, Canada (43°N, 79°W), the western-most embayment of Lake Ontario, with sampling sites and areas of remediation plotted. Green site markers show low contamination sampling sites, and red site markers show high contamination sampling sites. Gray with black-hatched borders show two highly contaminated areas of Hamilton Harbour undergoing remediation (RAP 1992; 2002).*

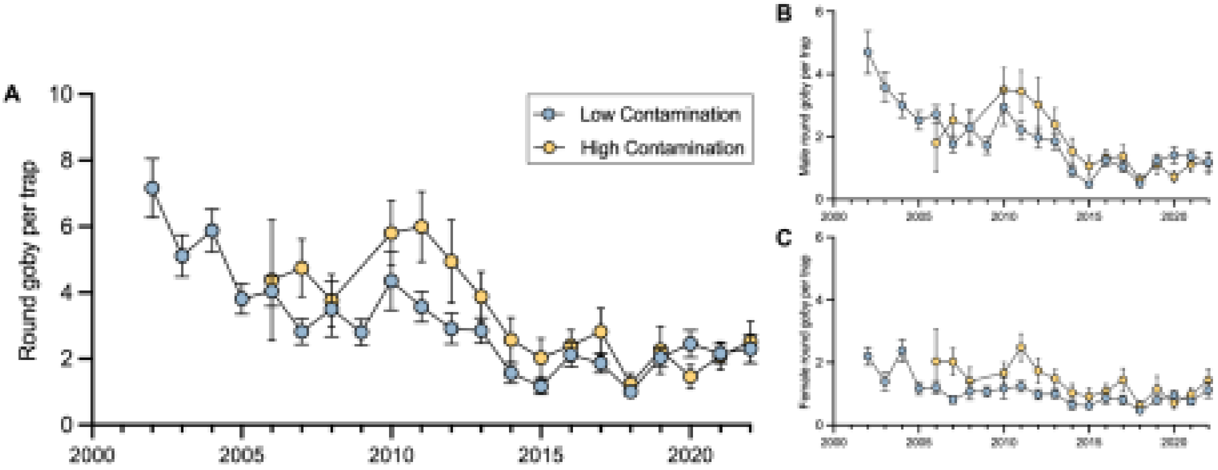

Figure E 2. *Mean (±) SE round goby population abundance separated by site type (i.e., low or high contamination) for (A) entire population, (B) males, and (C) females from 2002 to 2022.*

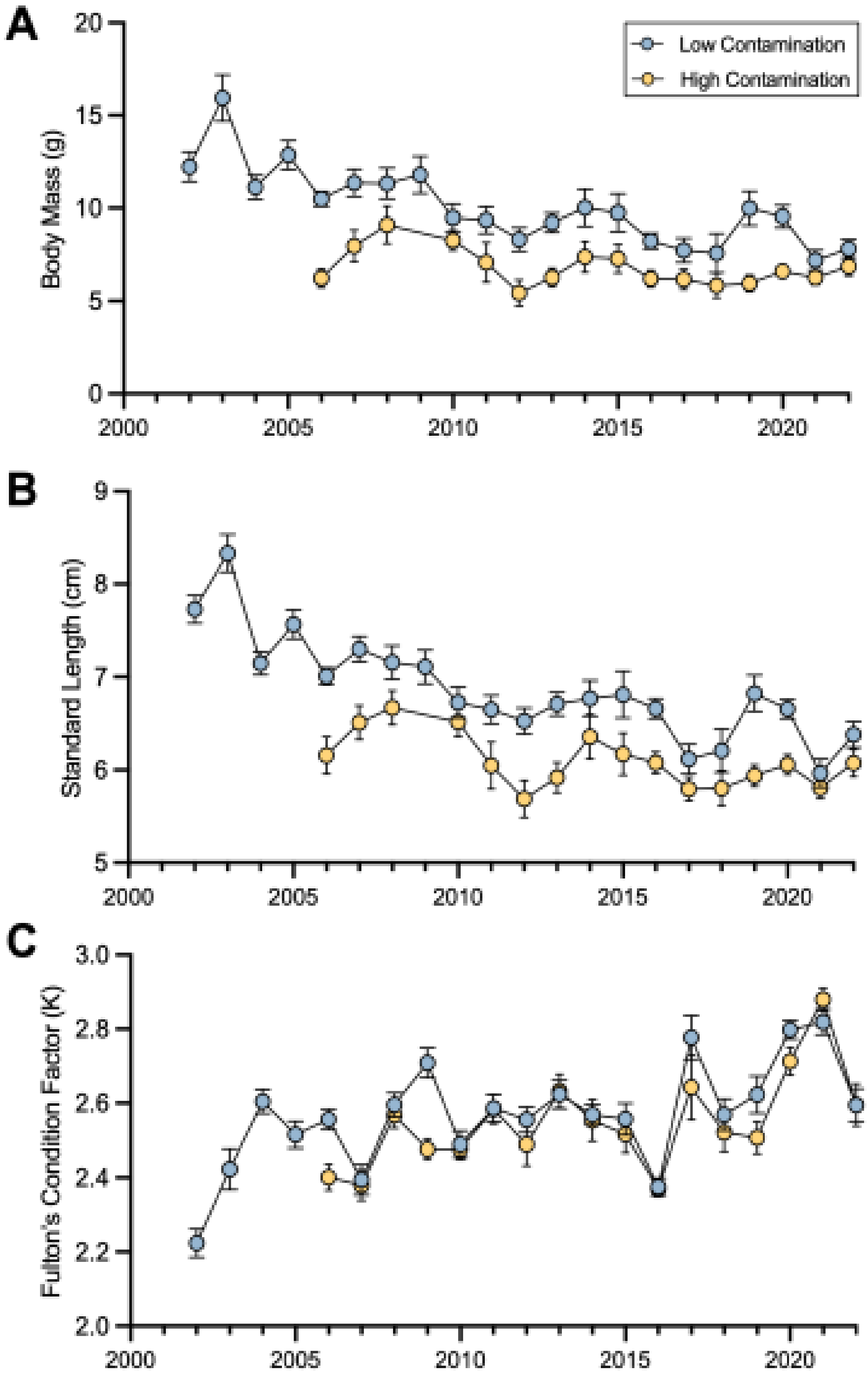

Figure E 3. *(A) Mean (±) SE body mass of round goby separated by site type (i.e., low or high contamination). (B) Mean (±) SE body size (standard length) of round goby separated by site type (i.e., low or high contamination). (C) Mean (±) SE body condition (Fulton's factor) of round goby separated by site type (i.e., low or high contamination). All graphs display trends from 2002 to 2022.*

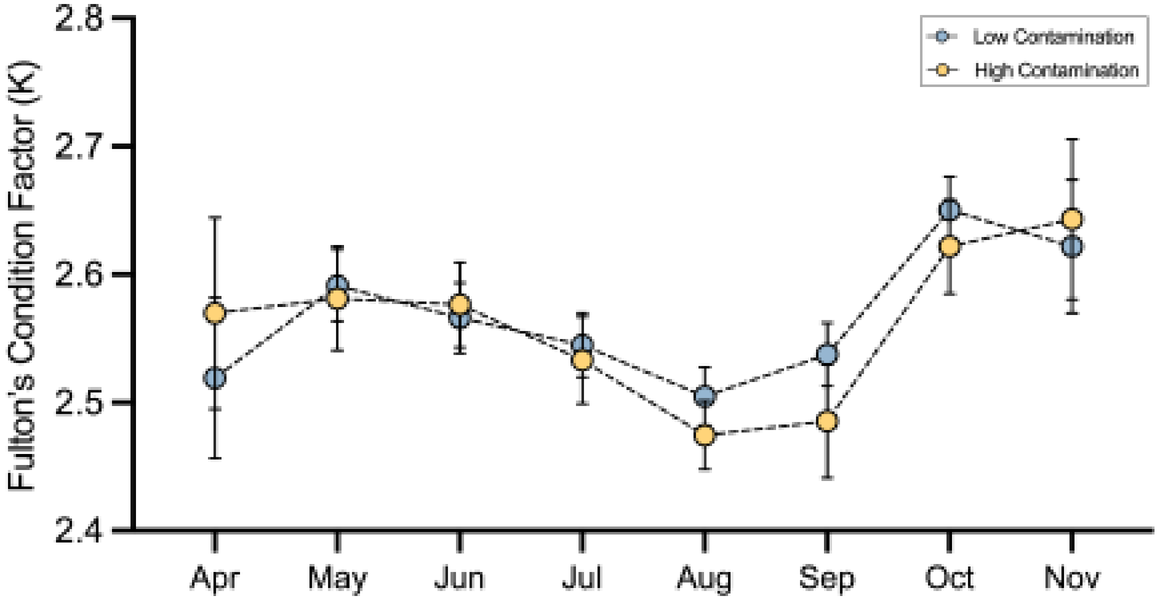

Figure E 4. *Seasonal trend (mean (±) SE) of round goby body condition (Fulton's factor) from 2002 to 2022 displayed by Gregorian month and separated by site type (i.e., low or high contamination).*

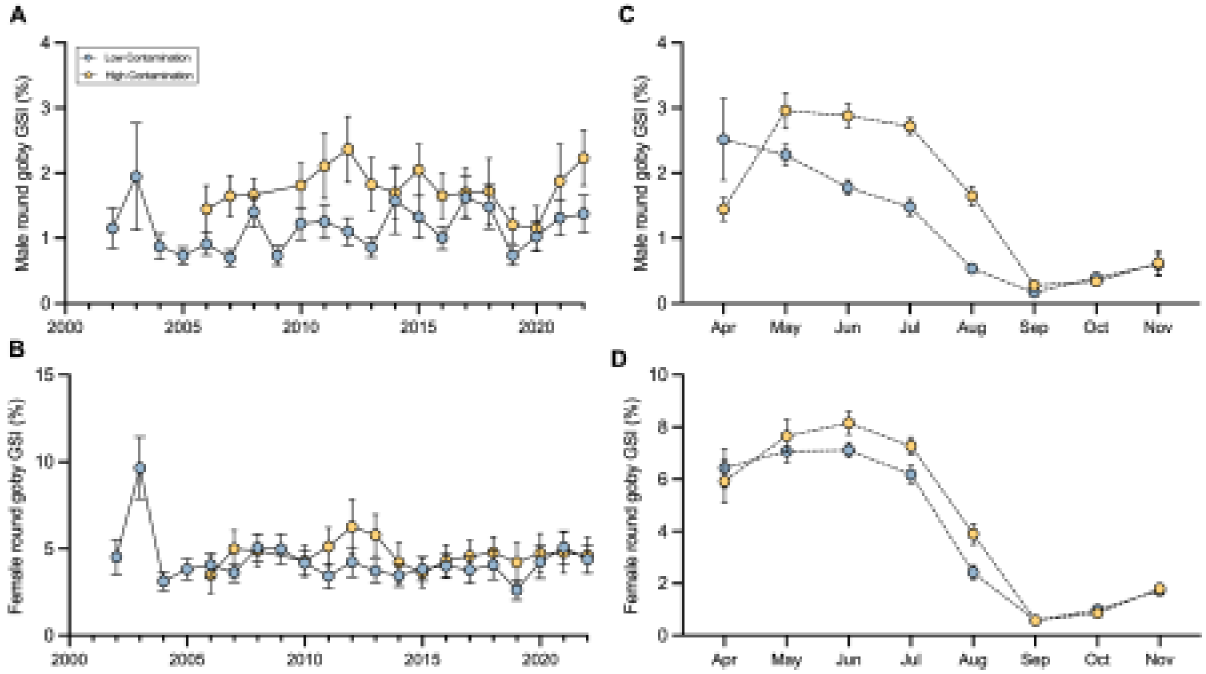

Figure E 5. *Mean (±) SE of (A) male and (B) female round goby gonadosomatic index (GSI) from 2002 to 2022 separated by site type (i.e., low or high contamination). Seasonal trend (mean (±) SE) of (C) male and (D) female round goby GSI from 2002 to 2022 displayed by Gregorian month and separated by site type.*

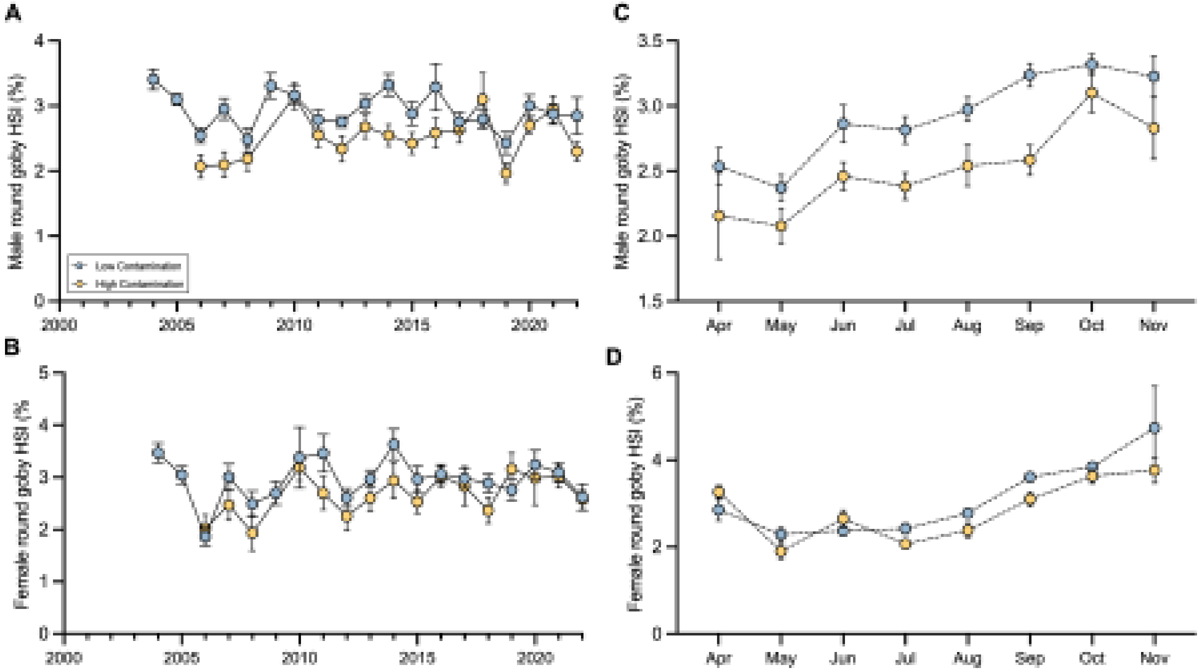

Figure E 6. *Mean (±) SE of (A) male and (B) female round goby hepatosomatic index (HSI) from 2002 to 2022 separated by site type (i.e., low or high contamination). Seasonal trend (mean (±) SE) of (C) male and (D) female round goby HSI from 2002 to 2022 displayed by Gregorian month and separated by site type.*

APPENDIX F: SUMMARY OF FISH COMMUNITIES STUDIES NEAR TWO WASTEWATER TREATMENT PLANTS THAT RELEASE EFFLUENT INTO HAMILTON HARBOUR

SUMMARY

Municipal wastewater treatment plant (WWTP) effluents are a ubiquitous source of contamination whose impacts on fish and other aquatic organisms span across multiple levels of biological organization. Few studies have ever assessed the effects of such a ubiquitous source of contamination on fish communities, and even fewer studies have done so during winter. At McMaster University, the Aquatic Behavioural Ecology Laboratory (ABEL) has been assessing the impacts of two WWTPs on fish communities in Hamilton Harbour in both summer and winter. We found that fish abundance, species richness, and species diversity were generally highest in sites closest to the WWTP outfalls, but only significantly so in the winter. Fish community compositions differed greatly along the effluent gradients, with sites closest and farthest from the outfalls being the most dissimilar. Our study suggests that fishes may seek WWTP plumes during winter as a form of thermal and/or nutrient refugia – at the cost of contaminant exposure.

KEY MESSAGES

Fish communities were sampled along the effluent gradients of two WWTPs in Hamilton Harbour (Dundas and Woodward WWTPs) in the summer and winter of 2018 and 2019. Sites sampled near wastewater outfalls generally had higher fish abundance, species richness, and species diversity; however, this was only the case during winter. Proximity to the effluent outfalls also affected the assemblages of fish communities, whereby communities of fish closest and farthest from the outfall areas were most dissimilar.

REMAINING CONCERNS AND UNCERTAINTY

There are several uncertainties regarding how wastewater effluents impact fish communities in summer and winter. It remains unknown whether fish are actively seeking refuge near WWTP effluents during winter or simply remaining there across seasons. We show that WWTPs are a high source of productivity (i.e., Mehdi et al. 2021a; Aristone et al. 2022; Mehdi 2022) in aquatic environments, especially during winter, where productivity is drastically higher than reference sites due to the thermal enhancing effect of WWTPs. However, it remains unknown whether WWTPs are truly an ‘ecological trap’ for fishes in winter. In the future, it would be helpful to quantify the relative costs and benefits of living in effluent-dominated environments using lab and field manipulation studies in fish and other aquatic organisms across seasons. Finally, while Hamilton Harbour provides a unique opportunity to study the impacts of anthropogenic disturbances in a historically industry-dominated embayment and growing pressure from human population growth, it would be beneficial to study and compare the impacts of wastewater inputs on fish communities in more homogenous environments (e.g., Grand River). Conducting community assessments similar to those outlined above but in a watershed with more homogenous sampling sites would allow us to disentangle whether the fish community differences observed were linked to site habitat differences or if they resulted from the proximity to WWTP outfall.

FUTURE MONITORING

It is pertinent to study fine-scale movements of fish in and out of wastewater plumes across seasons to understand why fish are abundant and speciose near wastewater plumes, particularly during winter. As of now, we do not know whether fish are staying near wastewater outfalls in the winter and/or if fishes are migrating towards effluent outfalls from nearby sites. Conducting fine-scale telemetry studies using established methods such as acoustic telemetry or mark-recapture studies (Cooke et al., 2013), corroborated with long-term temperature monitoring, will allow us to ascertain if fishes are actively seeking these environments as a form of behavioural thermoregulation (Golovanov, 2006).

RECOMMENDED ACTIONS

Based on our findings, there are numerous possibilities for future research and recommended actions. Our research examined the effects of two of the three WWTPs in Hamilton Harbour on fish communities in summer and winter across two years. This kind of research would benefit from additional monitoring to better establish temporal trends. According to our findings (Mehdi et al. 2021b), we conclude that fish communities are best assessed using multiple gear types; specifically, a combination of active and passive gears. A combination gear type approach would allow researchers to gain a more holistic and accurate view of the fish community or population surveyed, especially if surveys are conducted across seasons, where gear type selectivity can change drastically. This research would also benefit from sampling the Woodward WWTPs post upgrades and post relocation of the outfall to understand how changes to the infrastructure of the WWTP may influence fish communities. This research would also benefit from additional sampling points across Hamilton Harbour (e.g., Burlington Skyway WWTP and combined sewer overflow points). While community research allows for a high-level examination of ecosystems, as of now, we do not know whether fish are staying near wastewater outfalls in the winter and/or if fishes are migrating towards these effluent outfalls from nearby sites.

BACKGROUND

Municipal wastewater treatment plant (WWTP) effluents, although usually treated, still contain a complex mixture of chemicals, including but not limited to excess nutrients, pesticides, metals, micro- and macroplastics, pharmaceuticals and personal care products (PPCPs), as well as natural and synthetic hormones. These effluents are a ubiquitous source of contamination whose impacts on fish and other aquatic organisms span multiple levels of biological organization (e.g., endocrine disruption, represented by severe incidences of intersex, reduced androgen levels, and reduced fertilization success). Despite this, few studies have addressed the impacts of WWTP effluents on fish communities, especially during the winter.

METHODS

Fish communities were sampled along the effluent gradients of the Dundas and Woodward WWTPs (Figure F1). Five sites were sampled at each WWTP: three immediately downstream of the effluent outfalls (D1, D2, and D3 for the Dundas WWTP and W1, W2, and W3 for the Woodward WWTP) and two reference sites either upstream of the or farther downstream (D4 and D5 for the Dundas WWTP and W4 and W5 for the Woodward WWTP). Fish communities were surveyed in the summer and winter (2018 and 2019) using a combination of gear types: minnow traps, Windermere traps, and electrofishing from a boat. For detailed methodology, see Mehdi et al. (2021a) and (2021b).

RESULTS

Near the Dundas WWTP, 2388 fish were collected (2112 in summer and 276 in winter) consisting of 23 different fish species (Table F1). Near the Woodward WWTP, 1844 fish were caught (1546 in the summer and 298 in the winter) consisting of 26 species (Table F1). Fish abundance was lower in winter than in summer (Figure F2). Fish abundance was highest near the wastewater outfalls but only during winter (Figure F2). Fish species richness was highest near the wastewater outfalls but only during winter (Figure F3). Communities at sites closest to the outfall were most different from those farthest away, while there was considerable overlap in the intermediate sites (Figure F3; see Mehdi et al. 2021a).

DISCUSSION

In the winter, sites closer to the wastewater outfalls were generally higher in fish abundance, species richness, and species diversity compared to sites farther away. This trend was not as apparent in the summer. One of the reasons why we see such different trends between summer and winter could be linked to wastewater effluents being a significant source of nutrients and thermal refugia, particularly during winter. This would attract fish and other aquatic organisms to such polluted environments in search of refuge, particularly during winter, when food is scarce and difficult to encounter elsewhere. This suggestion is further supported by the elevated temperatures near the effluent outfalls observed during winter when compared to reference sites (Mehdi et al. 2021a). The idea of effluent outfall as an ecological trap is further supported by the higher productivity measures (as measured by higher benthic macroinvertebrate, higher zooplankton abundance, and higher nutrient levels; Mehdi et al. 2021a; Aristone et al. 2022; Mehdi 2022) observed near the effluent outfalls when compared to reference sites, particularly during winter.

Table F 1. *Fish species abundances from all sampling events at the Dundas and Woodward WWTPs. Abundance data is shown as the number of individuals caught of each species in the* *summer and winter (summer/winter). Abundance data are cumulatively represented from all sampling events within each season.*

	Dundas WWTP					Woodward WWTP				
	D1 (Outfall)	D2 (550 m)	D3 (1000 m)	D4 (2800 m)	D5 (3750 m)	W1 (Outfall)	W2 (350 m)	W3 (850 m)	W4 (-1000 m)	W5 (-1400 m)
Ambloplites rupestris (Rock bass)	0/1	0/5	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0
Ameiurus nebulosus (Brown bullhead)	1/2	67/20	30/3	24/0	172/25	0/2	0/5	0/0	2/1	1/1
Amia calva (Bowfin)	0/0	1/0	0/1	0/8	0/4	0/0	0/0	0/0	1/0	0/0
Carassius auratus (Goldfish)	2/1	187/2	53/3	4/0	78/0	1/0	1/0	11/0	8/0	2/0
Catostomus commersonii (White sucker)	51/8	3/1	10/1	7/0	1/0	51/3	37/1	12/0	1/0	5/1
Culaea inconstans (Brook stickleback)	0/0	0/0	0/0	0/0	0/0	30/0	12/0	7/8	0/1	0/2
Cyprinus carpio (Common carp)	1/0	1/0	0/14	1/0	1/0	2/0	0/2	0/0	4/0	0/0
Dorosoma cepedianum (Gizzard shad)	0/0	1/22	124/0	38/0	3/2	0/4	0/0	0/0	1/0	1/0
Esox lucius (Northern pike)	0/0	1/1	0/0	0/1	0/0	2/0	1/0	8/1	1/0	4/0
Labidesthes sicculus (Brook silverside)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/2
Lepisosteus osseus (Longnose gar)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/0	0/0
Lepomis cyanellus (Green sunfish)	27/8	11/2	3/0	5/0	19/0	40/57	16/33	37/8	41/5	58/6
Lepomis gibbosus (Pumpkinseed)	6/1	3/2	0/0	2/0	23/0	0/5	3/7	4/1	44/0	20/4
Lepomis macrochirus (Bluegill sunfish)	6/9	22/6	3/1	38/0	380/2	14/12	9/7	2/1	131/2	78/4
Luxilus cornutus (Common shiner)	9/0	28/1	1/1	9/0	0/0	0/0	0/0	0/0	9/0	2/0
Micropterus salmoides (Largemouth bass)	36/13	60/0	13/0	10/0	6/0	4/0	0/0	6/2	4/0	1/0
Morone americana (White perch)	0/0	0/1	0/0	0/0	117/0	0/0	4/1	1/0	2/0	0/0
Neogobius melanostomus (Round goby)	184/42	19/1	0/0	2/0	1/0	78/37	7/14	1/7	44/1	54/4
Notropis atherinoides (Emerald shiner)	0/0	0/0	0/0	0/0	1/0	8/2	0/0	0/1	8/1	2/5
Notropis hudsonius (Spottail shiner)	6/0	2/1	7/0	9/1	2/0	131/0	0/1	9/2	3/1	4/4
Perca flavescens (Yellow perch)	9/0	6/2	11/2	52/2	7/15	0/0	0/0	1/0	1/2	0/0
Percina caprodes (Common logperch)	5/7	0/3	2/0	3/3	2/0	11/1	3/0	0/0	5/0	2/0
Pimephales notatus (Bluntnose minnow)	0/3	5/0	0/0	1/0	0/0	17/0	35/0	6/0	1/1	0/1
Pimephales promelas (Fathead minnow)	10/2	2/4	2/1	1/0	1/0	137/3	23/7	12/2	147/0	23/11
Pomoxis nigromaculatus (Black crappie)	0/0	1/0	1/1	0/0	0/0	10/0	0/0	0/0	0/0	0/0
Scardinius erythrophthalmus (Rudd)	4/0	34/7	2/5	9/2	42/0	0/0	0/1	0/0	1/0	23/0
Semotilus atromaculatus (Creek chub)	0/0	0/0	0/0	0/0	0/0	0/0	5/0	0/0	0/0	0/0

Figure F 1. *Map of our sampling sites along a distance gradient from the (**A**) Dundas and (**B**) Woodward WWTPs. The location of each WWTP is also displayed. Maps generated in Google Earth Pro 7.3.2.5776, imagery date 06/30/2018 and accessed on 24/02/2020.*

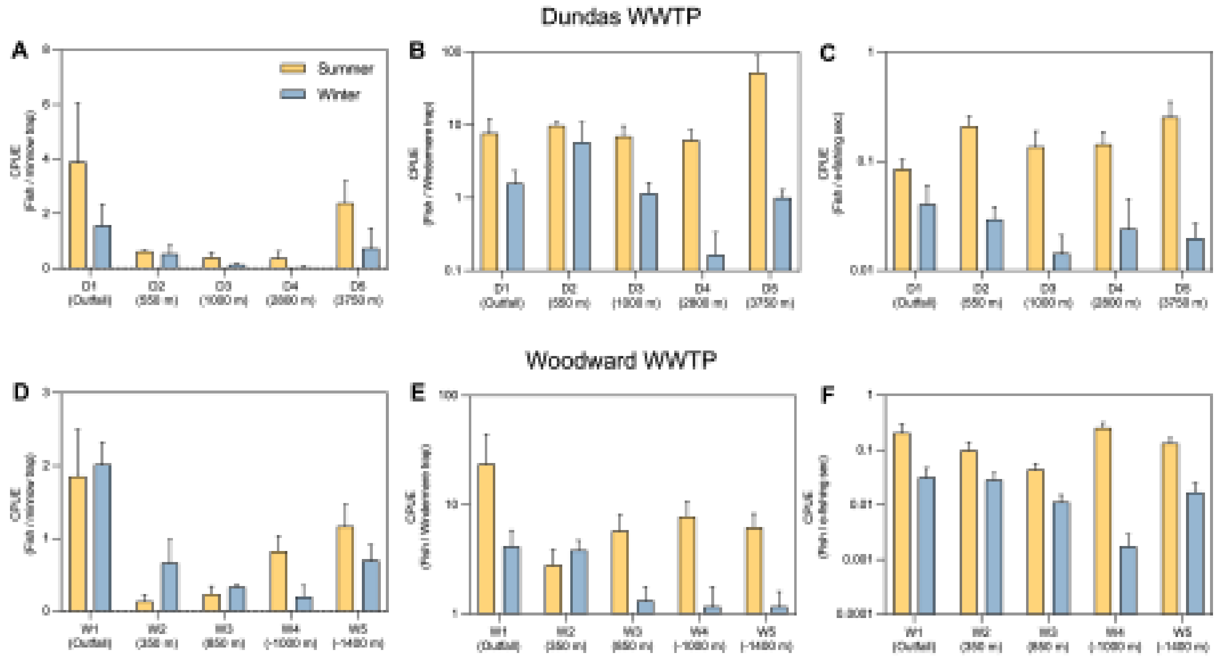

Figure F 2. *Mean (±) SE abundance of fish caught downstream of the effluent gradients of the Dundas and Woodward WWTPs using (A and D) minnow traps, (B and E) Windermere traps, and (C and F) electrofishing.*

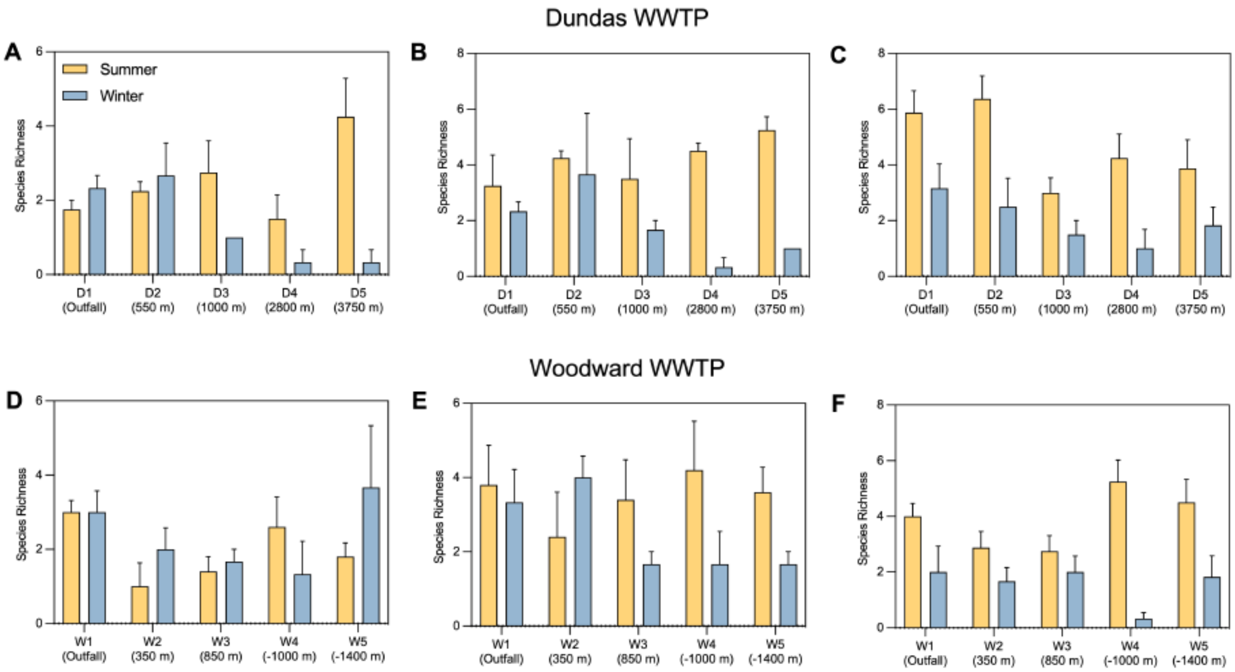

Figure F 3. *Mean (±) SE species richness of fish caught downstream of the effluent gradients of the Dundas and Woodward WWTPs using (A and D) minnow traps, (B and E) Windermere traps, and (C and F) electrofishing.*

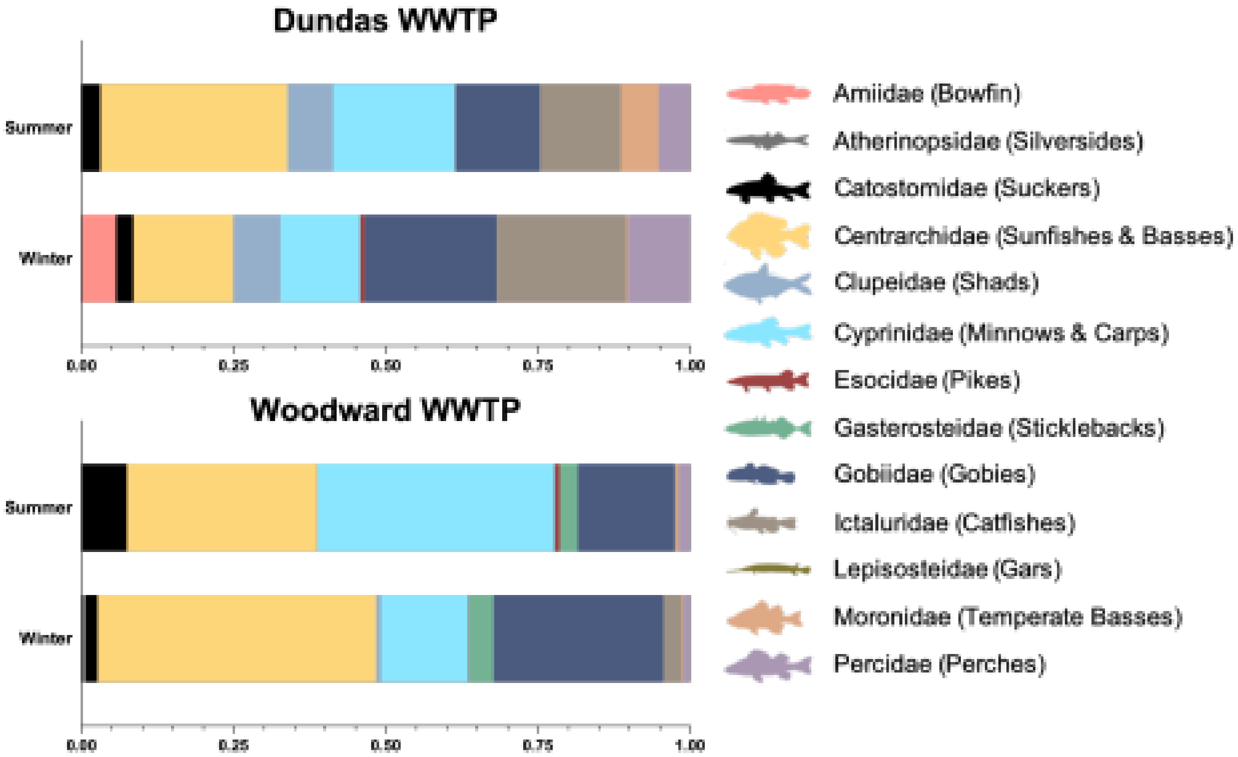

Figure F 4. *Fish family composition broken down by season and WWTP. Proportions based on gear-standardized catch per unit effort of all sampling events within each season (see Mehdi et al. 2021b)*

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APPENDIX G: ROYAL BOTANICAL GARDENS FISH COMMUNITY MONITORING SUMMARY

SUMMARY

As a part of the Hamilton Harbour Remedial Action Plan (HHRAP), Royal Botanical Gardens (RBG) was tasked with providing additional assessing elements of BUI III: Fish and Wildlife Populations within Cootes Paradise and Grindstone Creek marshes. DFO GLLFAS provides the baseline monitoring of fish for this BUI; however, to better judge the status of fish populations (Common Carp in particular), distribution, and species richness, RBG annually monitors through three processes: the Cootes Paradise Fishway/Carp Barrier catches, early season pike trap monitoring and late summer community index electrofishing monitoring. The Fishway can quantify the number of invasive fish trying to enter the marsh and the number of large native fish utilizing the marsh for spawning efforts. Fish narrower than 5cm fit through the fish exclusion bars and are only incidentally captured. The trap monitoring gives a species composition of successful spawning efforts as it targets highly vegetated, shallower areas of both Cootes Paradise and Grindstone Marshes (favourites of predatory Northern Pike and Bowfin). Finally, the community electrofishing monitoring provides an overview of YOY fish populations throughout both marshes. All three of which have a 20-plus year long-term data set.

While there are two delisting criteria within BUI 3a: Degradation of Fish Populations, RBG’s data speaks to the first regarding fish community composition. Despite a more recent decline, eutrophic fish make up the majority of the population while top predator species, aside from Bowfin, are scarcely found. The eutrophic fish population is largely made up of the native Brown Bullhead, as Common Carp numbers have drastically declined. Since the year 2000, over 40,000 large carp have been physically removed from Cootes Paradise Marsh, while at the Fishway within the last 5 years, on average, only about 3000 are caught attempting to enter each year. Even with the habitat improvements that have been achieved in the last few years, the species composition within Cootes and Grindstone continues to fall short of reflecting the targets set within the BUI.

KEY MESSAGE

- Within the first 5 years of the Fishway being operational, over 20,000 Common Carp were seen at the barrier annually. In the last six years (2017-2022), on average, 3,000 carp have been caught at the Fishway each year. Early years of operation included special modifications to cage entrances to reduce carp numbers caught to allow for other fish, later years did not require these modifications to reduce carp caught.

- Brown Bullhead are the most abundant large fish entering Cootes Paradise and have increased in number dramatically, representing an average of 55% of the total fish entering through the Fishway over the last 5 years.
- Northern Pike and Largemouth Bass numbers across all monitoring efforts have been steadily declining in recent years.
- During the monitoring period, several major external stressors caused noticeable impacts in the data: a large-scale raw sewage spill from the Chedoke Creek Main/King CSO tank in 2018; Lake Ontario water levels setting record highs in 2017 and 2019 leading to severe flooding, which continued into 2020 facilitating spawning opportunities uncharacteristically low water levels in the spring of 2021 and the fall of 2022 impacting fish movement and available habitat.

REMAINING CONCERNS AND UNCERTAINTY

- Eutrophic conditions resulting in low oxygen and poor water clarity tolerant fish species dominating such as Brown Bullhead and Gizzard Shad
- For Cootes Paradise, Combined Sewer Overflow (CSO) tanks have regularly spilled into the system negatively affecting habitat, nutrient concentrations, and water quality for fish.
- The habitat in the West Cootes/West Pond sub-area is typically covered in filamentous algae limiting fish use of the habitat.
- Existing predatory species (Northern Pike, Largemouth Bass) considered rare at the onset of the HHRAP have been through significant recent declines and are again rare.
- Young predator species are found in multiple sites, including areas of newly enhanced marsh habitat during spring trap monitoring, but are rarely found during August monitoring.
- Fish reproductive success has declined measurably in the marsh areas despite improved habitat suggesting that unresolved factors exist beyond habitat.
- Early season trap net monitoring regularly finds many young fish that do not appear to be subsequently represented in the August electrofishing index monitoring.
- The Walleye reintroduction project has not resulted in any fish migrating to Cootes Paradise/ Spencer Creek to spawn.
- Common Carp continue to dominate the harbour side of the carp barriers, and occasionally gain access to management/exclusion areas through periodic issues.

FUTURE MONITORING

1. RBG will continue to perform all three monitoring efforts annually in the near future to provide secondary fish community data to the HHRAP partners.

RECOMMENDED ACTIONS

1. Installation of a single Grindstone Marsh Fishway/Carp Barrier at the mouth of the creek would be highly beneficial to address ongoing breach issues for the current temporary berms system as well as assist in providing better access for larger size fish species (specifically predatory species using the area).
2. Common Carp should be added to the provincial invasive species list.
3. Maintain existing Common Carp exclusion/management until waters have returned to mesotrophic conditions.
4. Interim Harbour-wide management of Common Carp to reduce the population to a level of a mesotrophic environment.
5. Implementation of all HHRAP Stage 2 Update recommendations pertaining to surface water quality impairments.
6. Investigation of potential toxic/environmental effects limiting Young of the Year fish survival.
7. Review the Hamilton Harbour Fisheries Management Plan for further restoration opportunities as well as the RBG Pike Assessment Report 2021 for spawning habitat opportunities adjacent to Cootes Paradise.

BACKGROUND

Cootes Paradise Marsh and Grindstone Marsh are the primary spawning grounds for Hamilton Harbour fish populations and therefore part of the Hamilton Harbour AOC. The most significant contribution made by the Royal Botanical Gardens Wetland Restoration program is the management of Common Carp (*Cyprinus carpio*) in RBG's wetland systems. Common carp historically reached 90% of the marsh biomass, equivalent to an estimated 800 kg/ha (Theijsmeijer 2000, DFO Unpublished, Bowlby et al. 2009). Over 20 years with multiple scenarios, Common Carp directly impacted habitat in river mouth marshes at densities over 20 kg/ha (RBG staff observations). Key drivers of the carp population include eutrophication of the marsh, anoxia, ammonia issues in the hypolimnetic zone of the harbour, excessive inputs of watershed sediment, and alteration of the natural marsh water cycle (Theijsmeijer and Bowman, 2022). As a foundational carp management technique, the Cootes Paradise Fishway was created. The Fishway – located at the junction between Cootes Paradise Marsh and the Hamilton Harbour - was constructed as an element of the HHRAP in 1996 and fully operational in 1997. It not only acts as a barrier for large fish (>25 cm in length / 5 cm wide) but it also is utilized as a method to collect population and species composition data, as it is operated annually to facilitate fish movement between the two water bodies.

While the Fishway provides Cootes Paradise Marsh population data and an idea of what species come into spawn and when, it was unclear as to how successful these spawning efforts were. Therefore, two additional Young of the Year (YOY) monitoring efforts were implemented in both Cootes Paradise and Grindstone Creek Marshes. The first effort targeted Northern Pike YOY specifically. Despite all the previous efforts to restore pike spawning habitat, adult populations have shown limited recovery and recently have severely declined. Due to this alarming trend, RBG implemented an early season monitoring plan in 2001 targeting YOY Northern Pike to better assess reproductive success (Court and Theijsmeijer 2021).

The second effort acted as an extension of the Cootes Paradise fish survey program initiated by the Department of Fisheries and Oceans in the summer of 1994 (Theijsmeijer 2000). This form of monitoring has been in progress since 1994 and provides insight into the health of fish populations as well as conditions present in the marshes. The purpose of this monitoring program is to assess the reproductive success of fish and to measure changes in the fish community from rehabilitation measures.

METHODS

Fishway operation (1996 – 2022) - Fishway Operation Manual v.3 (Theijsmeijer, Fishway Operation Manual v.3, 2022)

The structure operates seasonally by operating 1- 6 cages at a time to facilitate the migration of fish impacted by the barrier into and out of Cootes Paradise Marsh and associated tributaries. Operation begins each spring after ice out and typically continues until the salmon run is over. Inbound cages are first lifted, dumped into a holding tank, and then identified, counted, and sorted as they exit the tank. Native fish are allowed passage into the marsh while non-native species (Common Carp, Goldfish, and Rudd) are sent back out into the Harbour. The same is then repeated for the outbound cages with the only difference being that all fish are sent out into the Harbour as that is where they intend to go. The frequency of lifts is dependent on the time of year and number of fish seen. As mentioned, all fish are counted as they pass through the Fishway and categorized as either incidental (<25 cm) or large (>25 cm). Large fish are selected at random to be weighed, sexed, measured, and tagged if necessary. Predatory fish (Bowfin, Northern Pike, Largemouth Bass) are checked for tags upon entry into the marsh, and if they are in good condition, will be inserted with a PIT tag for further tracking if need be. The tagging helps to establish a more comprehensive timeline of fish passage into and out of the marsh.

Pike trap monitoring (2001 – 2022) – Pike Report (Theijsmeijer & Court, 2018-2020 Status Assessment of Northern Pike at RBG Coastal Marshes, 2021)

Monitoring occurred in June and involved the deployment of customized plexiglass box traps (1ft x 2ft with a 15 ft lead) - referred to as pike traps, set for an overnight period (24 hr) in appropriate habitat conditions (about 2 ft of water) with the intent to capture YOY Northern Pike. See Figure G1 for recent (2020-2022) trap locations. Historically, monitoring had been focused on the upper floodplain ponds of Grindstone Creek Marsh as it was deemed the primary pike spawning habitat for Hamilton Harbour and was subject to specific HHRAP restoration projects (Fish and Wildlife Restoration Committee, 1991). These floodplain ponds have little (excluding Pond 1) to no lake level flooding influence under average water levels, resulting in a more flooded habitat area during the spring. Habitat improvements in Cootes Paradise Marsh have warranted additional monitoring and have been included in the last decade. However, this unique to RBG sampling gear is limited by high water levels, contributing to site selection decisions. It should be noted that no monitoring occurred in 2021 due to a combination of factors: the low water levels in the spring and staffing restrictions due to COVID-19. In addition, monitoring in 2020 was not completed in its entirety due to COVID-19 restrictions.

Index electrofishing monitoring (1994 – 2022) - (Fish Community Monitoring Royal Botanical Gardens v.2, 2021)

Monitoring since 2010 occurred consistently during the end of August. Prior to that, monitoring took place multiple times throughout May – October. On average, a total of twenty-six transects of 50 m in length were sampled by boat in Cootes Paradise and an additional thirteen 50m transects were sampled either by wading or canoe in Grindstone. All transects were broken down into three habitat types: near shore, offshore, and lower river, and were spaced as equally as possible throughout the marshes (See Figure G2 for a map of transect locations). The electrofisher was a 5PP Smith Root unit up until 2006, switching to the 1.5KVA unit subsequently. Shock was consistently administered between 4-6 amps; no uniform settings were established as conductivity greatly varies across the transects.

Fish were measured on-site, with a fish count >10 being totalled. From 1994 – 1999, fish were weighed in the field using a portable scale (Theijsmeijer 2000). From 2000 to the present day, weight was not measured in the field but was later calculated utilizing standard formulations to minimize stress levels in the fish. In addition, at the completion of each transect, time of day, electroshocking effort, and settings and habitat conditions were recorded on a field data sheet.

Carp removal (2000 – 2022)

Each year, carp removal efforts are made to attempt to eradicate Common Carp from the entire RBG coastal wetland system at sites where issues have occurred. This is accomplished through electrofishing and/or seine or gill netting. In Cootes Paradise, this occurs annually from May to December. In Grindstone Creek Marsh, the ponds are typically fished twice annually to correct issues: once in the summer and once in the fall, usually by seining, to further ensure any carp are removed.

RESULTS

Fishway operation (1996 – 2022)

Since the construction of the Fishway in 1996, there has been a noticeable difference in the number of Common Carp trying to enter the marsh. From 1996 – 2000, Common Carp represented most of the fish seen at the Fishway, reaching numbers of over 20,000 (Figure G3). Since 2000, not only has there been a shift to native species assuming dominance, but Common Carp numbers have been steadily declining; within the last 6 years, on average, about 3,000 carp are caught in the Fishway each year

(Figure G3). Specifically, in the last two years, Brown Bullhead and White Suckers have been the most prevalent species caught at the Fishway. Channel Catfish, Bowfin, Gizzard Shad, and Freshwater Drum have maintained consistent population numbers within the last 6 years, while Rainbow Trout, Northern Pike, and Largemouth Bass have experienced rapid decline in the last 2 – 3 years (Table G1). As seen in Figure G4, it is evident that some species indicative of eutrophic environments are on a downward trend, while other native species are tracking upwards. Figure G4 also reiterates that top predators make up the smallest population of fish community utilizing Cootes Paradise.

Pike trap monitoring (2001 – 2022)

The assessment of Northern Pike use of Grindstone Marsh and Cootes Paradise Marsh found mixed results. The overall Pike population remains very low and is now likely lower than it was during the onset of the HHRAP planning in 1991, despite improved spawning and nursery habitat in both marshes and increased spawning success within Cootes Paradise (Theijsmeijer and Court, 2021). In Figure G5, there is a noticeable spike in Common Carp caught from 2018 to 2022. In the 2022 season, 12 traps were set in Grindstone Marsh, catching 856 fish representing 20 species; however, only 2 were YOY Northern Pike (Rebalka, et al. 2023). Grindstone had an overall catch per unit effort (CPUE) of 1.73 fish/hr. with Ponds 2 and 3 experiencing the highest catch numbers. Only 10 traps were set in Cootes Paradise, catching 1331 fish representing 12 species for a CPUE of 6.08 fish/hr and only 4 YOY Pike were caught (Rebalka, et al. 2023). It should be noted, however, that just over 1,000 of those were from one female Brown Bullhead and her young. In 2020, only 6 traps were set per marsh due to COVID-19 staffing restrictions. Regardless, 13 YOY Northern Pike were caught (4 in Grindstone and 9 in Cootes) (Norris, et al. 2021). In 2019 no YOY Pike were caught in Cootes Paradise, but 9 were caught in Grindstone Marsh. Water levels were much higher in 2019, so it could be possible that the Pike were spawning in other newly accessible areas that weren't monitored (Mataya, et al. 2020).

Index electrofishing monitoring (1994 – 2022)

During the electrofishing monitoring, there has been a general decline in the number of fish caught each year, except for 2020, where there was a large spike in total catch which coincided with a large Bluegill and Pumpkinseed YOY influx that affected the numbers (Rebalka et al. 2023). The last big change in catch numbers occurred back in 2011 due to high water levels, allowing for floodplain inundation (Epp & Court, 2012). The mean number of YOY fish caught/ transect has remained relatively low over the last 9 years, not reaching a value of 20 YOY fish/transect since 2013 (Figure G6). Positively, YOY Common carp/transect has remained below 1 fish/transect since 2013, and in 2022, no YOY carp were found in either Marsh system through monitoring (Figure G7).

Carp removal (2000-2022)

Since 2000, RBG has successfully removed 40,037 large Common Carp from just Cootes Paradise Marsh alone. This doesn't include fish that are prevented from entering at the Fishway or Young of Year found (Figure G8). Additionally, from the protected areas of Grindstone Creek Marsh areas separated from the creek by a berm, another 3,413 have been removed over the last 22 years (Figure G8). Many of these fish were returned to the harbour system directly.

DISCUSSION

The BUI breaks down fish species into three categories: Eutrophic species (White Perch, Bullheads, Carp), Top Predators (Northern Pike, Bowfin, Largemouth Bass), and Other Natives (Suckers, Yellow Perch, Sunfishes). The goal is to have a low biomass of eutrophic species and a higher biomass of predators and other native species for delisting criteria to be met. When separating catch numbers at the Fishway each year, eutrophic species still outnumber Predators and Other Natives categories. However, monitoring data suggests a future shift in this dynamic.

While decreasing overall, Brown Bullhead and Common Carp still make up the majority of the population seen at the Fishway. There has been a shift in the total number of carp still present in the marsh, as numbers seen throughout monitoring and removal efforts have decreased. For example, as seen in Figure G7, there has been less than 1 YOY Carp per transect in the last 9 years. That being said, the Carp population remains a problem as there are still considerable numbers of Carp being removed from the marsh each year. While the Fishway is effective at preventing the movement of larger fish, particularly breeding female Carp, the 5cm grating allows for incidental Carp to enter, allowing them to grow to maturity in the marsh, and the Fishway is still periodically subject to extreme flood events. The grate size issue also exists in the Grindstone marsh system, with the manual fish barriers. In addition, the Grindstone Marsh ponds are also more susceptible to Carp introduction through other means. Flooding is a primary concern as the berms, while built up to about a meter above the water level, can only hold back so much water as they are primarily made up of old Christmas trees. Secondly, with all the habitat improvements, the already high beaver and muskrat population in the Grindstone Marsh system has grown. The beavers will often build a lodge directly in the berms and maintain active tunnels between the creek and ponds. Muskrats build lodges in the protected ponds and will also tunnel through the berms to access creek and pond habitats as they please. This creates holes that are difficult to detect and repair, which can leave the ponds vulnerable to Carp movement (Rebalka et al. 2023).

The installation of a Grindstone Marsh Fishway at the mouth of the creek would greatly benefit the health of the constructed wetlands. By preventing Common Carp from accessing the Grindstone Marsh at the mouth of the river (which is how carp are managed in Cootes Paradise) a Fishway would provide enhanced protection in a single location, which would protect habitat in the creek as well as in the floodplain ponds. This would reduce the amount of labour in removing carp from the protected areas, as the individual fish structures and berms are more easily breached, and management efforts are spread out over a large area. Following a decreasing carp population in the harbour, habitat along the creek channels has also been recovering. A Fishway would prevent access to this vegetation as well, which is currently available to carp with the current setup. The ponds would really benefit from improved carp exclusion, with a better opportunity to regenerate vegetation, improving habitat conditions andallowing the marsh mammals to use the habitat as they please. A Fishway would also provide additional information on fish movements in the Grindstone system which currently is not available. This information would complement the RBG Pike trap and electrofishing monitoring, and DFO telemetry data in understanding recovering top predator movements and habitat use.

Pike Traps and Electrofishing

Utilizing both the pike trap monitoring and electrofishing monitoring data is greatly beneficial in providing a more accurate overall picture of the fish population in Cootes Paradise and Grindstone Creek. For example, trap monitoring can provide species composition within Ponds 2, 3, and 4, all of which aren’t sampled by electrofishing. It also ensures that all potential YOY species are accounted for. For instance, the trap monitoring typically occurs in June, targeting not only predatory fish, but other early spawning fish. While electrofishing typically occurs during the end of August, targeting fish like Bluegill, which spawn later in the season. When looking at the electrofishing monitoring trends over the years, it is highly evident that fish populations in both marshes are decreasing (Figure G9 and Figure G6). Sporadically, there will be a spike in the numbers, but there are just too many external factors to facilitate homogenous trends from year to year. Things like Lake Ontario water levels, seiches, and CSOs occurring after major rain events are ever present and can greatly change the marsh habitat. While the seiches are integral to most coastal marsh systems (Maynard and Wilcox, 1997), when they are coupled with nutrient loading and invasive species disturbance, the vegetation is unable to adapt effectively (Maynard and Wilcox, 1997). The struggle to regenerate year to year puts added stress on the native fish that rely on both marshes for spawning.

While populations are decreasing, there are some promising trends that suggest an overall change in the fish community. As previously mentioned, most fish seen at the Fishway (fish >25cm in length) are primarily eutrophic species. However, as shown in Figure G4, these species are experiencing a slight decline while other native fish and top predators are gradually increasing. Comparatively, when translating the electrofishing data (predominantly incidental fish <25cm in length) into similar trophic categories, other native species (sunfishes, suckers, yellow perch, etc) are dominant (Figure G10). Eutrophic fish, on the other hand, represent the sub-dominant group with numbers slowly decreasing, while top predators are present in high amounts and are increasing (Figure G10).

In conclusion, after examining all RBG’s monitoring data and taking into consideration the 2022 trends, it is our recommendation that BUI 3 for fish populations remain impaired in both Cootes Paradise and Grindstone Creek marshes as criteria have not been met.

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Table G 1. *Annual comparison of large fish caught entering the marsh at Cootes Paradise Fishway.*

Species	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022
American eel															1												
Atlantic salmon																									1		
Bigmouth buffalo		1		2	5		5	2		3		8	16	8		8		5	2			18	2	4	2		1
Black bullhead		1	2	12	59	18	63	20	151	70	7	1				2					1						
Black bullhead x Brown bullhead								1		5	1	1				1					2						
Black crappie	7	14	1	3	1	2	14	15	7	9	3		1		1												
Bowfin	9	18	12	9	24	32	43	50	57	50	63	53	63	63	60	53	83	152	93	127	139	178	165	174	144	164	119
Brown bullhead	575	2,005	3,215	3,589	13,265	14,728	18,265	20,565	18,659	15,830	20,967	16,739	20,807	18,069	9,045	9,296	2,565	6,358	7,933	12,723	15,559	11,086	16,077	7,195	5,630	7,640	11,464
Brown trout		3		1		2	3	2	1	2						1		1									
Channel catfish	32	413	505	684	1,926	485	1,374	1,388	1,119	815	797	748	1,285	817	842	1,002	451	951	959	687	678	839	314	513	226	323	320
Chinook salmon		20	6			2	43	18	1	2	21	1	1		7	63	44		2							3	1
Freshwater drum	3	85	547	297	242	461	411	509	753	468	312	330	383	238	244	74	83	34	54	38	30	33	7	19	62	12	30
Gizzard shad	15	24	64	52	182	95	257	645	1,715	631	510	468	357	272	206	826	333	1,400	989	358	179	254	406	403	591	257	637
Golden redhorse										1																	
Greater redhorse										2																	
Lake trout		3	2	5				1				1											1		1		2
Largemouth bass	1			1	1	4	20	20	21	18	9	17	28	42	26	44	29	23	26	14	20	15	14	19	2	3	3
Longnose gar						1	2		1	1					2		1		1			1					
Longnose sucker																1											
Northern pike	27	13	15	3	128	52	35	31	24	9	5	21	13	8	17	21	31	34	9	27	44	45	49	33	14	6	8
Rainbow trout	20	66	106	6	139	145	102	112	53	63	27	67	77	28	33	94	73	206	181	82	75	50	41	59	51	35	29
Rock bass										1	1	2	3			5		2		1			1				
Sea lamprey													1				1										
Shorthead redhorse			1	2		2	1	2				1	2	1		1	2		1	1			1		1		
Silver lamprey													1		1												
Silver redhorse		2		2	2																						
Smallmouth bass				1	4	1	4	1	2	1	1	1	6	2	1	2						1			2		
Spotted gar											1																
Striped bass			1																								
Walleye							1	1		1							1	1								1	
White bass						1	2		2	2	1	2	5	4	4	1	5	6	6	3	3	1		4	4		
White perch	17	16	22	26	72	21	40	23	129	50	15	9	9	22	6	33	7	10	81	28	19	23	11	1	4	1	5
White sucker	491	488	632	320	3,215	3,683	5,433	4,447	2,559	2,644	1,089	2,435	2,369	2,032	1,735	3,695	1,757	3,217	3,926	3,831	2,604	2,456	3,294	3,746	1,399	2,642	2,623
Yellow perch	4	5	2	2	15	21	70	223	28	76	10	91	32	21	20	84	19	66	163	41	8	7	15	6	1	9	7
Sub-total	**1,201**	**3,177**	**5,133**	**5,017**	**19,288**	**19,756**	**26,188**	**28,076**	**25,282**	**20,754**	**23,840**	**20,996**	**25,459**	**21,627**	**12,251**	**15,307**	**5,485**	**12,466**	**14,426**	**18,961**	**19,787**	**15,007**	**20,398**	**12,176**	**8,135**	**11,096**	**15,249**
Common carp	1,739	14,667	8,517	10,158	26,681	14,443	14,974	10,068	6,176	4,971	3,920	3,379	10,422	5,946	2,987	5,658	1,603	8,695	7,161	4,091	2,684	9,249	1,836	4,528	1,986	1,082	1,176
Common carp x Goldfish	58	95			8	1	3	11	13	118	91	116	307	413	65	101	18	162	59	124	130	292	280	1,322	303	37	75
Goldfish	53	22	9	1	116	65	296	250	354	346	503	440	1,289	958	587	789	388	785	1,706	2,446	2,019	1,682	1,690	2,651	1,240	999	298
Rudd											1		1	1	1	2	1	1	3	5	7	44	16	20	25	38	49
Total	**3,051**	**17,961**	**13,659**	**15,176**	**46,085**	**34,265**	**41,461**	**38,405**	**31,825**	**26,189**	**28,355**	**24,931**	**37,478**	**28,945**	**15,891**	**21,857**	**7,495**	**22,109**	**23,355**	**24,627**	**24,201**	**26,274**	**24,220**	**20,697**	**11,689**	**13,252**	**16,847**

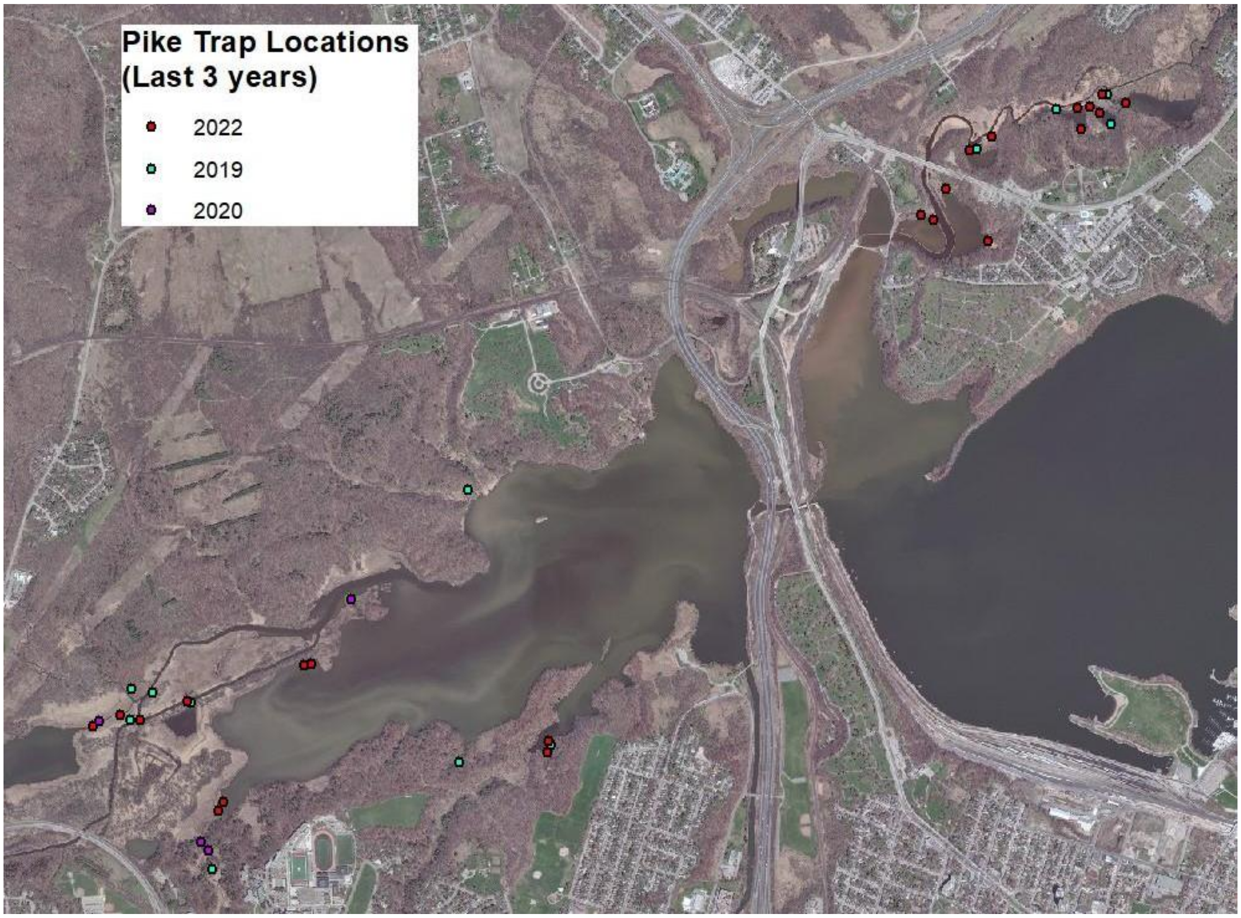


Figure G 1. *Locations of pike traps set in the last three sampling years.*

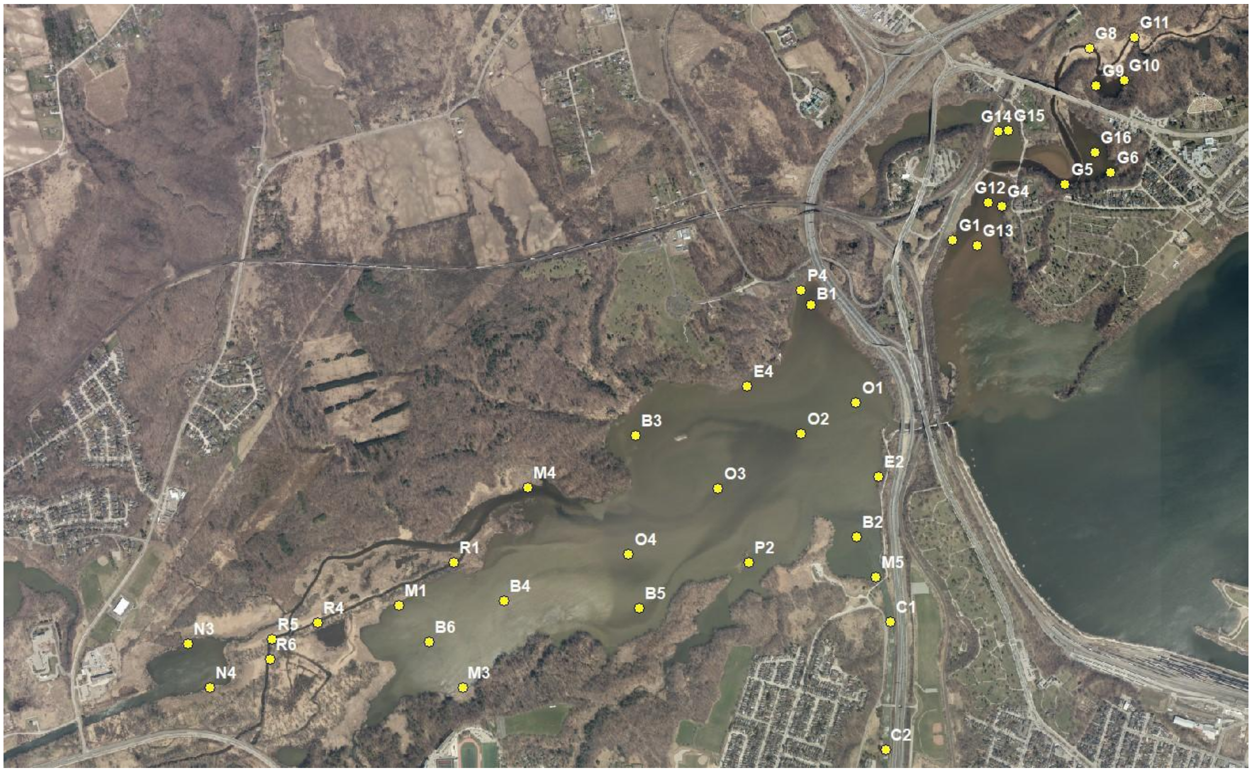


Figure G 2. *Electrofishing monitoring transect locations with Cootes Paradise and Grindstone Creek (G1-16).*

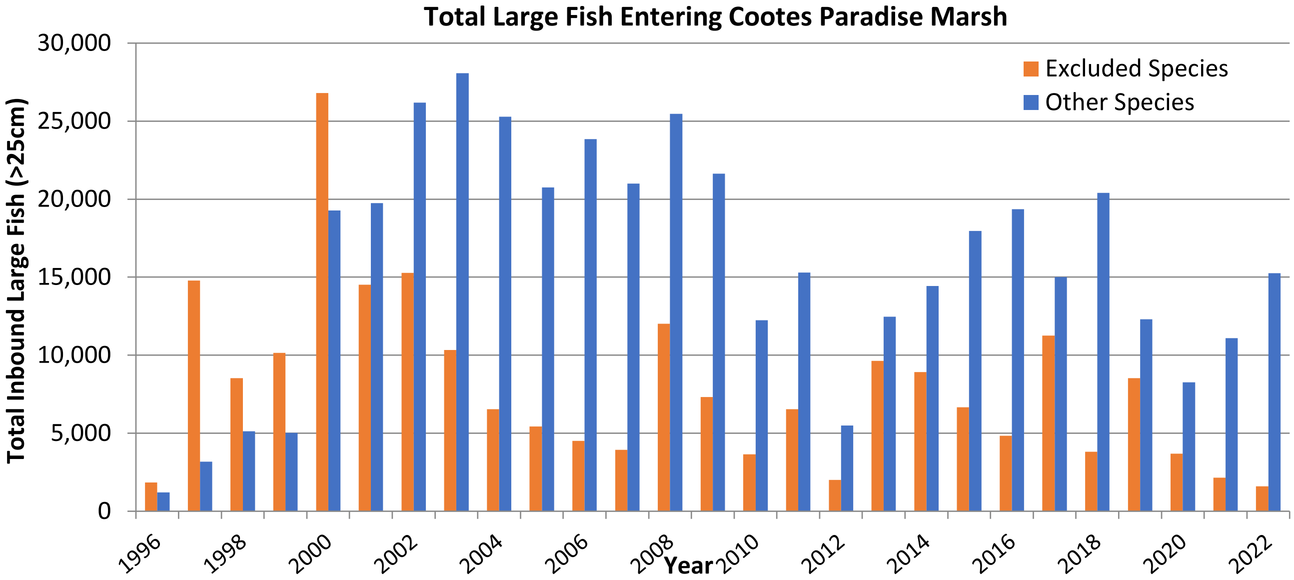


Figure G 3. *Annual number of inbound invasive species (excluded species) and native fish (other species) at Cootes Paradise Fishway. Excluded species includes Common carp, Goldfish, Common carp x Goldfish hybrids, and Rudd.*

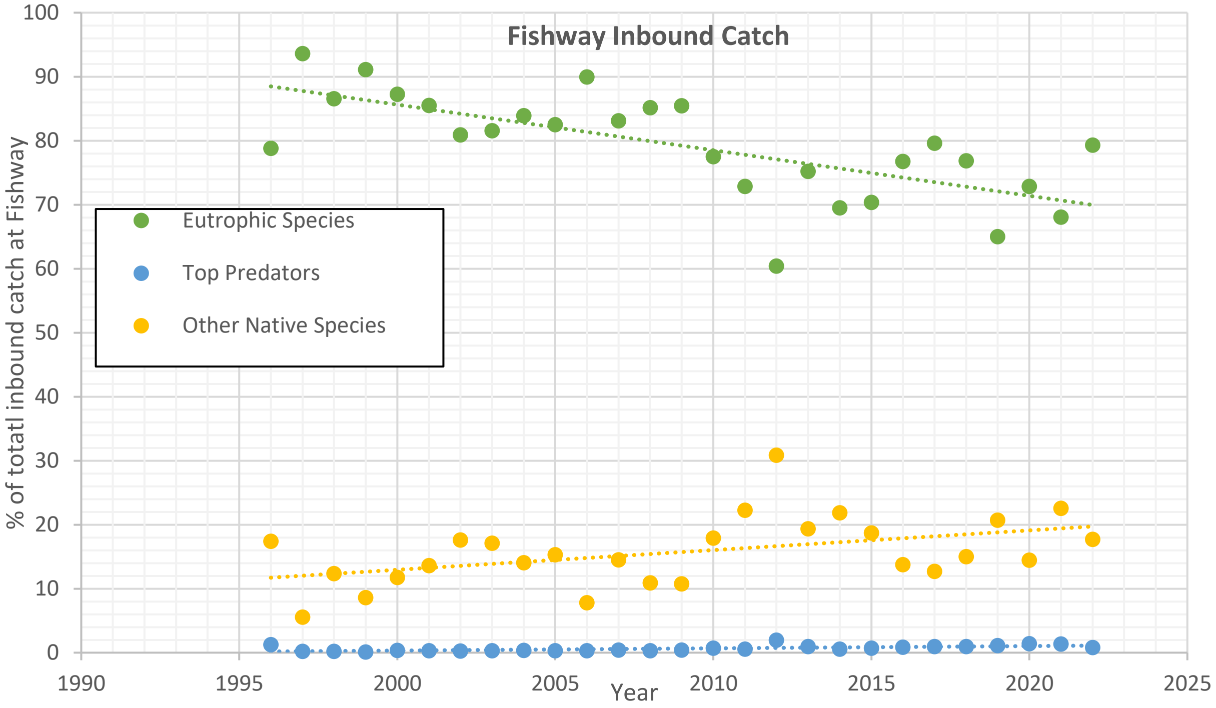
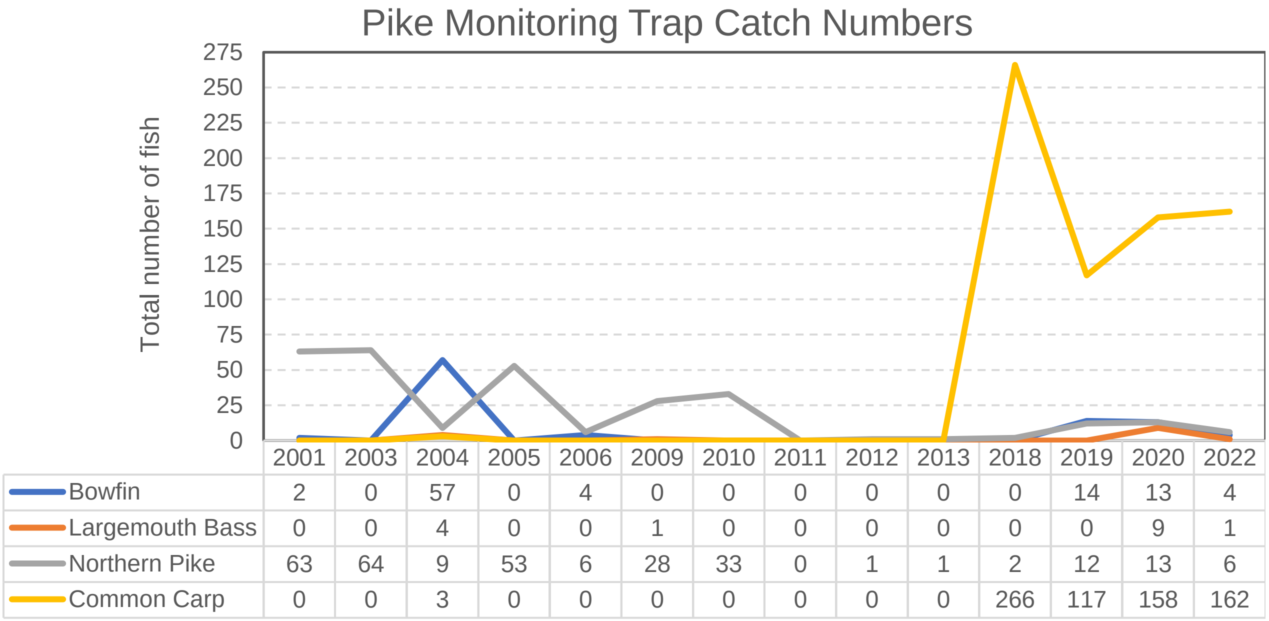


Figure G 4. *Percent of total inbound catch at the Fishway from 1996 – 2022 within three categories of fishes (Eutrophic, Predators, Other Natives).*



	2001	2003	2004	2005	2006	2009	2010	2011	2012	2013	2018	2019	2020	2022
Bowfin	2	0	57	0	4	0	0	0	0	0	0	14	13	4
Largemouth Bass	0	0	4	0	0	1	0	0	0	0	0	0	9	1
Northern Pike	63	64	9	53	6	28	33	0	1	1	2	12	13	6
Common Carp	0	0	3	0	0	0	0	0	0	0	266	117	158	162

Figure G 5. *Total number of predatory fish caught each year in the pike trap monitoring, compared against common carp. (No monitoring occurred in 2002, 2007, 2008, 2014-2017, 2021).*

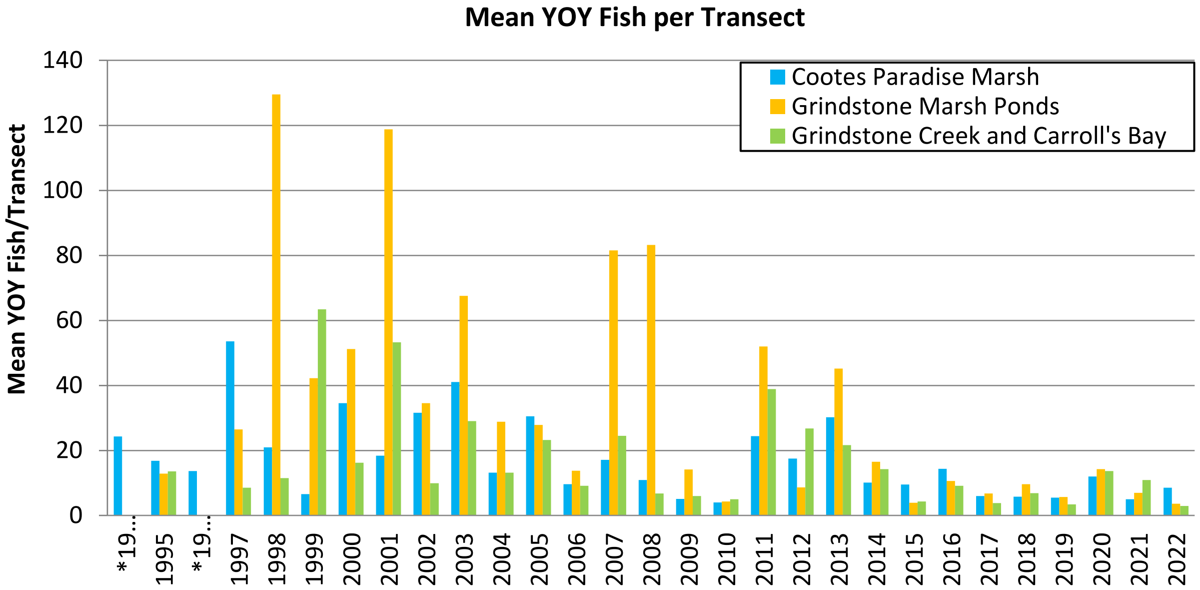


Figure G 6. *Mean YOY fish per transect, by year, for Cootes Paradise Marsh, Grindstone Marsh Ponds, and Grindstone Creek and Carroll's Bay Marsh.*

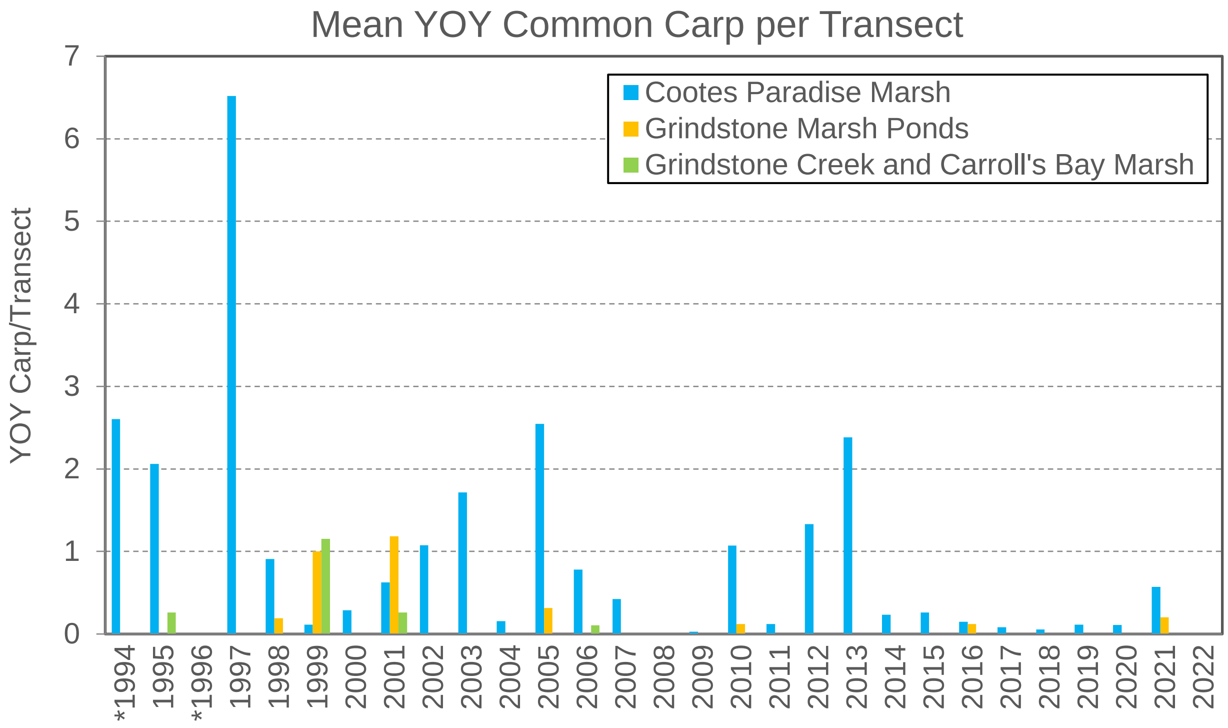


Figure G 7. *Mean number of YOY Common Carp (and Common Carp x Goldfish hybrids) caught in August electrofishing transects, by year, for Cootes Paradise Marsh, Grindstone Marsh Ponds, and Grindstone Creek and Carroll's Bay Marsh.*

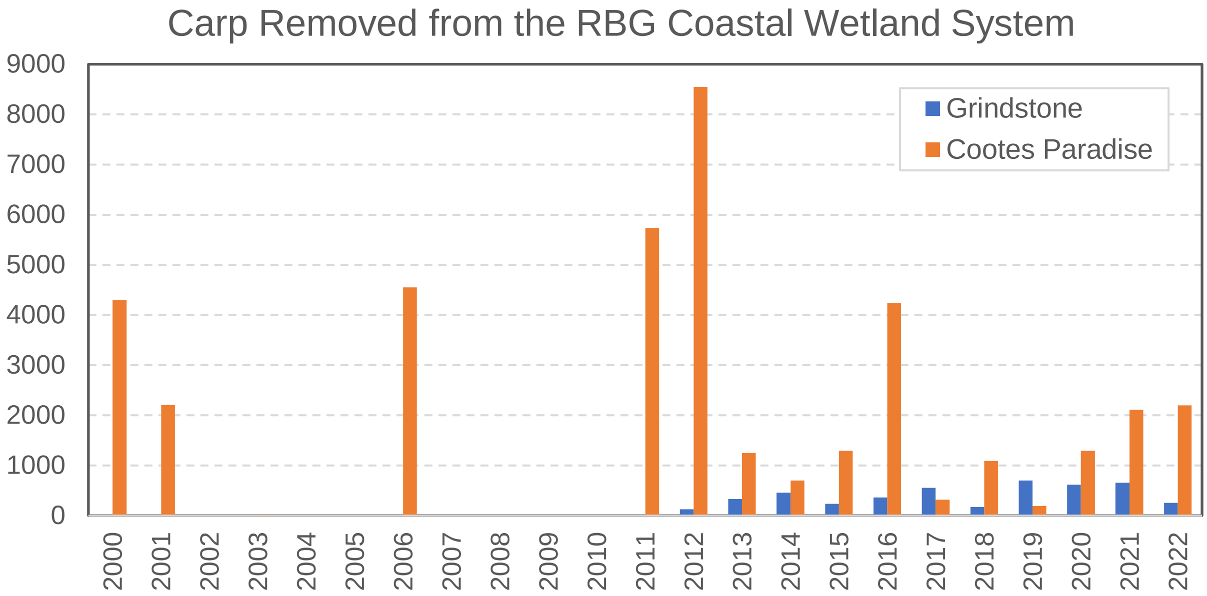


Figure G 8. *Total number of Common Carp removed from Cootes Paradise and Grindstone Marshes from 2000 - 2022. The Grindstone Marsh numbers only include carp removed from protected areas (i.e. the ponds/wetlands separated from the creek by berms).*

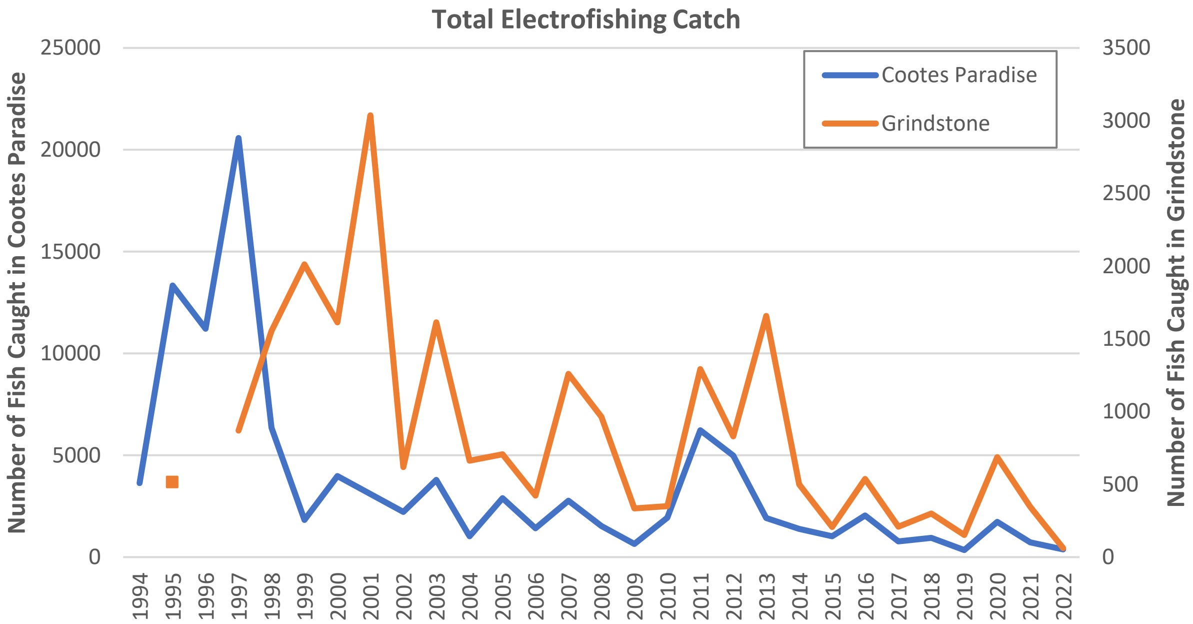
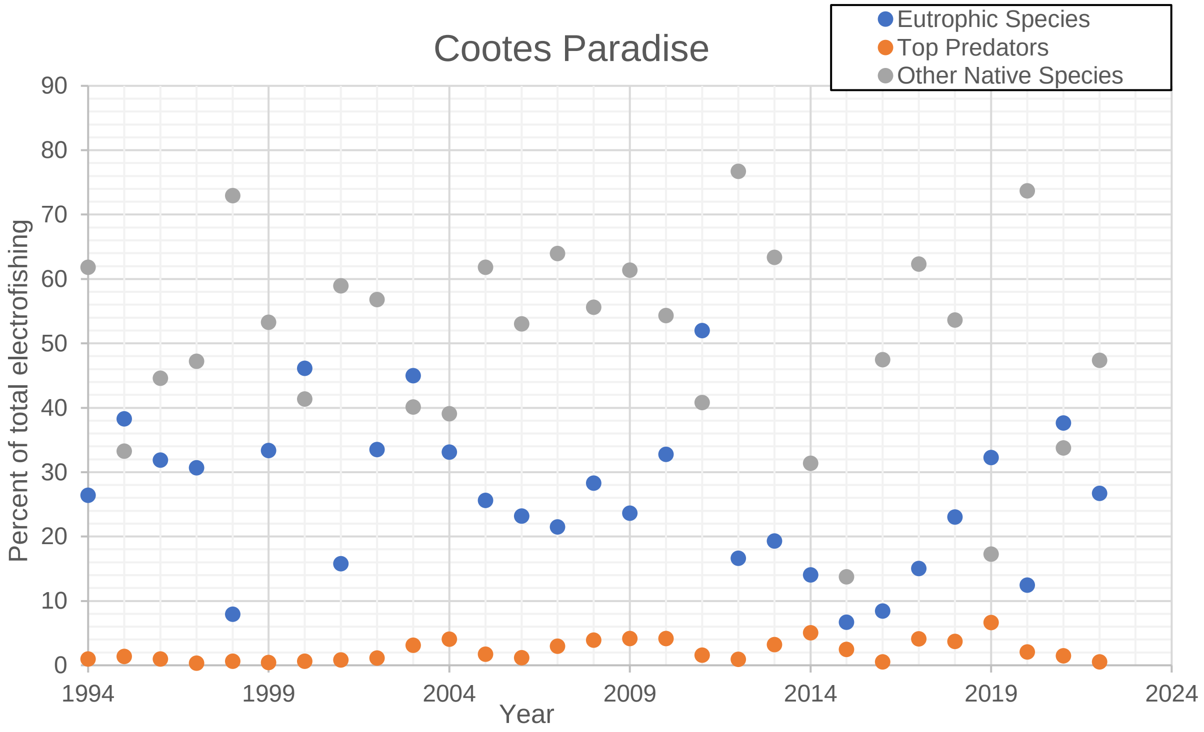


Figure G 9. *Total number of fish captured in Cootes Paradise and Grindstone marshes during annual electrofishing surveys. (No monitoring took place in Grindstone in 1994 and 1996).*



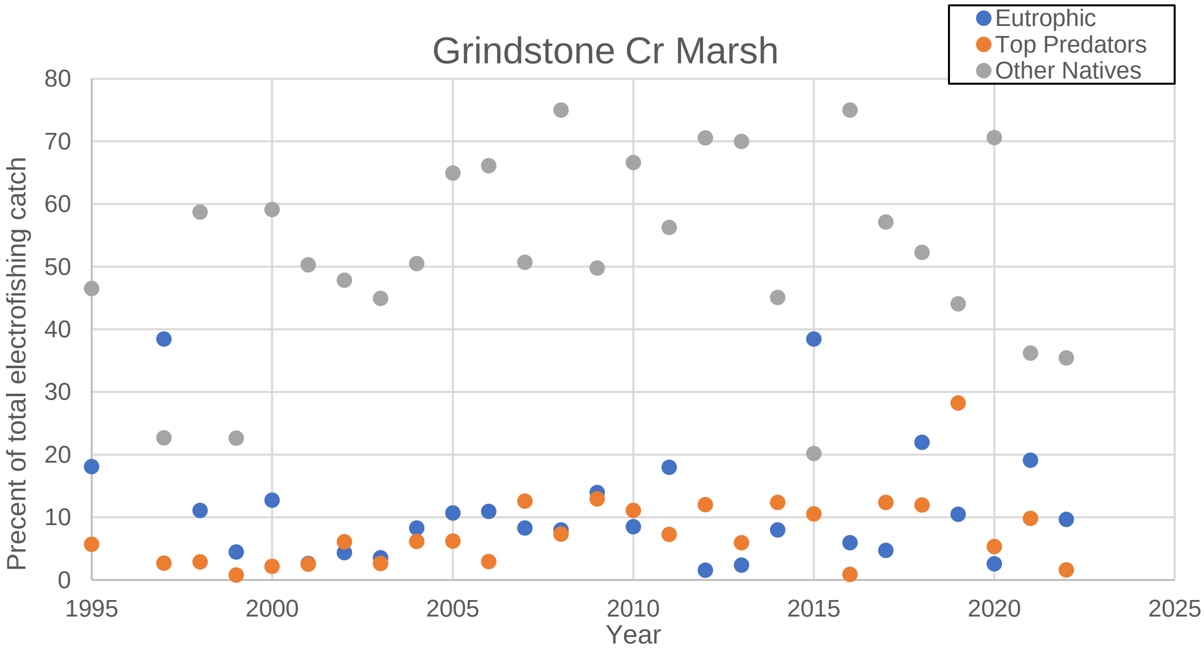


Figure G 10. *Percent of total electrofishing catch from 1995 – 2022 broken down into three categories of fishes: 1) Eutrophic = Alewife, Brown Bullhead, Common Carp, Common Carp x Goldfish, Gizzard Shad, White Perch; 2) Predators = Bowfin, Largemouth Bass, Northern Pike, Walleye, and 3) Other Natives = Bluegill, Channel Catfish, Freshwater Drum, Pumpkinseed, White Sucker, Yellow Perch.*