A multi-metric approach to characterize variability in Yellow Perch (*Perca flavescens*) use of Lake Ontario and two barrier-protected coastal wetlands

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Abstract Yellow Perch (*Perca flavescens*) inhabit both nearshore and coastal wetland habitats of the Laurentian Great Lakes throughout their lifetime and are known to exhibit different movement life histories. However, uncertainty persists in the spatial extent of this variation and in the duration of habitat use. To explore these uncertainties, we used a multi-metric approach that included water and otolith microchemistry and tissue stable isotope ratios (δ^{13}C, δ^{15}N). The ratio of manganese to calcium in otoliths was used to identify transitional movements between nearshore Lake Ontario and wetland habitats while carbon and nitrogen tissue isotope ratios revealed variable duration of wetland inhabitance. Our research suggests that the multi-metric approach was useful for addressing questions that could not be answered by one method alone. Our results demonstrate individual differences in duration of coastal wetland habitat residence among Yellow Perch, which may influence their susceptibility to recreational harvest. As Yellow Perch are an important species of consideration for management agencies such as the Great Lakes Fishery Commission, exposing such diversity is important when considering the potential for differential contributions of individuals with variable movement life histories to overall population stability and resilience over time.

Introduction

Great Lakes coastal wetlands (GLCWs) are highly complex, productive, and variable habitats that support many species of fish throughout ontogeny (Jude and Pappas 1992). GLCWs exist as multiple hydrogeomorphic types with varying degrees of surface water connections to an open Great Lake. The physicochemical characteristics of each GLCW are strongly influenced by the adjacent Great Lake in addition to other factors such as riverine or tributary output depending on the wetland classification (Albert et al. 2005; Uzarski et al. 2017). Multiple species of young-of-the-year (YOY) and juvenile fish benefit from the complexity of GLCW habitats in finding protection from predation and refuge from harsh waves and currents in open Great Lakes habitats (Jude and Pappas 1992; Tanner et al. 2004; Brazner et al. 2004; Parker et al. 2012). The high productivity of GLCWs also

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supports large quantities of invertebrate prey which can supplement the growth of juvenile and adult fish and facilitate these habitats as crucial spawning and nursery areas (Jude and Pappas 1992; Parker et al. 2012). Variable wetland hydrogeomorphology (Albert et al. 2005; Uzarski et al. 2017) results in surface water connections or "corridors" to open Great Lakes habitats that may physically vary over space and time (Albert et al. 2005). Thus, fish moving between open Great Lake habitats and these diverse GLCWs might be expected to display a variety of movement behaviors with both ecological and fishery-based implications.

One fish species that commonly uses both open Great Lakes habitats and GLCWs is the Yellow Perch (*Perca flavescens*). The movement of this species between these habitats can be highly variable and is important from both ecological and fishery-based perspectives (Schoen et al. 2016; Chorak et al. 2019; Senegal et al. 2020). For example, Schoen et al. (2016) observed that Yellow Perch collected in GLCWs throughout Lakes Michigan and Huron displayed variable movement patterns that included wetland residency, wetland use once annually, or juvenile wetland residency followed by open lake use. Yellow Perch that move between open Great Lake and GLCWs may also play important ecological roles as prey, predators, and purveyors of nutrients between habitats (Brazner et al. 2001; Sierszen et al. 2019; O'Reilly et al. 2023). Moreover, movements of Yellow Perch into GLCWs rarely go unnoticed by humans as this species is a popular target for recreational fisheries (Senegal et al. 2020). Because of this, there is growing interest in understanding the role that Yellow Perch moving in and out of GLCWs from open lake habitats play in recreational fisheries. This sets the stage for questions about the transitions between open Great Lakes and GLCW habitats and the duration of GLCW use by Yellow Perch.

Understanding fish movements prior to capture requires a method to retrospectively reconstruct habitat use. Otolith microchemistry is an effective approach in this regard and has been applied to reconstruct Yellow Perch movements between Lakes Michigan and Huron and adjacent GLCWs (Schoen et al. 2016). This approach relies on the incorporation of elements into otoliths in a way that reflects changes in element concentrations in the ambient environment (Campana 1999). However,

otolith microchemistry also has limitations particularly if fish only recently transitioned from one habitat to another prior to capture or if there is little variation in water element concentrations between or among the waterbodies of interest. Adding an additional proxy for movement can thus help mitigate such limitations (Campana 1999).

To complement the information obtained using otolith microchemistry, tissue stable isotope ratios of carbon and nitrogen provide means to investigate the duration of stay in a particular habitat based on isotopic differences between habitats (Cunjak et al. 2005). Carbon isotope ratios ($\delta^{13}C$) typically reflect dietary differences (DeNiro and Epstein 1978), while nitrogen isotope ratios ($\delta^{15}N$) are useful indicators of trophic position (Vander Zanden et al. 1997). When a fish transitions to feeding in another habitat, soft tissues such as dorsal muscle begin to turn-over or come to isotopically reflect the food web in the new habitat (Weidel et al. 2011). While the isotopic change is not immediate, it does occur incrementally and provides a basis for estimating duration of stay or relative time of arrival (Cunjak et al. 2005). This approach has been used to examine time spent by Yellow Perch in GLCWs and nearshore Lake Michigan and Lake Huron (Senegal et al. 2020; O'Reilly et al. 2023), but to our knowledge has yet to be explored in Yellow Perch using Lake Ontario and its GLCW habitats. As Yellow Perch are an important species of consideration to the Great Lakes Fishery Commission, it is critical to understand their complex movements and duration of stay in the Lake Ontario GLCWs to ensure effective habitat management and restoration strategies are considered.

The objective of this study is to characterize the spatial and temporal variability in movement patterns displayed by Yellow Perch captured in two GLCWs of southern Lake Ontario. To accomplish this, we applied a multi-metric approach that combined natural proxies of movement and habitat use duration (e.g., otolith microchemistry and tissue stable isotope ratios, respectively). We aimed to answer whether Yellow Perch caught in Lake Ontario and two coastal wetland systems display multiple movement life history types (e.g., GLCW resident versus those that move between Lake Ontario and the GLCW) and subsequently whether more mobile life histories, if present, use GLCW for different durations of time.

Methods

Study sites and fish collection

Yellow Perch were collected from nearshore Lake Ontario (approximately 2.3 km offshore in 17 m of water) adjacent to the Port of Rochester, NY, and from the Long Pond and Buck Pond barrier-protected wetlands in the Braddock Bay Wildlife Management Area located in Greece, NY, approximately 6.5 km northeast of the Port of Rochester (Fig. 1). Long Pond and Buck Pond each have singular, independent, channel connections to Lake Ontario with an open water lagoon behind a protective barrier beach which extends to the landward side edged with marsh vegetation.

Yellow Perch were collected during three periods. The first collection period occurred in early October 2019 from nearshore waters of Lake Ontario adjacent to the Port of Rochester, NY. The collection was conducted by the United States Geological Survey- Lake Ontario Biological Station (USGS-LOBS, Oswego, New York) during their annual benthic prey bottom trawl (Table 1). These Yellow Perch ($n=10$) were used to establish a putative Lake Ontario fingerprint for otolith microchemistry. The second collection

Fig. 1 Water, invertebrate, and Yellow Perch samples were collected from Lake Ontario outside of the Port of Rochester (inset map, black square) and two wetland sites (Long Pond and Buck Pond) during Summer 2020 (all sites) and Spring 2021 (Long Pond and Buck Pond only)

Table 1 Yellow Perch capture locations and dates, number of fish by site, and length and weight ranges. Benthic trawls were conducted by biologists from the United States Geological Survey, Lake Ontario Biological Station. Boat electrofishing (Boat e-fish) was conducted by SUNY Brockport

Site	Date(s)	Method	N	Length range (mm)	Weight range (g)	Age (s)
Lake Ontario (Port of Rochester)	10/7/19	Benthic trawl	10	75–116	3.9–16.6	0+ to 1+
Buck Pond	8/10/20	Boat e-fish	12	37–121	0.5–20.3	0+ to 1+
Long Pond	8/10/20	Boat e-fish	14	55–132	1.8–12.4	0+ to 1+
Buck Pond	4/14/21–5/12/21	Boat e-fish	50	79–228	4.6–193.3	0+ to 5+
Long Pond	4/14/21–5/12/21	Boat e-fish	50	74–267	4.3–240.1	0+ to 5+

period was between late July and mid-August of 2020 in Long Pond ($n = 14$) and Buck Pond ($n = 12$; Table 1) using boat electrofishing. These individuals were used to establish a putative wetland fingerprint for otolith microchemistry. Yellow Perch from these collections were limited to age-0+ and age-1+ given their relatively fast growth rates and greater resolution of otolith chemical data. The third collection period occurred on Long and Buck Ponds starting on April 14th, 2021, and continued every other week until May 12th, 2021. These dates overlapped the spawning period of Yellow Perch in the region, and it was anticipated that Yellow Perch moving into the wetlands from Lake Ontario would be encountered. In total, 50 Yellow Perch were collected from both Long Pond and Buck Pond using boat electrofishing. All Yellow Perch were stored frozen (-15 to -20 °C) until lab processing.

Water chemistry

Distinct water chemistry between Lake Ontario and wetland habitats is a requirement for reconstructions of past habitat transitions between these habitat types using otolith microchemical techniques. Water samples were collected from each sampling location to establish site-specific trace element profiles. The site-specific profiles were used together with otolith trace element concentrations to identify potential transitions between Lake Ontario and our wetland sites. All collection bottles, filters, and syringes were acid washed with 1.2 N HCl, triple-rinsed with nanopure water, and allowed to air dry under a class-100 laminar flow hood. Water samples were collected in triplicate from surface waters of Lake Ontario in August 2020 and from each wetland site in August 2020 and April 2021. The triplicate

samples in Long Pond and Buck Pond were collected at different locations in the ponds to best characterize the chemistry throughout the ponds. Following similar methods used by Shiller (2003), all water samples were filtered through 0.45-micron filters into acid-washed bottles, fixed with 125 μL of high purity, trace metal grade, and nitric acid to achieve a pH of < 2.0, and refrigerated until analysis at SUNY College of Environmental Science and Forestry (SUNY ESF). Water samples were analyzed for isotopes of ^{43}Ca, ^{88}Sr, ^{138}Ba, ^{24}Mg, and ^{55}Mn using inductively coupled plasma optimal emission spectrometry (Perkin Elmer Optima 3300DV). Instrument calibration was achieved using external standards spiked with known concentrations of the elements of interest and accuracy was deemed acceptable if external standards were measured within $\pm 10\%$ of known values (Hayden et al. 2013). All elements were detectable above background levels.

Invertebrate collection

Invertebrates were collected from Lake Ontario, Long Pond, and Buck Pond and used as indices of isotopic differences among sites. Invertebrates were sampled using a combination of D-frame net sweeps nearshore, PONAR grabs, and/or hand picking off rocky substrates (Table 2). In Lake Ontario, only PONAR grabs were used to collect invertebrates from the substrate where soft sediment could be found. In Long and Buck Ponds, D-frame nets, PONAR grabs, and hand-picking were employed. All invertebrates were separated from samples by hand and stored frozen (-15 to -20 °C) until they could be sorted by order and prepared for stable isotope analysis.

Table 2 Invertebrate δ^{13}C and δ^{15}N values relative to the standards of Vienna Pee Dee Belemnite and Air, respectively. Values are based on one sample containing multiple organisms of the same taxa. Invertebrates were collected across two years and seasons in the respective wetlands (Buck Pond and Long Pond) and Lake Ontario habitats using d-net sweeps, PONAR grabs, or by hand picking from substrate with forceps

Site	Season	Year	Order	$\delta^{13}C_{VPDB}$ (‰)	$\delta^{15}N_{Air}$ (‰)
Lake Ontario	Summer	2020	Amphipoda	-18.45	7.12
			Diptera	-18.67	9.45
Buck Pond	Summer	2020	Amphipoda	-25.28	3.94
			Diptera	-34.31	1.33
			Ephemeroptera	-28.52	3.79
			Odonata	-27.75	6.50
Buck Pond	Spring	2021	Amphipoda	-31.07	6.53
			Diptera	-40.51	4.00
			Hirudinea	-27.81	8.71
			Isopoda	-24.53	5.65
			Odonata	-29.48	8.95
Long Pond	Summer	2020	Diptera	-26.05	6.21
			Hemiptera	-22.98	6.10
			Isopoda	-24.53	6.71
			Odonata	-24.00	8.89
Long Pond	Spring	2021	Amphipoda	-21.37	6.94
			Diptera	-26.51	6.38
			Ephemeroptera	-23.91	9.41
			Hirudinea	-25.26	12.17
			Hydracarina	-24.56	9.25
			Isopoda	-24.41	7.34

Otolith chemical analyses

Both sagittal otoliths from Yellow Perch were extracted, cleaned of adhering tissue with deionized water and stored in 2-mL microcentrifuge tubes to dry. A randomly selected otolith from each fish was then embedded in epoxy and thin sectioned along the transverse axis using a Buehler Isomet™ Low Speed sectioning saw. Sectioned otoliths were affixed to petrographic microscope slides with Crystalbond 509™ and polished sequentially using 30 and 3-micron aluminum oxide lapping films. As validated aging structures (Blackwell and Kaufman 2012), sagittal otolith annuli were independently counted by two readers for each fish. Where age disagreement occurred, both readers attempted to reach a consensus age after another round of aging. If a consensus could still not be reached, the otolith was excluded from subsequent analyses.

Polished and aged otolith sections were combined onto petrographic microscope slides (10–12 otoliths per slide) for laser ablation inductively coupled mass spectrometry (LA-ICP-MS) analysis at SUNY ESF. LA-ICP-MS was conducted using a 193-nm Teledyne CETAC analyte excite excimer laser ablation system to measure the concentrations of multiple elements (^{7}Li, ^{24}Mg, ^{43}Ca, ^{63}Cu, ^{66}Zn, ^{55}Mn, ^{85}Rb, ^{88}Sr, ^{138}Ba, and ^{208}Pb) along a palindromic profile spanning the entire otolith from edge to core (fish hatch) to edge (fish death). The laser operational parameters included a 110-micron spot, scan speed of 7 μm s^{-1}, frequency of 10 Hz, and 70% power. We chose to monitor otolith ^{88}Sr, ^{138}Ba, ^{24}Mg, and ^{55}Mn in ratio to ^{43}Ca and used calcium as an internal standard in addition to two certified microanalytical standards (USGS MAPS-4 and USGS MACS-3). The excluded elements were typically observed in otoliths below the limits of detection or three times the standard deviation of background levels. Final element:calcium ratios were expressed in mmol mol^{-1} or μmol mol^{-1}. Percent relative standard deviations (RSD) as measures of analytical precision on MACS-3 for the elements of interest were 10.3% (^{24}Mg), 10.6% (^{55}Mn), 12.7% (^{88}Sr), and 22.8% (^{138}Ba).

Habitat transition thresholds

Habitat transition thresholds were created to assist in detecting movements by Yellow Perch between Lake Ontario and Long or Buck Ponds. Essentially, fish whose otoliths lacked chemical indications of a habitat transition into Lake Ontario were classified as having not yet left the wetland post-hatch in contrast to those that displayed at least one instance of Lake Ontario use. To generate baselines of otolith chemistry for fish caught in Lake Ontario and wetland habitats, we calculated the average Mn:Ca concentration of the two outermost laser points at the edge of the otolith long axis from age-0 + and age-1 + Yellow Perch caught in Lake Ontario during October 2019 and in Long and Buck Ponds during summer 2020. The edge of the otolith represents the most recently formed material, and we assumed that it would chemically reflect residence in the habitats of capture. An assessment of the water chemistry collected for this project indicated consistent differences in Mn:Ca between wetland habitats and Lake Ontario (Fig. 2).

To create an index of habitat use, we used a binary system to denote Lake Ontario or wetland inhabitance. We assigned a value of "1" for any otolith point along the laser transect with Mn:Ca concentrations at or below 5 µmol/mol indicating Lake Ontario inhabitance. For any otolith point that exceeded Mn:Ca concentrations of 5 µmol/mol, a "0" was assigned indicating wetland inhabitance. The Mn:Ca threshold of 5 µmol/mol was used because the median value of otolith edge Mn:Ca among fish caught in Lake Ontario was 4.72 µmol/mol while the median otolith edge Mn:Ca among fish caught in wetland habitats was 6.38 µmol/mol (Long Pond) and 16.11 µmol/mol (Buck Pond). The combination of "1 s" and "0 s" for each otolith point along the laser transect from the otolith core to edge was summed together to create individual index values. These values represented the relative amount of time that an individual fish had inhabited both Lake Ontario and wetland systems throughout its life.

Stable isotope analyses

Dorsal muscle tissue samples were collected from Yellow Perch caught across all three habitats in 2020 and from Long Pond and Buck Pond in spring 2021. Samples were dried using a Harvest Right© freeze dryer and then homogenized using a mortar and
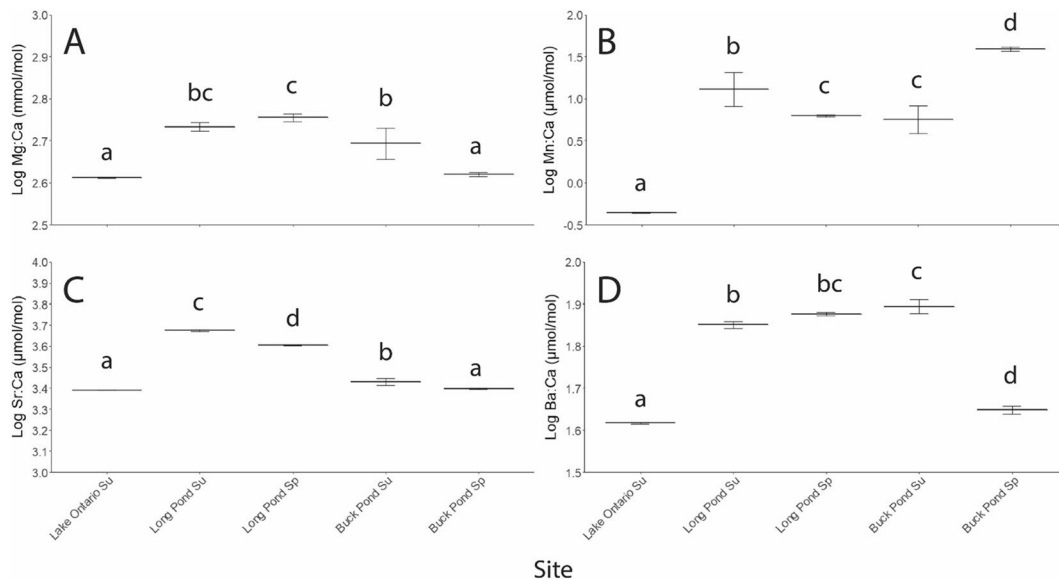
Fig. 2 Log transformed average element:calcium concentrations in water by site and season (summer 2020 = Su and spring 2021 = Sp) including Mg:Ca (A), Mn:Ca (B), Sr:Ca (C), and Ba:Ca (D). Differences among sites and seasons were tested using one-way ANOVA, and pairwise differences based on Tukey post hoc tests are indicated with lowercase letters. Summer samples were collected in 2020 while spring samples were collected in 2021 in both Long and Buck Ponds

pestle. The homogenized tissue (1.0 mg ± 0.2 mg) was encapsulated in tin capsules and sent to the UC Davis Stable Isotope Facility for analysis of combined $\delta^{13}C$ and $\delta^{15}N$. This process was repeated for each order of invertebrates. Although both gastropods and bivalves were collected, they were excluded from further analyses because the animals were not separated from their carbonate shells prior to stable isotope analysis. Carbonate shell material is known to be ^{13}C-rich relative to the soft parts of the organism which can influence isotopic values (Haines and Montague 1979). Isotope ratio values were recorded in standard delta notation (‰) and referenced to air for $\delta^{15}N$ and Vienna Pee Dee Belemnite for $\delta^{13}C$. Isotope ratios were derived using the equation below from Fry (2006).

$$\delta^H X = \left[\left(\frac{R\text{sample}}{R\text{standard}} - 1 \right) \right] * 1000$$

where δ signifies a ratio of heavy and light isotopes in a sample relative to those isotopes in a standard, H is the heavy isotope mass of that element, and R is the ratio of the heavy isotope to the light isotope for the element. This is multiplied by 1000 to amplify the differences measured between the samples and the standards (Fry 2006).

Statistical analyses

We chose to compare mean water element:calcium ratios among water bodies and seasons as our basis for subsequent otolith chemical comparisons and tested for differences using a one-way ANOVA and Tukey's HSD post-hoc test. Assumptions of normality were checked using a Shapiro-Wilks test, and homogeneity of the variance was assessed using a Levene's test. The significance level for all tests was set at $\alpha = 0.05$. None of the element:calcium ratios met the assumption of normality, but all met the assumption of equal variance. Data were $\log_{10}$ transformed in an attempt to correct for this departure from normality similar to Gahagan et al. (2012). After $\log_{10}$ transformations most of the data still violated the assumption of normality, but we proceeded with the analysis of variance (ANOVA) because ANOVAs are robust to divergence from normality (Zar 1996). Additionally, concern for a type I error was low because the

ANOVAs were highly statistically significant with large F values. The large F values imply that there is a high degree of variation between the trace element concentrations among sites which reduces the chance of incorrectly claiming that there are no differences in the elemental concentrations. All water element:calcium ratios met the assumption of equal variance. Statistical analyses were conducted using RStudio (R Core Team 2021: version 1.4.1106).

A linear regression was applied to examine the relationship between the age of sampled Yellow Perch and the summative otolith Mn:Ca index values. This was done to describe the use of Lake Ontario by Yellow Perch as they aged. For example, a positive trend in index values with age would indicate that cumulative time spent in Lake Ontario increased as fish aged. A visual assessment of the residuals indicated linearity and normally distributed data. The data appeared heteroscedastic though the positive linear trend remained after influential points based on Cook's distance were removed. Therefore, we chose to retain all the data for analysis.

Bivariate analyses of the tissue isotopic ratios by site type (i.e., Lake Ontario vs. wetland) and fish age were conducted by calculating Bayesian standard ellipses encompassing approximately 40% of the data using the R software package SIBER (Jackson et al. 2011) similar to Steube et al. (2021) and MacKenzie et al. (2022). An average wetland isotopic baseline signature was calculated by combining age-0 + Buck Pond and Long Pond fish that had no indication of Lake Ontario use (i.e., an otolith index value of 0). This "baseline" group was used to create a reference for comparison to more mobile fish. Similarly, average Lake Ontario isotopic baseline groups were established by combining age 0 + and 1 + and 0 + and 2 + Yellow Perch caught in the lake. An individual age-0 + Lake Ontario isotopic baseline group was not established because there were not enough fish in this category to meet the minimum sample requirement for the SIBER package. Finally, maximum likelihood estimates of the standard ellipse areas were calculated separately for spring-caught Yellow Perch ages 0 +, 1 +, and 2 + along with their corresponding site type grouping. Independent ellipse areas as well as the proportion of ellipse overlap were considered when inferring duration of time spent in the wetland system by fish that had previously inhabited Lake Ontario.

Results

Water chemistry

One-way ANOVAs comparing mean element:calcium ratios in water among sites and seasons revealed differences in Sr:Ca ($F_{4,10} = 921.9$, $p < 0.01$), Ba:Ca ($F_{4,10} = 582.1$, $p < 0.01$), Mn:Ca ($F_{4,10} = 112.5$, $p < 0.01$), and Mg:Ca ($F_{4,10} = 39.2$, $p < 0.01$). However, only Mn:Ca and Ba:Ca concentrations were consistently different between Lake Ontario and both wetland habitats across seasons (all Tukey HSD between Lake Ontario and wetlands $p < 0.01$, Fig. 2). While Ba:Ca concentrations did statistically differ between Lake Ontario and both wetland habitats, in the spring, water samples from Buck Pond, approached concentrations observed in Lake Ontario. Therefore, we conservatively used only Mn:Ca as our element ratio for discriminating between Lake Ontario and wetland inhabitance. Both Sr:Ca, and Mg:Ca displayed seasonal overlaps in concentrations with water from Lake Ontario.

Otolith chemistry

We created otolith index values based on Mn:Ca to identify Yellow Perch that had previously inhabited Lake Ontario given the differences in water chemistry noted above (Fig. 3). A fish with a cumulative otolith index value greater than zero was considered to have previously inhabited Lake Ontario at some point during its life whereas an individual with an index value of zero had not. Of the age-0 + Yellow Perch sampled in the spring of 2021 from wetland habitats ($n = 30$), 90% showed evidence of previous Lake Ontario inhabitance while the remaining 10% did not. Of the Yellow Perch older than age-0 + sampled in the spring of 2021 from wetland habitats ($n = 70$), 96% had inhabited Lake Ontario waters prior to capture. The remaining 4% were all age-1 + individuals that had not inhabited Lake Ontario prior to being captured. All Yellow Perch age-2 + and older appeared to have inhabited Lake Ontario based on cumulative otolith Mn:Ca index values greater than zero. Average index values also increased with age suggesting increased overall use of Lake Ontario with age (Fig. 3).
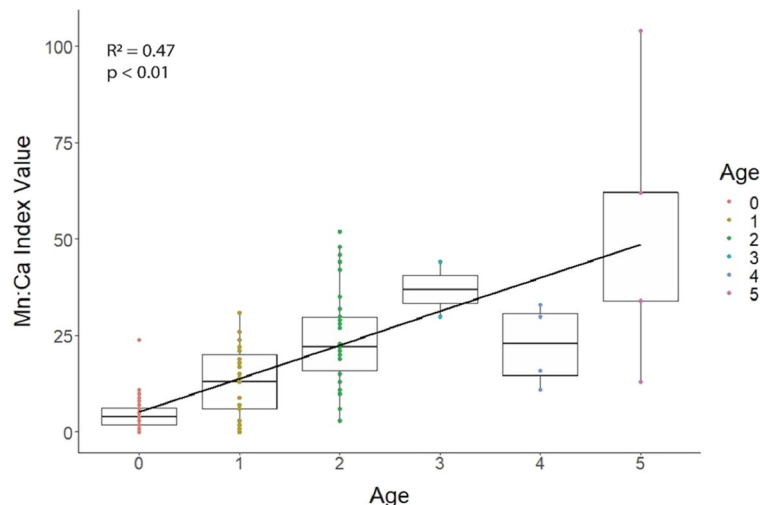
Fig. 3 Otolith Mn:Ca index values by age. Index values reported here represent the sum of all index values across the otolith transect for each individual fish. A cumulative index value of zero would suggest no use of Lake Ontario, and all fish index values exceeded zero by age-2 +. The occurrence of individual fish with cumulative index values of zero during their first and second year of life indicated different life history patterns existed related to timing of first entry into Lake Ontario. A linear regression indicated a positive relationship between Yellow Perch age and the Mn:Ca index values suggesting overall use of Lake Ontario increased over time

Stable isotope analysis

Invertebrate stable isotope composition was used to describe potential prey items of Yellow Perch and as indirect links to primary producers in each system. Mean ($\pm$SD) $\delta^{13}C$ values from invertebrates sampled in Lake Ontario were ^{13}C-rich ($-18.6‰ \pm 0.2$) relative to those of invertebrates sampled in the summer and spring from both Long Pond ($-24.4‰ \pm 1.5$) and Buck Pond ($-29.9‰ \pm 4.9$, Table 2, Fig. 4). $\delta^{15}N$ values however showed greater overlap among locations and seasons with complete overlap between Lake Ontario ($+8.3‰ \pm 1.6$) and Long Pond ($+7.9‰ \pm 2.0$) and partial overlap between Lake Ontario and Buck Pond ($+15.5‰ \pm 2.5$, Fig. 4).

Tissue stable isotopes in Yellow Perch aged $0+$, $1+$, and $2+$ were used to characterize representative isotopic signatures of each site and examine patterns in habitat use duration in Lake Ontario and wetland habitats. Mean ($\pm$SD) $\delta^{13}C$ and $\delta^{15}N$ tissue stable isotope values from Yellow Perch collected in Lake Ontario were $-22.74‰$ (± 2.77) and $13.58‰$ (± 0.85), respectively (Fig. 4). Mean $\delta^{13}C$ and $\delta^{15}N$ tissue stable isotope values from Yellow Perch collected in Long Pond during the summer were $-27.19‰$ (± 0.82) and $12.41‰$ (± 0.77),

respectively. Similarly, mean $\delta^{13}C$ and $\delta^{15}N$ tissue stable isotope values from Yellow Perch collected in Buck Pond during the summer were $-29.13‰$ (± 3.31) and $11.38‰$ (± 1.43). These patterns generally followed those observed for aquatic invertebrates collected from each of the systems (Fig. 4).

We examined standard C:N isotopic ellipse areas corrected for small sample sizes (SEA_C) using tissues from Yellow Perch sampled in the wetlands and Lake Ontario to explore patterns in isotopic variability as a metric of habitat use duration. The ellipse representing tissue isotopes for combined wetlands (i.e., baseline wetland isotopic signature) showed no overlap with the Lake Ontario isotopic ellipse indicating disparate isotopic conditions between the two habitats (Table 3). However, all C:N isotope ellipses representing ages $0+$, $1+$, and $2+$ Yellow Perch collected from wetlands during the spring of 2021 showed overlap with both wetland and Lake Ontario baseline ellipses and a broader range of isotopic values especially for $\delta^{13}C$ (Fig. 5). Relative to the wetland baseline ellipse area, the estimated isotope ellipse areas for Yellow Perch ages $0+$, $1+$, and $2+$, were 134%, 66%, and 88% larger, respectively (Table 3). Similarly, relative to the Lake Ontario baseline ellipse area, the estimated isotope ellipse areas for Yellow
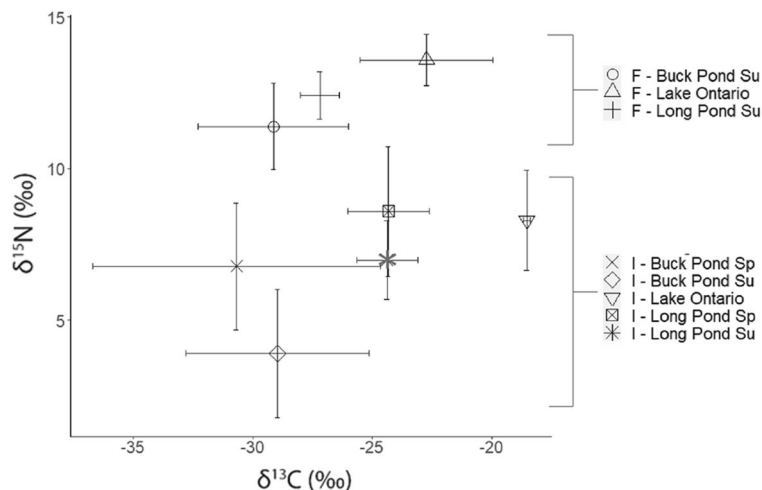
Fig. 4 Biplot of mean δ13C and δ15N (‰) values of Yellow Perch (F) and invertebrate (I) samples collected during the summer (Su) of 2020 and the spring (Sp) of 2021 from the three study sites. Yellow Perch from Lake Ontario were collected in the fall of 2019 while the invertebrates were collected in the summer of 2020. The bars represent the range of δ13C and δ15N (‰) values for each group. Brackets indicate the general location of fish and invertebrates on the biplot. Fish in this figure represent those used to develop baseline isotopic signatures for each habitat based on otolith edge chemistry. The isotopic differences between fish from Lake Ontario and the wetland habitats suggests a relationship exists between otolith edge chemistry and tissue stable isotope values

Table 3 Standard isotope ellipse areas corrected for small sample sizes (SEA$_C$) and total ellipse areas (TA) for Yellow Perch used to establish both Lake Ontario and coastal wetland baselines as well as ellipses established for fish aged 0+, 1+, and 2+ sampled in the spring from Long Pond and Buck Pond. The SEA$_C$ of the wetland habitats based on Yellow Perch tissues was roughly double that observed for Lake Ontario and neither overlapped. SEA$_C$ values across all age classes of Yellow Perch were larger than both baselines and typically showed overlap with both suggesting variation in the timing of arrival to the wetlands of capture

Category	SEA$_C$ (‰^{2})	TA (‰^{2})	SEA$_C$ (‰^{2})		% overlap WB	% overlap LB
			% different from WB	% different from LB		
Wetland baseline (WB)	4.66	9.12	N/A	195.8	N/A	0.00
Lake Ontario baseline (LB)	2.38	5.57	−95.8	N/A	0.00	N/A
Age-0+ Yellow Perch	10.91	21.89	134.1	358.4	1.58	0.88
Age-1+ Yellow Perch	7.75	18.30	66.3	225.6	2.47	0.93
Age-2+ Yellow Perch	8.47	28.67	81.8	255.9	0.93	0.08

Fig. 5 Stable isotope ellipses and polygons among three age classes of Yellow Perch, age-0+(**A**), age-1+(**B**), and age-2+(**C**). The ovals encompass 40% of the data for the wetland baseline (black oval, Δ), Lake Ontario baseline (light gray oval, +), and wetland caught Yellow Perch during the spring of 2021 (dark gray oval, O). The dashed convex polygons represent the maximum extents of the data along the carbon–nitrogen gradients. Overlap between the spring 2021 ellipses and polygons with both baselines suggest variable timing of wetland use duration by Yellow Perch across all ages
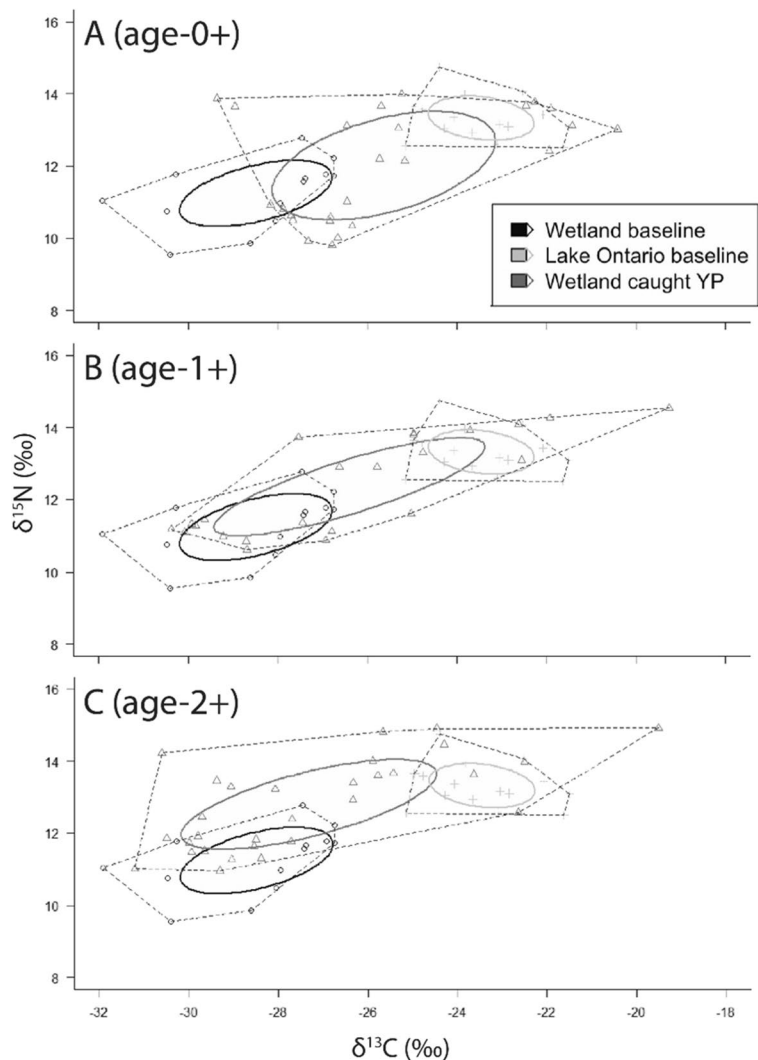
Perch ages 0+, 1+, and 2+, were 358%, 225%, and 255% larger, respectively (Table 3). Isotope ellipse overlap between the age-specific ellipses and baselines varied substantially and ranged from 0.08 to 2.47‰^{2} (Table 3). The amount of ellipse overlap peaked with age-1+ Yellow Perch and was lower for both age-0+ and age-2+ individuals.

Discussion

The goal of our study was to determine whether two coastal wetlands along southern Lake Ontario served as habitat for multiple life history types of Yellow Perch and if the duration of time spent in these habitats by Yellow Perch varied. By combining water and otolith chemistry with tissue stable isotope analyses, we detected the presence of two life history types and observed that the duration of stay in wetlands likely varied substantially. Identification of life history diversity among an ecologically and recreationally important fish species like Yellow Perch is important when considering the potential for populations to display stability and resilience in the face of stochastic perturbations such as low water levels that may prevent access to coastal wetland habitats.

Water chemistry

We observed that Mn:Ca in water differed consistently between Lake Ontario and the two coastal wetlands studied. The bedrock beneath Long Pond and Buck Pond consists primarily of stratified beds of shale, limestone, sandstone, and dolostone (NYS-DOT (New York State Department of Transportation), 2013). A large natural source of manganese originates from sedimentary and metamorphic rocks, such as those mentioned above, along with run off from terrestrial surfaces and decaying organic matter (Howe et al. 2004). Due to the small size of Long Pond and Buck Pond, the level of manganese is more concentrated in the coastal wetland systems than in Lake Ontario as there is less impact of dilution due to the restrained level of connectivity (Howe et al. 2004). Dissolved manganese may also be enhanced in these coastal wetlands through redox-reactions at the water–sediment interface under hypoxic conditions (Limburg et al. 2015). This mechanism seems plausible given the highly productive nature of both

Long and Buck ponds, though additional monitoring of both dissolved oxygen and manganese concentrations would be needed. Finally, while we were unable to secure additional Lake Ontario water samples during the spring of 2021, previous research indicates that dissolved manganese in Lake Ontario surface waters is relatively stable over time (Rossmann and Barres 1988). Understanding these properties justified the use of manganese for distinguishing inhabitance of Lake Ontario from the coastal wetlands by Yellow Perch.

Otolith chemistry

Using combined water and otolith chemistry, we determined that there are at least two movement life history types displayed by Yellow Perch caught in the wetlands we studied. Specifically, the majority of Yellow Perch caught displayed use of Lake Ontario within the first year of life. The remaining individuals appeared to first enter Lake Ontario sometime during the second year of life. Unlike other studies (Schoen et al. 2016; Senegal et al. 2020), we did not find evidence to support the presence of a full time "wetland resident" life history in the coastal wetlands we studied.

The apparent absence of a resident Yellow Perch life history type in the wetlands we studied could be related to the complexity and habitat availability within the wetlands. Perhaps these smaller wetland systems may not support long-term residence of this species in contrast to larger, more bathymetrically complex coastal wetland systems (Chorak et al. 2019). For example, larger coastal wetlands of eastern Lake Michigan that support resident populations of Yellow Perch have well-defined littoral and profundal zones that host a seasonally dynamic mix of both resident and migratory Yellow Perch (Senegal et al. 2020). Our study wetlands are comparatively shallow throughout, lack profundal zones, and have maximum depths of 1.5 m (Buck Pond, NYSDEC (New York State Department of Environmental Conservation), 2016) and 2.1 m (Long Pond, Sherwood 1999). Nonetheless, the use of these small coastal wetlands by Yellow Perch highlights their importance within a continuum of available habitats used by this species. Larger, more bathymetrically complex coastal wetland habitats of southern Lake Ontario (e.g., Irondequoit Bay, Sodus Bay, Port Bay) do exist and

beg the question of whether they might support additional movement life history types of Yellow Perch not observed in this study. Access to multiple habitat types, even those as small as our study sites, is largely important because they help maintain "lakescape connectivity" which is highly crucial for maintaining population resilience, promoting fish production, and aiding in nutrient and energy flows between systems (O'Reilly et al. 2023).

The otolith Mn:Ca index values we developed indicated that relatively few age-0+fish displayed purely wetland signatures. In fact, a majority (90%) of age-0+fish captured in the spring from wetland habitats had index values greater than zero indicating that they spent time in Lake Ontario during their first year of life. This observation is similar to observations made by Brazner et al. (2001) who documented tens of thousands of YOY Yellow Perch leaving the Bark Bay Slough wetland for Lake Superior during the month of July. Age-0+Yellow Perch were also present in the sample collected from nearshore Lake Ontario by USGS biologists for this project. In contrast, very few (10%) of age-0+fish captured in the spring did have otolith index values equal to zero indicating no use of Lake Ontario during the first year of life. This suggests that these individuals likely remained in their natal wetland habitats until capture. This is an important observation for understanding differential contributions of life history variation to population stability and resilience (Schindler et al. 2015). The underlying concept as relevant to this project, is that not every young Yellow Perch displays the same propensity to leave their natal wetlands, nor do they maintain residence in a particular habitat for the same amount of time. Such diversity within populations is often viewed as an attribute that supports population stability and resilience by reducing the likelihood of synchronous responses to environmental conditions (Kerr et al. 2010). The outcome is a degree of buffering to stochastic changes that manifests as greater stability in metrics like population abundance (Schindler et al. 2015). Continued exploration into this concept could prove beneficial especially in New York waters of Lake Ontario where significant inter-annual variation in Yellow Perch CPUE is observed (NYSDEC (New York State Department of Environmental Conservation), 2020). An interesting question for future research is whether different hydrogeomorphic wetland types (e.g., lacustrine or riverine)

support different Yellow Perch life histories that buffer populations of this species to stochastic variation due to potential differences in lake connectivity and habitat complexity, both of which are important for this species.

Stable isotope analysis

Our second question aimed to understand if adult migratory Yellow Perch use coastal wetland systems for different amounts of time. Stable isotope analysis is often used in a food-web context to understand Yellow Perch resource use and trophic position, but such studies typically do not delve deeper into possible temporal inference associated with stable isotope analysis (Vander Zanden et al. 1997). We posit that increased variability in $\delta^{13}C$ values relative to baseline conditions suggests differential timing of wetland arrival and duration of stay within the wetland systems we studied. The expanded isotopic ellipse area of Yellow Perch caught in coastal wetlands during the spring of 2021 suggests that some individuals use wetlands for different amounts of time than others. We applied the concept that recently migrated Yellow Perch from Lake Ontario caught in coastal wetlands would presumably transition to have similar $\delta^{13}C$ values to the baseline conditions of age-0+Yellow Perch that had yet to leave the wetlands for Lake Ontario. The isotopic ellipse area of fish sampled in wetland habitats during the spring spawning period largely spanned the gap between the wetland and Lake Ontario baselines. This indicates that the fish sampled likely represented a mix of both more recent arrivals to the wetlands and those that had been present in wetlands long enough to become isotopically indistinguishable from the wetland baseline.

We found that Yellow Perch caught in Lake Ontario were ^{13}C-rich relative to the wetland caught baseline fish and that invertebrate ^{13}C values followed similar trends across habitats. In a similar setting, Keough et al. (1996) observed differences in $\delta^{13}C$ values between nearshore Lake Superior and a coastal wetland food web (Allouez Bay). These authors found that wetland organisms were relatively ^{13}C-poor ($\delta^{13}C$ values of $-32\permil$ and $-27\permil$), whereas Lake Superior's organisms and plankton were relatively ^{13}C-rich ($\delta^{13}C$ values of $-29\permil$ and $-23\permil$). They suggested that differences in the origins of dissolved organic carbon (e.g., atmospheric deposition in Lake Superior versus

decomposition of vascular plant matter in coastal wetlands) likely drove this difference. This could explain not only the difference in $\delta^{13}C$ values between Lake Ontario and the wetland habitats in our study but also the difference between wetlands because Buck Pond hosts much greater macrophyte densities than Long Pond and is also slightly ^{13}C-poor.

Our assertion above should consider natural variation in isotopic composition over time and tissue turnover rates. Although seasonal variations in $\delta^{13}C$ values are known for Yellow Perch caught in Lake Ontario (Zhang et al. 2012), these authors reported a range of $\delta^{13}C$ values (~ -22 to $-16‰$) from Yellow Perch sampled spring through fall in 2009 that were similar to the Lake Ontario isotopic baseline established in this study. Similar data is not available for Long Pond or Buck Pond wetlands, but average invertebrate $\delta^{13}C$ values between summer and spring remained almost unchanged in Long Pond and were slightly higher in Buck Pond. Considering tissue turnover rates, Weidel et al. (2011) determined that the isotopic half-life of carbon in Yellow Perch was 8, 58, and 116 days in age-0+, 1+, and 2+ individuals, respectively. The expanded ellipse areas across all three age classes in this study suggest that variable durations of stay in wetland habitats are common among fish of differing ages despite disparate tissue turnover rates. These observations in conjunction with those based on otolith chemistry support the use of multiple habitats during early life history, as well as variable amounts of time spent in both Lake Ontario and wetland habitats.

The relatively small differences in $\delta^{15}N$ values between Lake Ontario and wetland baselines make the utility of this isotope for addressing questions about duration of stay somewhat tentative. Like carbon, nitrogen differed between Lake Ontario and wetland baselines and variation along a $\delta^{15}N$ gradient was evident among wetland caught Yellow Perch during the spring of 2021. More commonly, $\delta^{15}N$ values are used to infer the trophic position of an organism within a food chain (Cabana and Rasmussen 1996; Vander Zanden et al. 1997). Although we did not monitor Yellow Perch diets in this study, it is possible that some Yellow Perch moving from Lake Ontario to the study wetlands transitioned from feeding at higher levels in Lake Ontario to lower trophic levels in the wetlands. This could be particularly relevant for older and larger Yellow Perch that are known

to become increasingly piscivorous with ontogenetic development (Brown et al. 2009). In our study, tissues from some age-2+ wetland-caught Yellow Perch from the spring of 2021 were relatively ^{15}N-poor similar to the wetland baseline. Assuming these fish were Lake Ontario migrants, they may have been using the wetlands for longer durations of time than other age-2+ fish that displayed relatively ^{15}N-rich values. However, to make such a connection, more information about spatial and temporal variation in diet is needed especially when considering inherent variation in diet composition even within fish from the same location (Happel et al. 2015).

Conclusions

Yellow Perch are a popular target for recreational anglers in the Great Lakes region and an important component of the aquatic food chain (Robinson et al. 2018). Because Yellow Perch are a highly desirable species to multiple stakeholders, the Great Lakes Fishery Commission included Yellow Perch as an important species of consideration when creating the Lake Ontario Fish Community Goals and Objectives (Stewart et al. 2017). Maintaining healthy populations of Yellow Perch is critical in achieving the Great Lakes Fishery Commission Nearshore Zone Goal which is to "protect, restore, and sustain the diversity of the nearshore fish community, with an emphasis on self-sustaining native fishes, such as Walleye, Yellow Perch, Lake Sturgeon…(Stewart et al. 2017)." Yellow Perch is one of four fish considered to be a status/trend indicator meaning that healthy populations are partially indicative of the health of the nearshore lake habitat and biota (Stewart et al. 2017). Ultimately, it is critical to recognize the value that Yellow Perch bring to the Great Lakes region from both economic and ecological standpoints. Thus, understanding the mechanisms behind long-term persistence of populations and the sustainability of productive fisheries is a priority in fisheries management (Kerr et al. 2010). We suggest that exploring the diversity of movement behaviors in Yellow Perch throughout the Great Lakes is a needed step toward understanding the importance of this diversity for population stability and resilience in the face of stochastic perturbation (Schindler et al. 2015). The implementation of studies similar to this one, which strive to understand the

intricate dynamics of Yellow Perch populations, will help to ensure that Lake Ontario Yellow Perch fisheries remain sustainable.

Data availability The data are available from the corresponding author upon reasonable request.

Declarations

Ethical approval All fish in this research were handled in compliance with the standards set forth by the New York State Department of Environmental Conservation.

Conflict of interest The authors declare no competing interests.

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