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Telemetry-Determined Habitat Use Informs Multi-Species Habitat Management in an Urban Harbour

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Abstract Widespread human development has led to impairment of freshwater coastal wetlands and embayments, which provide critical and unique habitat for many freshwater fish species. This is particularly evident in the Laurentian Great Lakes, where such habitats have been severely altered over the last century as a result of industrial activities, urbanization, dredging and infilling. In Toronto Harbour, extensive restoration efforts have been directed towards improving the amount and quality of aquatic habitat, especially for fishes. To evaluate the effectiveness of this restoration work, use of the restored area by both target species and the fish community as a whole must be assessed. Individuals from four species (Common Carp, Largemouth Bass, Northern Pike and Yellow Perch) were tagged and tracked continuously for 1 year using an acoustic telemetry array in Toronto Harbour area of Lake Ontario. Daily site fidelity was estimated using a mixed-effects logistic regression model. Daily site fidelity was influenced by habitat restoration and its interactions with species and body size, as well as season and its interactions with species and body size. Daily site fidelity was higher in restored sites compared to non-restored sites for Yellow Perch and Northern Pike, but lower for Largemouth Bass and Common Carp. For all species, daily site fidelity estimates were highest during the summer and lowest during autumn. The approach used here has merit for evaluating restoration success and informing future habitat management activities. Creating diverse habitats that serve multiple functions and species are more desirable than single-function-oriented or single-species-oriented designs.

Keywords Restoration ecology · Habitat restoration · Fish habitat management · Habitat use · Acoustic telemetry in fisheries management · Mixed models · Great lakes

Introduction

Alteration of physical habitat and degradation of water quality associated with urbanization, industrial activities, agriculture and other development, coupled with introduction of invasive species and resource exploitation, have had devastating effects on freshwater ecosystems around the globe (Richter et al. 1997; Strayer and Dudgeon 2010). There has been a greater loss of biodiversity in freshwater systems than any other ecosystem (Dudgeon et al. 2006). A range of aquatic flora and fauna has been negatively affected, resulting in species extirpations, loss of productivity and alterations in ecosystem function (Carpenter et al. 2011). In freshwater ecosystems, fishes not only play integral roles as apex predators or forage species, they also generate important ecosystem services that directly benefit

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humans, such as the cultural and economic aspects of commercial, subsistence and recreational fisheries (Holmlund and Hammer 1999; Lynch et al. 2016).

In the Laurentian Great Lakes, coastal wetlands provide critical spawning, nursery, foraging and refugia habitat for over 80 % of fish species in the community (Jude and Papas 1992; Randall et al. 1996; Wei et al. 2004; Midwood and Chow-Fraser 2015). However, within the Great Lakes basin, over 70 % of all wetlands have been lost (Whillans 1982; Snell 1987; Midwood and Chow-Fraser 2015). Many of the remaining wetlands have seen declines in habitat quality (Chow-Fraser 2006; Cvetkovic and Chow-Fraser 2011) and are further threatened by increasing human development (Niemi et al. 2007). Suitable habitat is a fundamental component for maintaining productive fish populations (Lapointe et al. 2014). Habitat loss or modification is a major driver of declining fisheries productivity (Randall et al. 2012); hence the focus on improving or restoring economically important fisheries has often been rooted in restoration or creation of novel fish habitat.

In response to the negative impacts of habitat loss on the productivity of animal populations, habitat restoration (and similarly termed activities such as rehabilitation, creation and enhancement) is practiced by nearly every conservation organization (Bernhardt et al. 2005). It is generally accepted that newly restored aquatic areas can contribute positively to the biodiversity and productivity of local fish populations. However, specific responses of different fishes to changes in the physical structure of habitat are variable (Rogers and Bergensen 1999; Smokorowski and Pratt 2007). Furthermore, most research on the responses of fish to habitat restoration has focused on a single species (i.e., salmonids; Poplar-Jeffers et al. 2009) or a single usage of habitat (i.e., spawning habitat; Kondolf et al. 1996). These fish habitat projects have had variable impacts at different levels, ranging from life-stage (e.g., smolts), species level or whole assemblage (Ruiz-Jaen and Aide 2005). The intent of the project often dictates the implementation scope, ranging from whole-system improvements, to targeted vegetation planting or installation of gravel beds. While some comparative work has validated (or rejected) some of these techniques (e.g., salmonid structures; Stewart et al. 2009), these evaluations have often been focused on the narrow scope or intent of the restoration and rarely do they evaluate the performance of the features for the broader fish community/aquatic ecosystem in general (but see Moerke and Lamberti 2003 for an example of monitoring responses of a fish community responses to stream restoration).

The majority of habitat restoration or creation projects fail to adequately monitor the effectiveness of habitat restoration (Block et al. 2001). This is often the result of poor program design, but can also be partially explained by limited funding and the desire to devote most funding to the habitat project itself, which is often very expensive. Without proper validation of expected outcomes, however, managers may be employing techniques that do not reflect the best practices available or ones that are not locally suited. In cases where funding is available to monitor the long-term success of restoration, traditional methods for evaluating success rely on measurements of abundance, richness or community composition (Paller et al. 2000; Moerke and Lamberti 2003; Ruiz-Jaen and Aide 2005). These methods are usually discrete 'snapshots' in time that may not be representative of biologically relevant endpoints that determine demographic success such as survival in nursery habitat or reproductive success in spawning grounds (Lindell 2008; Farrugia et al. 2014). Observing the year-round behaviour of fish in restored habitats is essential to inform managers about the spatiotemporal function of the habitat. To date, biotelemetry has provided supportive evidence regarding habitat preferences of various species of fish, but until recently, has rarely been used in post-restoration validation monitoring (Lapointe et al. 2013) or to truly inform habitat management (Cooke et al. 2016).

Many conservation organizations and practitioners have moved away from single-species management in the context of habitat restoration in lieu of ecosystem management at the landscape level (Simberloff 1998). To date, however, most telemetry-based animal movement studies have tracked individuals of one species, but there is increasing recognition of the importance of understanding multi-species movement patterns and interactions (Cooke 2008; Hussey et al. 2015). In Toronto Harbour, a large system of embayments situated on the northern shore of Lake Ontario, specific habitat restoration activities aimed at improving the overall aquatic habitat conditions by creating sheltered embayments with wetland areas have occurred over the last two decades and further projects have been proposed. To better measure the fish community response to these restoration efforts, we used a multi-species tagging approach. We selected four species from the fish community to represent different trophic levels, thermal preferences or resource management interests (i.e., game species and non-native species). Largemouth Bass (*Micropterus salmoides*) is the dominant resident warmwater predator and Northern Pike (*Esox lucius*) is the dominant coolwater piscivore in this system. Both species are important game species targeted by anglers. Yellow Perch (*Perca flavenscens*) is a mid-trophic level feeder and potential prey item for piscivores and Common Carp (*Cyprinus carpio*) is a benthic feeder, as well as, a non-native species that can have negative impacts on spawning and nursery-vegetated habitat of native fishes (Parkos et al. 2003). There is considerable literature on the space use patterns of Largemouth Bass (e.g., Hanson et al. 2007),

Fig. 1 Receiver locations of the Toronto harbour acoustic telemetry array. *Circles* represent receivers ($n = 39$). *Red circles* represent receivers in restored areas; *black circles* represent receivers in non-restored areas. *Labels* denote regions discussed in the text

Northern Pike (e.g., Kobler et al. 2008), Common Carp (e.g., Penne and Pierce 2008) and Yellow Perch (e.g., Radabaugh et al. 2010) in a variety of lake and riverine environments. There are comparatively fewer accounts of space use patterns for these fishes in highly urbanized habitats (i.e., a harbour, but see Carter et al. 2012 and Murphy et al. 2012). However, we believe this is the first account describing the spatial ecology of these fishes in response to habitat restoration in a highly urbanized aquatic system. Using a model of daily site fidelity, we evaluated the spatiotemporal use of restored habitat areas for these four species in Toronto Harbour. Restored habitats are designed to improve the structure and function of existing habitat. We hypothesize that fish will preferentially occupy restored habitats because restored habitats provide higher quality habitat. Specifically, fishes that prefer structurally complex habitat will spend proportionately more time occupying restored habitats where structural complexity is higher while fishes that are benthic and tolerant of poorer water quality will spend proportionately less time occupying restored habitats.

Methods

Study Site

Toronto Harbour area (~15 km^2) is a set of large coastal embayments connected to Lake Ontario, situated directly adjacent to the downtown core of Toronto, ON, Canada. Historically, the eastern region of Toronto Harbour was an expansive marsh complex at the mouth of the Don River known as Ashbridge's Bay. After this wetland area was drained and reclaimed to serve as industrial port lands, only a fragment of this original bay remains (separated from the current Toronto Harbour by the reclaimed land). For our purposes, the harbour is operationally divided into the inner harbour and the outer harbour (Fig. 1). The inner harbour is dominated by two uses: the city waterfront (urban and industrial landscape) and the Toronto Islands (a series of channels and islands). The outer harbour contains an interconnected series of embayments known as Tommy Thompson Park (TTP). The eastern gap (a channel) joins the inner and outer harbours, and both harbours are directly connected to Lake Ontario proper: one connection for the inner harbour is via the western gap channel connected to Humber Bay and then the open lake, and the other via the mouth of the outer harbour. TTP is located on a man-made peninsula that was started in the early 1970's and construction is ongoing. The peninsula is made from infill materials and has been modified to naturalize portions of Toronto Harbour, and restore lost coastal features. This aquatic and terrestrial park projects 5 km into Lake Ontario and covers a total surface area over 250 ha (TRCA 2000). To create a more thermally and structurally complex system, the aquatic portions of the park are functionally divided into three cells and four embayments (TRCA 2000; Fig. 1). In addition to providing aquatic habitat, the cells in the park have continued to function as deposition sites for dredged material from the active harbour areas and the mouth of the Don River, which are then capped when active dumping into each cell is complete. Heavy construction in Cell 1 was completed in 2006. The Cell 2 confined waste disposal facility stopped receiving dredge material during the mid-2000s. Cell 3 was receiving dredge material during the study period. The telemetry receiver in Cell 3 was placed outside of the area where sediment material was being deposited.

Habitat restoration activities in Embayments A, B and C, Cell 1, and Spadina slip have consisted of a variety of broadly grouped techniques including, but not limited to: shoreline modification (slope profile and linear complexity) and creation (spawning channels, and island crests and peninsulas), shoreline vegetation planting and creation of areas to facilitate establishment (riparian, emergent and submergent), structural habitat addition (e.g., anchored log tangles, boulder clusters, submerged log cribs and stump fields, reefs and shoals), and control of non-target organisms (e.g., Common Carp exclusion gates; Wilcox and Whillans 1999). In Cell 1 and Spadina Slip, the areas of restoration work include both the littoral zone and the benthic region of the limnetic zone. In Embayments A, B, C and D, the restoration work has largely been confined to the littoral zone.

Telemetry Array

To track the space use of tagged fish in Toronto Harbour, we deployed a passive acoustic telemetry array (see Donaldson et al. 2014 for overview of acoustic telemetry methods and terminology). For this study, 39 Vemco VR2W receivers (Vemco Ltd., Halifax) were strategically positioned throughout the harbour to cover a variety of habitat sites, as well as key movement corridors (Fig. 1). In shallow areas (<5 m), acoustic receivers were attached to a rope approximately 1 m above a steel or concrete anchor with a Castro float at the top to keep the receiver positioned vertically. Anchors were tethered to the nearest attachment point on shore by submerged steel cable. In deeper water (up to 10 m), the anchor was connected by floating rope to an additional weight approximately 20 m away from the primary anchor weight. Receivers were retrieved every 6 months to offload data, remove any accumulated biofouling and check receiver condition. Receivers were then redeployed in the same locations. Range testing (see Kessel et al. 2014) was conducted in different habitat types and in different seasons to inform receiver placement (see Veilleux 2014).

Fish Tagging

All fish in this study were captured via boat electrofishing (SR-18EH, 6.0–7.0 A, 60 Hz, 340V DC, Smith-Root, Inc., Vancouver, WA) between May and September 2012. After capture, each fish was held in the boat live well and transported to an on-shore surgery location. Post surgery, all tagged fish were released at their original capture location. Largemouth Bass, Common Carp and Yellow Perch were anesthetized using a portable electroanesthesia system (PES) (Smith-Root, Inc., Vancouver, WA), which has been demonstrated to be an effective tool for anesthetising fish for handling (Vandergoot et al. 2011; Trushenski and Bowker 2012; Rous et al. 2015). Preliminary trials with Northern Pike anesthetized using the PES showed poor long-term survivorship (Personal Observation, S.J. Cooke). Consequently, Northern Pike were anesthetized using a 60 ppm eugenol bath (Anderson et al. 1997), which improved long-term survivorship (S.J. Cooke, unpublished data). For surgery, fish were moved from the live well with a wetted net onto a padded surgical table with the fish in a supine position. During surgery, lake water was continuously passed through the gills of the fish except for Northern Pike, where the water contained a 30 ppm eugenol solution. Each individual was measured for total length. Prior to implanting an acoustic transmitter into an individual, the transmitter and all surgical tools were disinfected in an iodine solution and rinsed. An incision (<10 mm) was made with a sharp scalpel on the ventral surface of the fish. Curved forceps were used to lift the skin and body wall to avoid any injury while making the incision. The transmitter was inserted into the coelomic cavity of the fish. The incision was closed using two simple interrupted sutures (Ethicon PDS II, 3/0, FSL needle). Largemouth Bass ($N = 18$), Common Carp ($N = 18$) and Northern Pike ($N = 17$) were tagged with Vemco V13TP transmitters (13 mm × 48 mm, 13 g in air, 69 kHz, mean delay = 200 s, Vemco Ltd., Halifax), while Yellow Perch ($N = 9$) were tagged with smaller Vemco V9 transmitters (9 mm × 21 mm, 2.9 g in air, 69 kHz, mean delay = 340 s, Vemco Ltd., Halifax).

Analysis of Daily Site Fidelity

The detection history of each tagged fish from 22 September 2012 to 23 September 2013 was collated into a database (1 768 299 total detections). For each individual, we calculated the proportion of detections per receiver station per day. Prior to analysis, influential observations, multicollinearity and relationships between the response and explanatory variables were assessed using Cleveland dotplots, scatterplots and conditional box and whisker plots. Daily site fidelity (the proportion of detections per individual per receiver station per day) was assumed to be binomially distributed because it represented the number of successes (detections at an individual receiver) and the number of failures (total detections at all other receivers). Explanatory variables included equinox-based seasons (winter, spring, summer, autumn), species, restoration status of the habitat (yes/no), site exposure (continuous covariate) and body size (divided into five classifications per species based on quartiles; Table 1). A habitat site was considered restored if there had been previous documented restoration activities completed by the local habitat managers in proximity to the location of the acoustic receiver. In assigning this status, we did so broadly such that we did not discern between the spatial extent of the restored area or the individual types of technique (e.g., shoreline modification or structural habitat addition). All the restored areas are composites of all or many of the techniques described. Site exposure is the relative level of exposure in the Toronto Harbour determined by estimating the mean fetch at each receiver via a wind fetch model. Continuous covariates were centered [i.e., value-(mean/standard deviation)] to aid with model convergence. Based on the study design, both individual fish ID and receiver station were included as crossed random effects. Given the statistical design, we fitted generalized linear mixed models with restricted maximum likelihood (Zuur et al. 2009). We expected the error to be normally distributed. Model selection was performed by generating a set of candidate models ($n = 13$) that were compared using second-order AIC (Akaike 1998; Mazerolle 2015). Fitted values from the top model were plotted to illustrate the relative influence of the fixed effects (Wickham 2009). All candidate models were validated by plotting the normalized residuals and testing for overdispersion (i.e., the occurrence of more variance in the data than predicted by a statistical model; Bolker et al. 2009) using methods described by Zuur et al. (2009). Possible spatial autocorrelation in the residuals was assessed by plotting the size of the residuals at each receiver coordinate. Data exploration and analyses were carried out in the R statistical environment (R Core Development Team 2014).

Table 1 Body size quartiles per species

Species	Minimum	25 %	Median	75 %	Maximum
Largemouth bass	307	408	470	476	535
Common carp	470	515	658	693	741
Yellow perch	216	224	225	241	271
Northern pike	556	733	811	972	1003

Total length measurements are in mm

Results

The total number of detections varied by species. Northern Pike comprised 741 539 or 42 % of the 1 768 299 total detections. Common Carp and Largemouth Bass each comprised 451 712 or 26 %, and 446 201 or 25 % of the detections, respectively. Yellow Perch comprised 128,847, or 7 % of the total detections.

The top model of daily site fidelity included terms for restoration status, species, season, body size, restoration × species, restoration × body size, species × season, species × body size and season × body size (Table 2). Site exposure did not appear in the top model to explain daily site fidelity for fish in Toronto Harbour.

Pooling seasons, daily site fidelity was higher in restored sites than in non-restored sites for Yellow Perch (+10.4 %) and Northern Pike (+2.2 %), but lower for Largemouth Bass (−3.8 %) and Common Carp (−10.7 %; Table 3). Across all seasons and restoration status, daily site fidelity decreased with body size for Northern Pike, but increased with body size for Perch, except during summer (Fig. 2). For Largemouth Bass, large individuals had higher site fidelity in restored areas compared to non-restored areas, but smaller individuals had lower site fidelity in restored areas compared to non-restored areas.

Yellow Perch showed the highest daily site fidelity of all species, as a typical individual occupied a single receiver station 100 % of the time on a given summer day, with far more variation in each other season. Generally, all species showed their highest site fidelity estimates during the summer and lowest estimates during autumn. Pooling across body size and restoration status, daily site fidelity estimates in the summer were 0.48 (0.28–0.68, 95 % CI) for Largemouth Bass, 0.41 (0.23–0.63, 95 % CI) for Common Carp, 0.99 (0.30–1.0, 95 % CI) for Yellow Perch and 0.61 (0.39–0.81, 95 % CI) for Northern Pike. In contrast, daily site fidelity estimates in the autumn were 0.32 (0.16–0.52, 95 % CI) for Largemouth Bass, 0.29 (0.15–0.50, 95 % CI) for Common Carp, 0.57 (0.34–0.76, 95 % CI) for Yellow Perch, and 0.34 (0.17–0.58, 95 % CI) for Northern Pike.

Median site fidelity estimates were highest for receiver stations in the Toronto Islands and TTP (Embayment C, Cell 2 and Cell 3; Fig. 3). Daily site fidelity was estimated

Table 2 Model selection statistics for models on the proportion of recorded detections/day (daily site fidelity)

Fixed effects	AICc	ΔAICc	wAICc	Log(*L*)	*K*
Restoration + Species + Season + Body size + Restoration: Species + Restoration:Body size + Species:Season + Species: Body size + Season:Body.size	1,654,067	0	1	−827,004	30
Restoration + Species + Season + Exposure + Restoration: Species + Species:Season	1,655,837	1769	0	−827,896	23
Restoration + Species + Season + Restoration:Species + Species:Season	1,655,837	1769	0	−827,897	22
Restoration + Species + Season + Body.size + Species: Season + Species:Body.size + Season:Body.size	1,658,657	4589	0	−829,302	26
Species + Season + Species:Season	1,659,539	5471	0	−829,752	18
Restoration + Species + Season + Species:Season	1,659,541	5473	0	−829,752	19
Restoration + Species + Season + Body.size + Species: Season + Species:Body.size	1,659,543	5475	0	−829,749	23
Restoration + Species + Season + Body.size + Exposure	1,663,669	9601	0	−831,822	12
Restoration + Species +Restoration:Species	1,685,146	31,078	0	−842,563	10
Species	1,687,862	33,794	0	−843,925	6
Restoration + Exposure	1,687,965	33,797	0	−843,928	5
Restoration	1,687,865	33,798	0	−843,929	4
Restoration + Species + Body.size + Species:Body.size	1,687,866	33,799	0	−843,922	11

AICc is the bias-corrected Akaike Information Criterion, Δ*AICc* is the difference in bias-corrected AIC between a given model and the top ranked model, *wAICc* is the relative weight of the bias-corrected AIC, *Log(L)* is the log-likelihood of the models, *K* is the number of parameters. All models contain fish ID and station name as a random intercept

Table 3 Pooled daily site fidelity estimates for each species on receivers in restored and non-restored areas

Species	Restored sites	Non-restored sites
Largemouth bass	33.1 %	36.9 %
Common carp	29.3 %	40.0 %
Yellow perch	60.1 %	49.7 %
Northern pike	59.1 %	56.9 %

to be lowest in areas along the waterfront of the Inner Harbour and the interface between the Outer Harbour and Lake Ontario.

Discussion

The habitat restoration work in Toronto Harbour has aimed to enhance both the quantity and the quality of the coastal wetland, sheltered embayment and rocky habitat available for the fish community. Our study reveals that two native species that were tracked in the harbour (Northern Pike and Yellow Perch) had higher site fidelity estimates in restored habitat areas, compared to non-restored areas. In contrast, non-native Common Carp had lower site fidelity estimates for restored compared to non-restored habitats. Overall, Largemouth Bass had lower site fidelity estimates for restored compared to non-restored habitats, but there was an interaction with body size where large individuals had slightly higher site fidelity in restored habitat areas, compared to non-restored areas. Restored habitats, which include a variety of physical structures, provide a more complex heterogeneous environment for both for sit-and-wait predators like adult Northern Pike, which tend to use deep weed edges to wait for prey to appear (Casselman and Lewis 1996), while also providing the necessary cover components for Largemouth bass and Yellow Perch to avoid such predation events. In a lake with high habitat heterogeneity, Yellow Perch movement rates were lower than in a simple lake (Radabaugh et al. 2010). In our system, Yellow Perch tended to stay in restored areas possibly because of the increased habitat complexity and heterogeneity in these areas. Similarly, Northern Pike need dense vegetation for spawning, foraging and to reduce vulnerability to predation for smaller individuals (Casselman and Lewis 1996). In Toronto Harbour, our analysis of the spatial distribution of fish habitat use identified several ‘hotspots’ of high site fidelity. Fish tended to spend a large portion of their time in Cells 2 and 3 of TTP, and the channels of the Toronto Islands, especially the southwest extent of this area. The fish that used these areas were less likely to split their time between two or more adjacent habitats where receivers were located compared to other areas in the harbour. These

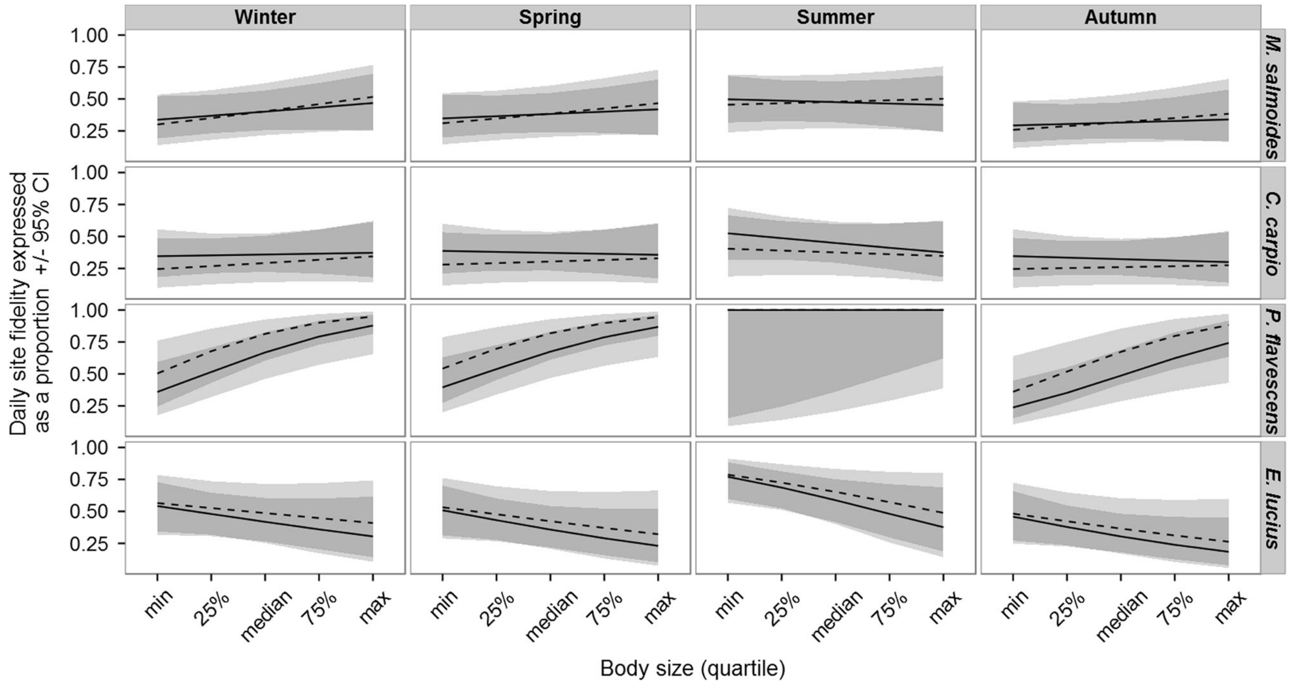

Fig. 2 Daily site fidelity estimates for each species (*M. salmoides, C. carpio, P. flavescens and E. lucius*) by body size. *Solid lines* and *dark shading* represent daily site fidelity estimates ± 95 % CI for sites in non-restored areas; *dashed lines* and *light shading* represent daily site fidelity estimates ±95 % CI for sites in restored areas

areas represent some of the more sheltered portions of the harbour, include both areas with and without restored habitat, and support the development of submerged aquatic vegetation beds.

Daily site fidelity was seasonally dependent. For all four species, site fidelity estimates were highest during the summer, while estimates were lowest during autumn for all species. With the onset of warmer temperatures in the summer, fish tended to move from inshore habitat towards slightly deeper offshore habitat but where submerged vegetation still exists (Headrick and Carline 1993; Penne and Pierce 2008). Higher water temperatures in the summer can force coolwater fish to seek out the coolest habitats with optimal depth. Vehananen et al. (2006) and Kobler et al. (2008) reported that movement rates of Northern Pike were highest during the summer. However, several authors have reported contradictory findings in regard to the seasonal movement rates of Northern Pike (Diana et al. 1977; Jepsen et al. 2001). At our Toronto study site, frequent intrusions of cold water from Lake Ontario inundate the harbour and reach several of the sheltered embayments (Hlevca et al. 2015). As such, throughout the summer Northern Pike may be able to remain in close proximity to productive warm-water habitats where their preferred prey are located, instead of making movements between coolwater and warmwater habitats for feeding forays (Headrick and Carline 1993). Despite their preference for cool water habitat, Yellow Perch have lower movement rates during the summer (Radabaugh et al. 2010), which likely explains their complete site fidelity during this season. Largemouth Bass are typically more sedentary than Northern Pike and therefore more highly resident during the summer (Mesing and Wicker 1986; Sammons and Maceina 2005; Hanson et al. 2007). Once the submerged aquatic vegetation cover is high enough to provide complex habitat for cover and refuge, Largemouth Bass have sufficient habitat for foraging and there is little incentive to move widely among habitats (Hanson et al. 2007; Ahrenstorff et al. 2009). Cooling water temperature and fall turnover in autumn may force fish to move more to search out prey and retreat from their resident summer habitats into optimal overwintering habitats. Studies have found that higher movement rates occur during autumn for Largemouth Bass (Karchesky and Bennett 2004; Sammons and Maceina 2005; Hanson et al. 2007), Yellow Perch (Radabaugh et al. 2010) and Common Carp (Penne and Pierce 2008), which supports our observation of reduced site fidelity during this season. Finally, during winter fish tend to have lower activity levels and would be less likely to move large distances between habitats, but will make movements in response to prey availability and oxygen concentrations, especially Northern Pike (Casselman and Lewis 1996; Baktoft et al. 2012).

Daily site fidelity in our study was dependent on fish size. Foraging and predation risk heavily influence the

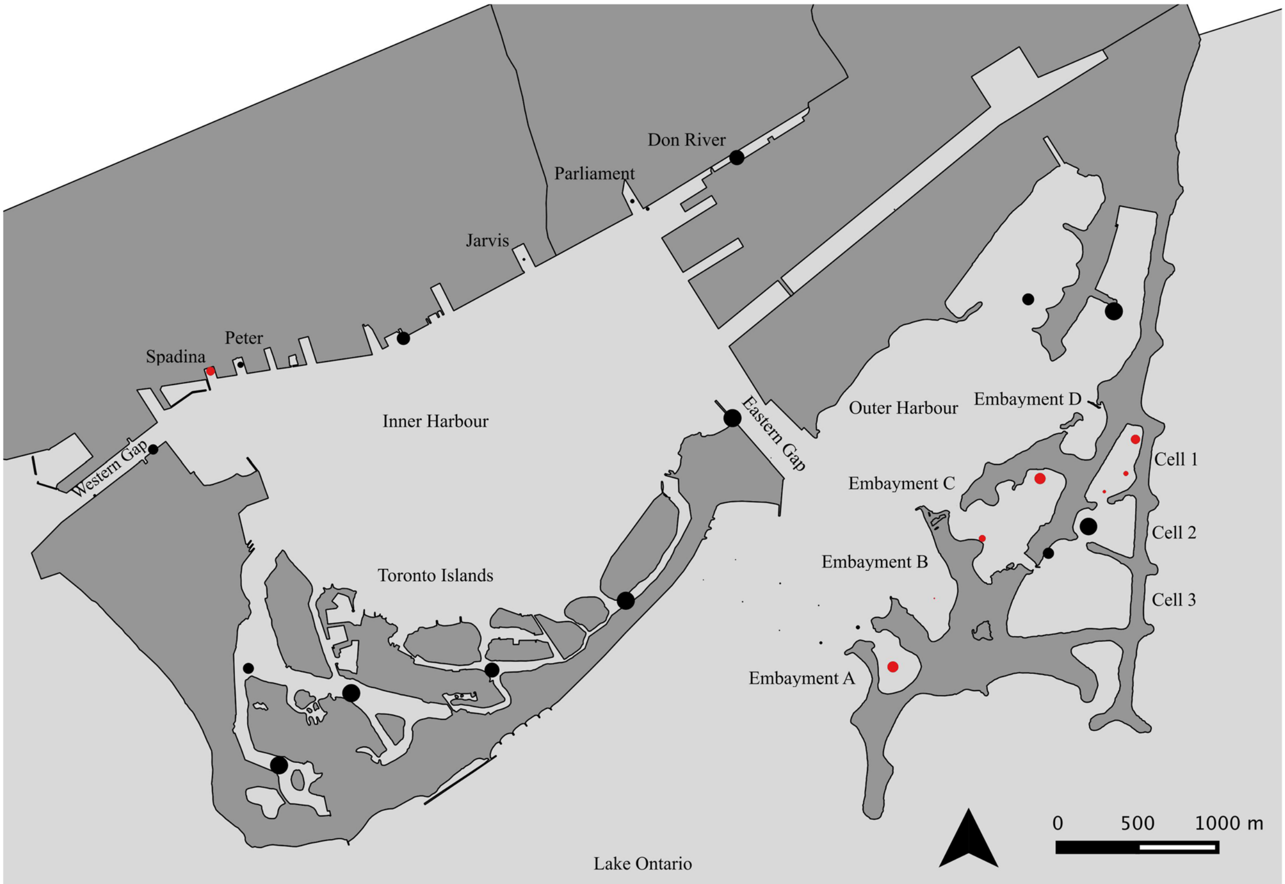

Fig. 3 Median daily site fidelity for each receiver ($n = 39$) in Toronto Harbour. *Red circles* represent receivers in restored areas; *black circles* represent receivers in non-restored areas. The size of the circle is relative to the proportion of the daily site fidelity, where *larger circles* represent greater site fidelity

habitat choice and movement behaviour of many species. For Northern Pike specifically, site fidelity decreased with body size. Casselman and Lewis (1996) found that the relationship between abundance of adult Northern Pike and macrophyte coverage was inversely related to body size. Large individuals tend to reside in less dense aquatic vegetation, so that they can strike more easily and locate larger prey items, while smaller individuals are more likely to select areas with more dense cover to reduce vulnerability to predation (Chapman and Mackay 1984; Casselman and Lewis 1996). Larger individuals need more food and are more likely to move between habitats to search for prey than smaller individuals because the former are at a lower risk for predation (Kobler et al. 2008). In contrast to the negative relationship we found for pike, site fidelity increased with body size for Yellow Perch. Similarly Bauer et al. (2009) found that small Yellow Perch were more active than larger individuals in two South Dakota lakes. Additionally, in the lake with more complex habitats, smaller individuals were located farther from shore. In simple habitats with limited areas for refuge, the ideal despotic distribution would predict that individuals, particularly smaller individuals, are forced to move extensively to avoid predation (Gilliam and Fraser 1987; Newman and Caraco 1987).

Conclusion

The functionality of a restored habitat is an important consideration when deciding on the design and assessing the success of restoration (Cortina et al. 2006; Herrick et al. 2006). Surveying the fish community of a habitat traditionally involves using non-selective fishing methods, such as electrofishing and trap netting. These methods are useful for comparing trends in annual and seasonal catch, species richness and abundance at standardized locations (Pope et al. 2010). However, they are seasonally and weather restricted, labour intensive and only capture a snapshot of the community in space and time (Fausch et al. 1990; Harris 1995; Pope and Willis 1996). Determining whether the fish community uses different habitats for foraging, spawning, nursery and/or refuge sites and whether non-native species are using the area is crucial information for habitat managers (Minns 2001; Lapointe et al. 2014; Cooke et al. 2016). Traditionally, biotelemetry has benefitted restoration projects by providing information regarding the habitat preferences of various fishes (Lapointe et al. 2013), but until recently, has rarely been used in pre-restoration and post-restoration validation monitoring. To date, acoustic telemetry studies of fish movement and behaviour in restored estuarine habitat has revealed important habitat function for juvenile Gray Smooth-hound Sharks (*Mustelus californicus*) (Espinoza et al. 2011) and Shovelnose Guitarfish (*Rhinobatos productus*) (Farrugia et al. 2011).

We demonstrate the utility of passive acoustic telemetry for continuously tracking multi-season spatial habitat use concurrently for multiple fish species. This allowed us to confirm that the restoration efforts in Toronto Harbour appear to be successful as these areas are being highly used by the two target native species, but less highly used by a non-native fish. The combination of biotelemetry and traditional biodiversity surveying methods could prove an ideal approach to assessing the success of restoration projects given that collectively they provide information on both ecological patterns and processes (Herrick et al. 2006).

For restoration ecologists and habitat managers alike, understanding the responses of communities to habitat restoration activities is crucial in determining the success of restoration projects (Lake 2001). Here, we demonstrate the spatial ecology of several members of the fish community in restored and non-restored habitat areas of a large set of coastal embayments. We acknowledge that an ideal design to assess restoration success would be a before-after-control-impact design (Underwood 1994). We did not have pre-restoration information on the distribution of fish in this system, but it is fair to say that the regions that were restored were previously void of complex habitat after it was stripped out or infilled as part of the harbour's development. Also notable in this study were the interactions of species, body size and season on site fidelity. All factors collectively influenced the patterns of habitat use and movement behaviour. Given this, managers can plan for and design multi-species and multi-life stage habitat restoration projects. For example, it may be possible to identify habitats that are undesirable for invasive fishes, but of high value to native fishes thus providing opportunities for restoration activities to target the species groups of interest. Indeed, habitat managers and restoration planners working on Toronto Harbour are already incorporating such concepts arising from telemetry data into their development of future plans in an effort to ensure that habitats frequented (inferred as habitat preference) by the non-native Common carp are not unintentionally created.

Our results demonstrate that aquatic habitat restoration aimed at improving the overall habitat conditions were collectively beneficial for target fishes and effective at limiting use by a non-native fish. In an ideal world, all habitat restoration would be done with some level of understanding of the specific habitat needs and preferences in mind of key members of the fish community, especially if these are site specific. However, in practice such efforts would be resource intensive. As such, any efforts to incorporate telemetry techniques to evaluate restoration activities, such as completed here, could help to not only address site-specific issues, but also improve the broader evidence base regarding ecological restoration.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no competing interests.

References

Ahrenstorff TD, Sass GG, Helmus MR (2009) The influence of littoral zone coarse woody habitat on home range size, spatial distribution, and feeding ecology of largemouth bass (*Micropterus salmoides*). Hydrobiologia 623:223–233

Akaike H (1998) Information theory and an extension of the maximum likelihood principle. In: Parzen E, Tanabe K, Kitagawa G (eds) Selected papers of Hirotugu Akaike. Springer, New York, pp 199–213

Anderson WG, McKinley RS, Colavecchi M (1997) The use of clove oil as an anesthetic for rainbow trout and its effects on swimming performance. North Am J Fish Manage 17:301–307

Baktoft H, Aarestrup K, Berg S, Boel M, Jacobsen L, Jepsen N, Koed A, Svendsen JC, Skov C (2012) Seasonal and diel effects on the activity of northern pike studied by high-resolution positional telemetry. Ecol Freshwater Fish 21:386–394

Bauer WF, Radabaugh NB, Brown ML (2009) Diel movement patterns of yellow perch in a simple and a complex lake basin. North Am J Fish Manage 29:64–71

Bernhardt ES et al. (2005) Synthesizing U.S. river restoration efforts. Science 29:636–637

Block WM, Franklin AB, Ward JP, Ganey JL, White GC (2001) Design and implementation of monitoring studies to evaluate the success of ecological restoration on wildlife. Restor Ecol 9:293–303

Bolker BM, Brooks ME, Clark CJ, Geange SW, Poulsen JR, Stevens MHH, White JSS (2009) Generalized linear mixed models: a practical guide for ecology and evolution. Trends Ecol Evol 24:127–135

Carpenter SR, Stanley EH, Vander Zanden MJ (2011) State of the world's freshwater ecosystems: physical, chemical, and biological changes. Annu Rev Environ Resour 36:75–99

Carter MW, Weber MJ, Dettmers JM, Wahl DH (2012) Movement patterns of smallmouth and largemouth bass in and around a Lake Michigan harbour: the importance of water temperature. J Great Lakes Res 38:396–401

Casselman JM, Lewis CA (1996) Habitat requirements of northern pike. Can J Fish Aquat Sci 53(Suppl.1):161–174

Chapman CA, Mackay WC (1984) Direct observation of habitat utilization by northern pike. Copeia 1:255–258

Chow-Fraser P (2006) Development of the water quality index (WQI) to assess effects of basin-wide land-use alteration on coastal marshes of the Laurentian Great Lakes. In: Simon TP, Stewart PM (eds) Coastal wetlands of the Laurentian Great Lakes: health, habitat and indicators. 1st edn. Authorhouse, Bloomington, IN, pp 137–166

Cooke SJ (2008) Biotelemetry and biologging in endangered species research and animal conservation: relevance to regional, national, and IUCN red list threat assessments. Endanger Species Res 4:165–185

Cooke SJ, Martins EG, Struthers DP, Gutowsky LFG, Power M, Doka SE, Dettmers JM, Crook DA, Lucas MC, Holbrook CM, Krueger CC (2016) A moving target – incorporating knowledge of the spatial ecology of fish into the assessment and management of freshwater fish populations. Environ Monit Assess 188:239

Cortina J, Maestre FT, Vallejo R, Baeza MJ, Valdecantos A, Pérez-Deves M (2006) Ecosystem structure, function, and restoration success: are they related? J Nat Conserv 14:152–160

Cvetkovic M, Chow-Fraser P (2011) Use of ecological indicators to assess the quality of Great Lakes coastal wetlands. Ecol Indic 11:1609–1622

Diana JS, Mackay WC, Ehrman M (1977) Movements and habitat preferences of northern pike in Lac Ste. Anne, Alberta. Trans Am Fish Soc 106:560–565

Donaldson MR, Hinch SG, Suski CD, Fisk AT, Heupel MR, Cooke SJ (2014) Making connections in aquatic ecosystems with acoustic telemetry monitoring. Front Ecol Environ 12:565–573

Dudgeon D, Arthington AH, Gessner MO, Kawabata Z-I, Knowler DJ, Leveque C, Naiman RJ, Prieur-Richard A-H, Soto D, Stiassny MLJ, Sullivan CA (2006) Freshwater biodiversity: importance, threats, status and conservation challenges. Biol Rev 81:163–182

Espinoza M, Farrugia TJ, Lowe CG (2011) Habitat use, movements and site fidelity of the gray smooth-hound shark (*Mustelus californicus* Gill 1863) in a newly restored southern California estuary. J Exp Mar Bio Ecol 401:63–74

Farrugia TJ, Espinoza M, Lowe CG (2011) Abundance, habitat use and movement patterns of the shovelnose guitarfish (*Rhinobatos productus*) in a restored southern California estuary. Mar Freshwater Res 62:648–657

Farrugia TJ, Espinoza M, Lowe CG (2014) The fish community of a newly restored southern California estuary: ecological perspective 3 years after restoration. Environ Biol Fish 97:1129–1147

Fausch KD, Lyons J, Karr JR, Angermeier PL (1990) Fish communities as indicators of environmental degradation. Am Fish Soc Symp 8:123–144

Gilliam JF, Fraser DF (1987) Habitat selection under predation hazard: test of a model with foraging minnows. Ecology 68:1856–1862

Hanson KC, Cooke SJ, Suski CD, Niezgoda G, Phelan FJS, Tinline R, Phillip DP (2007) Assessment of largemouth bass (*Micropterus salmoides*) behaviour and activity at multiple spatial and temporal scales utilizing a whole-lake telemetry array. Hydrobiologia 582:243–256

Harris JH (1995) The use of fish in ecological assessments. Aust J Ecol 20:65–80

Headrick MR, Carline RF (1993) Restricted summer habitat and growth of northern pike in two Southern Ohio impoundments. Trans Am Fish Soc 122:228–236

Herrick JE, Schuman GE, Rango A (2006) Monitoring ecological processes for restoration projects. J Nat Conserv 14:161–171

Hlevca B, Cooke SJ, Midwood JD, Doka SE, Portiss R, Wells M (2015) Characterization of water temperature variability within a harbour connected to a large lake. J Great Lakes Res 41:1010–1023

Holmlund CM, Hammer M (1999) Ecosystem services generated by fish populations. Ecol Econ 29:253–268

Hussey NE, Kessel ST, Aarestrup K, Cooke SJ, Cowley PD, Fisk AT, Harcourt RG, Holland KN, Iverson SJ, Kocik JF, Mills Flemming JE, Whoriskey FG (2015) Aquatic animal telemetry: a panoramic window into the underwater world. Science 348:1221–1231

Jepsen N, Beck S, Skov C, Koed A (2001) Behavior of pike (*Esox Lucius* L.) >50 cm in a turbid reservoir and in a clearwater lake. Ecol Freshwater Fish 20:26–34

Jude DJ, Papas J (1992) Fish utilization of Great Lakes coastal wetlands. J Great Lakes Res 18:651–672

Karchesky CM, Bennett DH (2004) Winter habitat use by adult largemouth bass in the Pend Oreille River, Idaho. North Am J Fish Manage 24:577–585

Kessel ST, Cooke SJ, Heupel MR, Hussey NE, Simpfendorfer CA, Vagle S, Fisk AT (2014) A review of detection range testing in aquatic passive acoustic telemetry studies. Rev Fish Biol Fish 24:199–218

Kobler A, Klefoth T, Wolter C, Fredrich F, Arlinghaus R (2008) Contrasting pike (*Esox lucius* L.) movement and habitat choice between summer and winter in a small lake. Hydrobiologia 601:17–27

Kondolf GM, Vick JC, Ramirez TM (1996) Salmon spawning habitat rehabilitation on the Merced River, California: an evaluation of project planning and performance. Trans Am Fish Soc 125:899–912

Lake PS (2001) On the maturing of restoration: linking ecological research and restoration. Ecol Manage Restor 2:110–115

Lapointe NWR, Thiem JD, Doka SE, Cooke SJ (2013) Opportunities for improving aquatic restoration science and monitoring through the use of animal electronic-tagging technology. BioScience 63:390–396

Lapointe NWR et al. (2014) Principles for ensuring healthy and productive freshwater ecosystems that support sustainable fisheries. Environ Rev 22:110–134

Lindell CA (2008) The value of animal behavior in evaluations of restoration success. Restor Ecol 16:197–203

Lynch AJ, Cooke SJ, Deines A, Bower S, Bunnell DB, Cowx IG, Nguyen VM, Nonher J, Phouthavong K, Riley B, Rogers MW, Taylor WW, Woelmer WM, Youn S, Beard Jr. TD (2016) The social, economic, and ecological importance of inland fishes and fisheries. Environ Rev 24:115–121

Mazerolle MJ (2015) AICcmodavg: Model selection and multimodel inference based on (Q)AIC(c). R package version 2.0-3. http://CRAN.R-project.org/package=AICcmodavg

Mesing CL, Wicker AM (1986) Home Range, Spawning Migrations, and Homing of Radio-Tagged Florida Largemouth Bass in Two Central Florida Lakes. Transactions of the American Fisheries Society 115(2):286–295

Midwood JDM, Chow-Fraser P (2015) Connecting coastal marshes using movements of resident and migratory fishes. Wetlands 35:69–79

Minns CK (2001) Science for freshwater fish habitat management in Canada: current status and future prospects. Aquat Ecosyst Health Manage 4:423–436

Moerke AH, Lamberti GA (2003) Responses in fish community structure to restoration of two Indiana streams. North Am J Fish Manage 23:748–759

Murphy S, Collins NC, Doka SE, Fryer BJ (2012) Evidence of yellow perch, largemouth bass, and pumpkinseed metapopulations in coastal embayments of Lake Ontario. Environ Biol Fish 95:213–226

Newman JA, Caraco T (1987) Foraging, predation hazard and patch use in grey squirrels. Anim Behav 35:1804–1813

Niemi GJ, Kelly JR, Danz NP (2007) Environmental indicators for the coastal region of the North American Great Lakes: introduction and prospectus. J Great Lakes Res 33(Suppl. 3):1–12

Paller MH, Reichert MJM, Dean JM, Seigle JC (2000) Use of fish community data to evaluate restoration success of a riparian stream. Ecol Eng 15:S171–S187

Parkos III JJ, Santucci Jr. VJ, Wahl DH (2003) Effects of adult common carp (*Cyprinus carpio*) on multiple trophic levels in shallow mesocosms. Can J Fish Aquat Sci 60:182–192

Penne CR, Pierce CL (2008) Seasonal distribution, aggregation, and habitat selection of common carp in Clear Lake, Iowa. Trans Am Fish Soc 137:1050–1062

Pope KL, Lochmann SE, Young MK (2010) Methods for assessing fish populations. In: Hubert WA, Quist MC (eds) Inland fisheries management in North America, 3rd edn., American Fisheries Society, Bethesda, MD, p 325–351

Pope KL, Willis DW (1996) Seasonal influences on freshwater fisheries sampling data. Rev Fish Sci 4:57–73

Poplar-Jeffers IO, Petty JT, Anderson JT, Kite SJ, Strager MP, Fortney RH (2009) Culvert replacement and stream habitat restoration: implications from brook trout management in and Appalachian watershed, USA. Restor Ecol 17:404–413

Radabaugh NB, Bauer WF, Brown ML (2010) A comparison of seasonal movement patterns of yellow perch in simple and complex lake basins. North Am J Fish Manage 30:179–190

Randall RG, Bradford MJ, Clark KD, Rice JC (2012) A science-based interpretation of ongoing productivity of commercial, recreational or Aboriginal fisheries. DFO Canadian Science Advisory Secretariat Research Document 2012/112 iv + 26 p.

Randall RG, Minns CK, Cairns VW, Moore JE (1996) The relationship between an index of fish production and submerged macrophytes and other habitat features at three littoral areas in the Great Lakes. Can J Fish Aquat Sci 53(Suppl. 1):35–44

R Core Team. (2014) R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria, http://CRAN.R-project.org/package=MuMIn

Richter BD, Braun DP, Mendelson MA, Master LL (1997) Threats to imperiled freshwater fauna. Conserv Biol 11:1081–1093

Rogers KB, Bergensen EP (1999) Utility of synthetic structures for concentrating adult Northern Pike and Largemouth Bass. North Am J Fish Manage 19:1054–1065

Rous AM, Forrest A, Hart McKittrick E, Letterio G, Roszell J, Wright T, Cooke SJ (2015) Orientation and position of fish affects recovery time from electrosedation. Trans Am Fish Soc 144:820–828

Ruiz-Jaen MC, Aide TM (2005) Restoration success how is it being measured? Restor Ecol 13:569–577

Sammons SM, Maceina MJ (2005) Activity patterns of largemouth bass in a subtropical US reservoir. Fish Manage Ecol 12:331–339

Simberloff D (1998) Flagships, umbrellas, and keystones: is single-species management passé in the landscape era? Biol Conserv 83:247–257

Smokorowski KE, Pratt TC (2007) Effect of a change in physical structure and cover on fish and fish habitat in freshwater ecosystems – a review and meta-analysis. Environ Rev 15:15–41

Snell, E. A. 1987. Wetland distribution and conservation in southern Ontario. Working paper No. 48. Inland Waters and Land Directorate. Environment Canada: Ottawa, Ontario

Stewart GB, Bayliss HR, Showler DA, Sutherland WJ, Pullin AS (2009) Effectiveness of engineered in-stream structure mitigation measures to increase salmonid abundance: a systematic review. Ecol Appl 19:931–941

Strayer DL, Dudgeon D (2010) Freshwater biodiversity conservation: recent progress and future challenges. J North Am Benthol Soc 29:344–358

TRCA. (2000) Tommy Thompson Park – public urban wilderness: habitat creation and enhancement projects 1995–2000, Toronto, ON, pp 1–46

Trushenski JT, Bowker JD (2012) Effect of voltage and exposure time on fish response to electrosedation. J Fish Wildlife Manage 3:276–287

Underwood AJ (1994) On beyond BACI: sampling designs that might reliably detect environmental disturbances. Ecol Appl 4:3–15

Vandergoot CS, Murchie KJ, Cooke SJ, Dettmers JM, Bergstedt RA, Fielder DG (2011) Evaluation of two forms of electroanesthesia and carbon dioxide for short-term anesthesia in Walleye. North Am J Fish Manage 31:914–922

Vehananen T, Hyvarinen P, Johansson K, Laaksonen T (2006) Patterns of movement of adult northern pike (*Esox lucius* L.) in a regulated river. Ecol Freshwater Fish 15:154–160

Veilleux MAN (2014) Spatial ecology of fish in Toronto Harbour in response to aquatic habitat enhancement (M.Sc. Thesis). Ottawa, ON, Carleton Univeristy.

Wei A, Chow-Fraser P, Albert D (2004) Influence of shoreline features on fish distribution in the Laurentian Great Lakes. Can J Fish Aquat Sci 61:1113–1123

Whillans TH (1982) Changes in marsh area along the Canadian shore of Lake Ontario. J Great Lakes Res 8:570–577

Wickham H (2009) ggplot2: elegant graphics for data analysis. Springer, New York

Wilcox DA, Whillans TH (1999) Techniques for restoration of disturbed coastal wetlands of the Great Lakes. Wetlands 19:835–857

Zuur A, Ieno EN, Walker N, Saveliev AA, Smith GM (2009) Mixed effects models and extensions in ecology with R. Springer, New York