# Telemetry-derived seasonal fish-habitat associations and spatial use in the Hamilton Harbour Area of Concern in western Lake Ontario

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# Telemetry-derived seasonal fish-habitat associations and spatial use in the Hamilton Harbour Area of Concern in western Lake Ontario

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## ABSTRACT

Larocque, S.M., Boston, C.M., Brooks, J. L., Brownscombe, J.W., Cooke, S.J., Doka, S.E., and Midwood, J.D. 2024. Telemetry-derived seasonal fish-habitat associations and spatial use in the Hamilton Harbour Area of Concern in western Lake Ontario. Can. Tech. Rep. Fish. Aquat. Sci. 3593: vii + 193 p.

Understanding fish habitat associations can help direct fish habitat management, particularly in degraded systems that require habitat restoration. In the Laurentian Great Lakes, Hamilton Harbour is an Area of Concern and it is necessary to verify the type of habitat that fish are using to focus future fish habitat remediation efforts. We determined general seasonal and spawning-window spatial and habitat use of 11 species in Hamilton Harbour using acoustic telemetry data collected from 2016 to 2020. There were both species-specific associations within the harbour and commonalities among the tagged fish community. Most species used roughly similar habitats in Hamilton Harbour as identified in the literature. Spatially, the west end of Hamilton Harbour was important for all species in at least one season, and fishes generally used shallower depths in spring and summer, and deeper depths in fall and winter. Several species moved into Lake Ontario during the late summer but most returned to the harbour to overwinter. Results of this study can be used to inform future restoration efforts in Hamilton Harbour and other degraded areas to help improve impaired fish habitat and populations. Future works could attempt to apply more in-depth habitat selection models to further identify specific habitat features limiting population recovery.

## RÉSUMÉ

Larocque, S.M., Boston, C.M., Brooks, J. L., Brownscombe, J.W., Cooke, S.J., Doka, S.E., and Midwood, J.D. 2024. Telemetry-derived seasonal fish-habitat associations and spatial use in the Hamilton Harbour Area of Concern in western Lake Ontario. Can. Tech. Rep. Fish. Aquat. Sci. 3593: vii + 193 p.

Comprendre les associations espèce-habitat peut aider à orienter la gestion de l'habitat du poisson, en particulier dans les systèmes dégradés qui nécessitent une restauration de l'habitat. Dans les Grands Lacs laurentiens, le port de Hamilton est un secteur préoccupant, et le type d'habitat utilisé par les poissons doit être vérifié afin d'orienter les futurs efforts de restauration de l'habitat du poisson. Nous avons déterminé l'utilisation générale de l'espace et de l'habitat de onze espèces dans le port de Hamilton, selon la saison et pendant la période de fraie, au moyen de données de télémétrie acoustique recueillies de 2016 à 2020. Il y avait à la fois des associations propres aux espèces dans le port et des éléments communs au sein de la communauté de poissons marqués. La plupart des espèces utilisent des habitats à peu près similaires dans le port de Hamilton, tels que décrits dans les publications scientifiques. Sur le plan spatial, l'extrémité ouest du port de Hamilton était importante pour toutes les espèces pendant au moins une saison, et les poissons occupaient généralement des profondeurs plus faibles au printemps et en été, et des profondeurs plus importantes en automne et en hiver. Plusieurs espèces se déplaçaient dans le lac Ontario à la fin de l'été, mais la plupart retournaient dans le port pour y passer l'hiver. Les résultats de cette étude peuvent être utilisés pour éclairer les futurs efforts de restauration dans le port de Hamilton et dans d'autres zones dégradées afin d'améliorer l'habitat et les populations de poissons altérés. Dans les travaux futurs, on pourrait tenter d'appliquer des modèles de sélection de l'habitat plus approfondis afin de déterminer de façon plus précise les caractéristiques de l'habitat qui limitent le rétablissement des populations.

# INTRODUCTION

Understanding fish habitat use and associations is important for effective fish habitat management. Access to critical habitat across more sensitive life stages (e.g., spawning) and seasons (e.g., overwintering) can influence population dynamics, particularly if these habitats are impaired, removed, or limited within a system. By improving our knowledge of fish habitat use, fish habitat management can better protect and recover critical fish habitat for species of interest but also fish communities/guilds (Minns 2001). Acoustic telemetry is often used as a tool to understand the spatial use of fish, and involves passively tracking individuals tagged with transmitters on receivers placed throughout the system of interest (Hussey et al. 2015; Matley et al. 2022a). This approach allows for near-continuous tracking that can provide information across seasons and in areas or times of year when it may otherwise be difficult to sample. Until recently, acoustic telemetry-derived data were primarily used to understand and describe the spatial ecology and movement patterns of fishes yet making connections between these patterns with environmental variables was an underutilized area of research (Brownscombe et al. 2022). However, studies are increasingly incorporating habitat features and environmental variables with acoustic telemetry data to study fish habitat use and selection (e.g., Brownscombe et al. 2021; Griffin et al. 2021; Rudolfsen et al. 2021). Such telemetry-based fish habitat associations can help direct fish habitat management, particularly in degraded systems that require habitat restoration.

In the Laurentian Great Lakes, Hamilton Harbour was listed as an Area of Concern (AOC) by the International Joint Commission in 1985, due to long-term industrialization and urban expansion that led to the degradation of the natural environment (COA 1992a). Specific beneficial use impairments (BUI) in the AOC included eutrophication, beach closings, fish tumours and other deformities, among others (COA 1992a). For fish, both BUI#3 (degradation of fish and wildlife populations) and BUI#14 (loss of fish and wildlife habitat) were originally listed as impaired in Hamilton Harbour (Holmes 1988; COA 1992b). A Remedial Action Plan intended to improve these BUIs, to monitor recovery, and assist in delisting Hamilton Harbour as an AOC has been in place since 1992 (COA 1992b). Efforts to improve habitat conditions and aid recovery of fish populations in Hamilton Harbour have included upgrades to sewage treatment plants to reduce nutrient loading, creation of islands and other habitat features, and active removal of non-native Common Carp (*Cyprinus carpio*) via the Cootes Paradise Fishway (Boston et al. 2016; Hiriart-Baer et al. 2016). Results from these efforts have been mixed, with clear success from Common Carp management actions, with marked declines in their biomass in the harbour (Boston et al. 2016), and less clear benefits from some of the island creation efforts (Maynard et al. 2022). To focus future fish habitat remediation efforts, as a first step it is necessary to verify the type of habitat that fish are currently using in Hamilton Harbour, then determine if such habitat is limited, and thus potentially constraining the recovery of fish populations. Focusing remediation efforts on key fish habitat that is considered limiting will increase the recovery potential for both BUIs #3 and #14, and ultimately aid in the delisting of Hamilton Harbour as an AOC. Also, further understanding the habitat use of aquatic invasive species (AIS), like Common Carp and Goldfish (*Carassius auratus*), will assist with development of potential management actions that may include selective fragmentation (i.e., barriers for non-native species that do not impact non-targeted, native species; Piczak et al. 2022), or more targeted active removal during times of congregation (Taylor et al. 2012). Any such reductions in these AIS can help reduce their direct and indirect impact on native fishes and ultimately support the recovery of the Hamilton Harbour fish community.

Hamilton Harbour has also been the site of a multi-year acoustic telemetry project where a variety of top-predator, non-native, and ecologically important fish species have been tagged and tracked since 2015 to understand their spatial ecology (see Brooks et al. 2017 for overview of project objectives). Some aspects of this work have been published focussing on single species results over short, defined time periods (e.g., (Brooks et al. 2019; Marcaccio et al. 2022; Croft-White et al. 2023; Boston et al. 2024), this report provides a comprehensive multi-year and multi-species synthesis. By using acoustic telemetry, the year-round habitat use of these tagged fishes can be determined. Residency and movement patterns can be used to determine the spatial distribution of habitat use within the harbour, and combined with local aquatic habitat information (Doolittle et al. 2010; Dosen, J., unpublished data), can infer local habitat associations. Information on habitat associations can be used to identify potential remediation efforts if the physical habitat is deemed limiting in the system. The overall objective of this study was to determine the seasonal habitat associations of 11 fish species in the Hamilton Harbour AOC using acoustic telemetry over four years, from spring 2016 to spring 2020. Specifically, we determine residency within the harbour and at general habitat types, as well as movement and depth-use patterns, including in and out of the harbour itself. Analyses were undertaken seasonally but also with a focus during each species' documented spawning window. Species-specific results are compared to published literature and a synthesis of general trends and commonalities across the fish community are highlighted and discussed, including how this information impacts Hamilton Harbour fish population and habitat recovery.

# METHODS

## ACOUSTIC TELEMETRY TAGGING AND ARRAY

In Hamilton Harbour, detection data were available for fish from April 30, 2016 to April 25, 2020. Over the course of the study period, a total of 261 fish across 11 species were tagged with acoustic transmitters (henceforth called tags). The majority of fish were tagged with V13 pressure (i.e., depth) sensor tags (V13P tags; 13 mm × 39 mm, 11 g in air, 69 kHz, mean delay = 200 s, max depth reading = 34 or 68 m, InnovaSea, Nova Scotia), but some were tagged with V13 tags without depth sensors (V13 tags; 13 mm × 30.5 mm, 9.2 g in air, 69 kHz, mean delay = 200 s, InnovaSea, Nova Scotia). All Yellow Perch (*Perca flavescens*) were tagged with V7 tags (7 mm x 19.5 mm, 1.5 g in air, 69 kHz, mean delay = 200 s). Capture and surgical tag implantation followed the methods described by Brooks et al. (2019) and procedures were approved and followed Canadian Council on Animal Care protocol administered by Carleton University (#110723) and Fisheries and Oceans Canada (DFO; GLLFAS/WSTD ACC #2079).

The array in Hamilton Harbour in April 2016 consisted of 32 acoustic receivers (VR2W 69 kHz, InnovaSea, Nova Scotia). Over time the array expanded to a total of 59 receivers by 2020 (Figure 1). The array captured a variety of habitat conditions (e.g., shoals, vegetated areas, deeper open waters, and inlets) within the harbour, and covered the sole connection point with Lake Ontario (Burlington shipping canal) to determine if fish left the harbour (see Brooks et al. 2019; Figure 1). Note that not all receivers were continuously in place after their original deployment, as some sites had seasonal deployments (e.g., in Grindstone Creek), were lost and replaced, or could not be deployed due to logistics with COVID-19. A timeline of receiver deployments is shown in Appendix A Figure A1.

## ENVIRONMENTAL DATA

Using available environmental data and habitat features around receivers we created seven generic habitat clusters to determine habitat associations based on detection data. Receivers can detect fish within a buffer of variable distance (i.e., their detection range) and therefore we do not know the exact location of a fish upon detection within that buffer nor the specific habitat features within that buffer that they are targeting. As such, we used a 350 m buffer around each receiver as it approximates the average detection range during isothermal and stratified periods determined by Wells et al. (2021). From this 350 m buffer, we only included areas within line of sight of the receiver, as islands or land can interfere with detections of fish. Within each receiver buffer, we calculated the mean value of available environmental data. The environmental data and habitat features used were bathymetric depth, fetch (to distinguish sheltered vs more wind exposed sites), percent cover of submerged aquatic vegetation (SAV), and whether the site was in a river (lotic; presence/absence).

Bathymetric depth data were derived from a 1 m resolution digital elevation model (DEM; Doolittle et al. 2010) with the water level set to the average water level above sea level in the area between 2016 and 2020 (75.0 m). Wind fetch was calculated at 11.25 degree increments around the entire compass for each receiver position using the *fetchR* package (Seers 2020). Fetch estimates for each bearing were then multiplied by the proportion of wind observed from its respective direction based on hourly wind data from April 30 2016 to April 25 2020 and an overall mean weighted wind fetch was calculated for each receiver position. Estimates of SAV percent cover were based on a model applied to the harbour at a water level of 74.2 m (Doolittle et al. 2010; J. Dosen, unpublished data). The mean values of depth, fetch and SAV within the receiver buffers were then calculated using ArcMap (v.10.8.1). However, SAV values at some receiver sites were adjusted based on local knowledge (i.e., areas with high turbidity and consequently lower than predicted SAV percent cover) and a more recent 2020 hydroacoustic survey (Gardner-Costa et al. *in prep*). Additionally, as the SAV model was not applied to areas such as Cootes Paradise Marsh or Grindstone Creek, values were informed by field sampling conducted by the Royal Botanical Gardens (J. Bowman, *unpublished data*).

Using the mean depth, fetch, and adjusted mean SAV values at each receiver, a principal component analysis (PCA) was performed to group receivers into similar habitat types. Five groups or clusters were visually determined from the PCA and receivers were assigned to a cluster using a scaled k-means cluster analysis. The optimal number of clusters using the silhouette method (N = 3) oversimplified the habitats that receivers covered in the array and we increased the clusters to five, which better matched the natural groupings in the PCA (Appendix A Figure A2). An additional cluster was manually added for sites that were associated with rivers or lotic waters, for a total of six habitat clusters. The receiver on the lake-side of the canal was manually adjusted to the appropriate cluster as the fetch and SAV data layers did not extend outside of the harbour. General descriptors were given to each cluster based on the environmental variables (Table 1). A habitat cluster was assigned to each receiver location and linked to the detection data for further analyses (Figure 2). Note that SAV values (and all other environmental variables) were treated as a static value to create and provide a simplified, broad-scale habitat cluster or habitat description occurring around receivers. However, seasonally (and potentially annually) the amount of SAV would naturally fluctuate as it grows and senesces through the seasons or vary based on other environmental conditions (e.g., water depths, turbidity). Such that when interpreting fish using areas of dense SAV during a time of senescence (e.g., winter), that fish may not be associating with SAV specifically but other environmental variables in that habitat cluster (i.e., water depths, shelter/exposure via fetch). The use of static values was done to gain a more general sense of the habitat types that fish were using in Hamilton Harbour within the limits and scale of the available habitat data.

## SEASONAL DESIGNATION

Seasons were based on temperature profiles collected using a chain of temperature loggers that was deployed annually at the centre of Hamilton Harbour from early-spring to late-fall (43.288° N, -79.845° W). Season was defined by temperature dynamics and thermocline delineation after Larocque et al. (2020): spring (> 5 °C and warming isothermal), summer (established thermocline), fall (first full water column mixing), and winter (temperature is no longer declining and < 5 °C isothermal). Temperature profiles were unavailable in the harbour in 2019, and 2019 seasons were based on the mean Julian day of seasonal delineation in the harbour from Larocque et al. (2020): Spring –

April 25 to June 6, Summer – June 7 to October 3, Fall – October 4 to November 17, and Winter – November 18 to April 24.

## DATA PREPARATION

All data preparation and analyses were conducted in R version 4.0.2 (R Core Team 2023). Detection data collected from 2016 to 2020 within the Hamilton Harbour and Lake Ontario array were used for analyses. Data were filtered to remove fish that were presumed dead. Fish were inferred to be dead if they continuously exhibited constant depth-use profiles and stayed within the same area of the array for the remainder of their detections (potentially detected on multiple receivers all within the same vicinity; Klinard and Matley 2020). If fish were alive for a period > 1 month prior to suspected mortality, then only the suspect data were removed. Fish with < 1 month of detections were removed from analyses. All instances of depth sensor malfunctions were removed from the dataset. Depth sensor malfunctions would sometimes occur at the end of a tag's battery life and would indicate that a fish was at the maximum depth value the tag can sense (34 or 68 m), which was deeper than Hamilton Harbour (when detected in the array) and therefore known to be erroneous. All depth values that were zero or negative (in air) were changed to 0.1 m depths, as can be caused by sensor drift in the tag. Data that met the criteria for false detections were also excluded from our analyses (Pincock 2012), as were data in which tags were detected on the same receiver earlier than the minimum ping rate of the tags, and those that were not spatially possible (e.g., in another lake system). Due to the close proximity of receivers in Hamilton Harbour, a single ping from a tag can be heard on multiple receivers. Thus, to best associate the fish with a single receiver’s habitat values, we subset detections such that only the first receiver to detect that tagged fish were included and any other detections before the minimum lag time to another ping, were removed. Otherwise, a tag could potentially be heard at further receivers where the fish was not actually present and skew the habitat assessment.

Overall, detection data from 181 tagged fishes from 11 species were included in the analyses: Bowfin (*Amia calva*; N = 4), Common Carp (N = 27), Freshwater Drum (*Aplodinotus grunniens*; N = 13), Goldfish (N = 12), Largemouth Bass (*Micropterus nigricans*; N = 25), Longnose Gar (*Lepisosteus osseus*; N = 13), Northern Pike (*Esox lucius*; N = 24), Smallmouth Bass (*Micropterus dolomieu*; N = 6), Walleye (*Sander vitreus*; N = 39), White Sucker (*Catostomus commersonii*; N = 8), and Yellow Perch (N = 10). The duration of detection data available for each species and tags are provided in Appendix A Figure A3.

## DATA ANALYSES

### *Receiver-based habitat coverage changes*

As the telemetry study objectives have advanced over the years, the Hamilton Harbour array’s expansion needs to be considered when interpreting spatial use by each fish species, particularly if they were tagged in earlier years when there was less coverage. In 2016 and 2017, there were 29 and 35 receivers in the Harbour, respectively (Figure 1). In 2018, the array expanded to a total of 49 receivers, including more in Cootes Paradise Marsh, Piers 5-7, a few additional sites along the north shore, and some in the east end behind islands (in more sheltered areas with SAV). By 2019, the array further expanded to include Indian Creek mouth, wetlands adjacent to Grindstone Creek (a potentially important spawning area for fishes), and a few other areas for a total of 59 receivers.

The array's expansion over time influenced the receiver coverage of different habitat cluster types (i.e., proportion of receivers within the harbour that covered each habitat cluster types; Figure 3). Across the years, receiver coverage was greater at deeper habitat cluster sites (e.g., moderate (5 – 10 m) and deep (> 10 m) depths) than shallow sites (< 5 m). On average across years, receivers covered areas with no SAV at deeper depths the most (33 ± 9 %), followed by sparse SAV at moderate depths (23 ± 4 %), moderate SAV at moderate depths (16 ± 4 %), sparse SAV at shallow depths (13 ± 5 %), no SAV, shallow, lotic areas (8 ± 3 %), and dense SAV at shallow depths the least (7 ± 4 %). Thus, there was an imbalance in the types of habitats covered by receivers within the array and this imbalance was greater during earlier years of the study (e.g., 2016 and 2017; Figure 3). At that time, there was less proportional coverage in areas with dense SAV at shallow depths, and in lotic areas; however, by 2019, coverage across habitat clusters was better balanced (Figure 3). Similar to the spatial context, habitat associations should be interpreted carefully given overall and year-to-year variation of receiver coverage across habitat clusters. For example, a species with data only in 2017 may have skewed habitat associations at deeper depth sites due to the array having greater representation at this habitat cluster than other habitat clusters. These habitat associations may not be as accurate compared to a species that had information primarily from the array in 2019. Similarly, a species with high residency at shallow sites in 2017 may have underestimated the importance of this habitat as these sites were underrepresented in the array at that time.

Detections of species that were available for all years during the study were each compared across receiver stations that were present for the majority of the study duration (i.e., core receiver stations) across years and seasons. If purported changes in habitat associations were related to the expansion of the array and subsequent increased habitat coverage rather than changes in fish behaviour over time, the number of detections at core receiver stations should remain relatively similar across years within seasons (assuming annual variation in water depths or other water quality variables that could potentially impact detection range were relatively low). Freshwater Drum had the most complete detection history across the study period and had relatively consistent detections at core receiver stations across years within each season, albeit winter was slightly more variable, likely owing to increased detection range during this season (Figure A4). Walleye, Northern Pike, and Largemouth Bass had similar detection patterns across core receivers. This supports that the expansion of the array over time could alter fish habitat associations based on where fish were able to be detected/monitored and less attributed to the behaviour of fish changing among core receivers over the study period. All other species did not have detection data for the entire study period and thus interpretation of the results from their detection patterns are constrained to the years when they were tracked and the nature of habitats covered during those time periods. This is particularly a challenge for species that had data primarily in the earlier years (e.g., 2016 – 2017) with reduced array coverage (e.g., Yellow Perch and Largemouth Bass). As such, data were interpreted with these potential biases acknowledged.

Another influence of the array design on the data is having a wide receiver detection range that covers heterogeneous habitat. Mean environmental values within the detection range of receivers were used to create broad habitat clusters (losing the heterogeneity of the area with these values), since an exact location for the fish (and associated specific environmental value) could not be determined. As many fish can use the shoreline, they may be using slightly different habitats than the general habitat clusters indicate. Estimating a tagged fish's position can be done using centers of activity (COA) based on Simpfendorfer et al. (2002), however, it artificially pulls an estimated position towards the center of the array and away from the shoreline. This would potentially skew habitat associations towards the more homogenous deeper waters in Hamilton Harbour. An array designed to better triangulate and get accurate positions would improve the habitat association estimates here. However, we present broader scale habitat associations based on the data available and future work could look into more specific habitat feature selection.

### ***Detection trends***

Data for each species were analyzed in the same manner. The mean and standard deviation (SD) of the monthly detections across individuals were plotted over time and grouped based on 1) the general area of detection, 2) the associated habitat clusters, and 3) whether they were detected in or out of the harbour.

To determine if fish detections varied with the time of day (and could indicate periods of greater activity), we assigned dusk, dawn, day, or night to each detection. Detections were assigned using the 'getSunlightTimes' function in the *suncalc* package (Thieurmel and Elmarhraoui 2019) in R to account for the duration of each time of day group changing throughout the year. Dawn was considered the time between night end and an hour after sunrise (morning golden hour end), daytime started an hour after sunrise and ended an hour before sunset (evening golden hour start), dusk started an hour before sunset and ended at the start of night, and nighttime was between start of night and night end. The daily duration of each daylight category was calculated to determine the relative proportion of monthly detections weighted by the duration of the daylight category over the month. A linear mixed model (LMM) determined if the weighted relative proportion of detections varied by daylight categories, using tag ID as a random effect with the *nlme* package (Pinheiro et al. 2020) in R. A Tukey HSD test using the *emmeans* package (Lenth 2023) was used to determine how categories varied from one another.

We also determined if fish were detected more frequently at different moon phases and by proxy whether activity levels were related to moon phases (for example, potentially suggestive of greater activity during periods of lighter or darker nights based on moon phase). The four moon phases (i.e., waxing, waning, full, new) were assigned to each detection using the 'lunar.phase' function in the *suncalc* package. As each moon phase has an equal chance of occurring over months, we did not have to weigh it against varying durations to get the relative proportion of monthly detections of each moon phase. A general linear mixed model (GLMM) with a binomial family determined if the proportion of monthly detections differed by moon phase categories, using tag ID as a random effect with the 'glmer' function in *lme4* package (Bates et al. 2015), followed by a Tukey HSD test if moon phase was significant. Assumptions of heteroscedasticity and normality were visually assessed using Q-Q plots and significance was determined at $\alpha = 0.05$.

### *Depth use*

The mean and SD of the mean daily depths across individuals were plotted over time. As seasonal depth patterns appeared to be repeatable over years, differences in mean daily depths by season were assessed using a LMM using tag ID and year as random effects with the 'lmer' function in *lme4* package, followed by a Tukey HSD test if season was significant. Seasonal depth use was reported based on the model predicted mean and standard error (SE; note this could result in a negative value if fish were extremely shallow). For a more detailed visual of depth use over time, monthly boxplots of mean daily depths and monthly mean and SD were reported.

### *Harbour and habitat residency*

Seasonal mean residency was calculated within the harbour based on each individual's residency. Residency was calculated as the number of distinct days detected at each receiver location divided by the total distinct days detected within a given season using the 'residence_index' function in the *glatos* package (Holbrook et al. 2020). Any detections on receivers outside of the harbour were given a single "location" designated as outside the harbour to determine residency when not in the harbour, and not focused on a location *per se*. Detections within a season, across years were combined for easier cross season comparison. Within the harbour proper, the array coverage is thorough so when a fish is not detected for a day, it is likely in the same area it was last detected and either behind some structure obscuring the detections or in an area upstream of the last detection (e.g., Grindstone Creek). To account for this, any days within the season that a fish was not detected were given a detection at the last position it was detected (Last Observation Carried Forward; LOCF; Lowe et al., 2020), which was then incorporated into the residency analyses. Residency was similarly determined based on habitat clusters instead of the receiver locations. Harbour and habitat cluster residency was also calculated during the species-specific spawning time in the harbour (see below).

### *Lake-wide home range*

For species that frequently left the harbour during the study, the seasonal space use in Lake Ontario for each individual was calculated using core and general homeranges or 50% and 95% kernel utilization distribution (KUD) using the ‘kernalUD’ function in the *adehabitatHR* package (Calenge 2006). We did not adjust the data using the LOCF since receiver coverage in Lake Ontario is more spread out and when a fish was not detected for a day, we did not have confidence that the fish was within the last position it was detected. To account for study-wide variation in receiver coverage that resulted in high detectability in Hamilton Harbour and lower detectability in Lake Ontario, we reduced the dataset to daily detections at a receiver to calculate KUDs. To show the overall species spatial use in Lake Ontario, each tagged individuals had their home range plotted as a semi-transparent layer, such that overlapping individual home ranges appear darker on the figures to show species ‘hot spots’.

### *Spawning*

The time of spawning for each species was estimated based on the literature (e.g., timing at similar locations/latitudes and temperatures; Scott and Crossman 1998) and local knowledge (Table 2). Detection data were subset for the duration of the estimated spawning window and boxplots of residency across the habitat clusters were made. Similarly, harbour residency during spawning was also determined and visualized.

# RESULTS AND DISCUSSION

## SPECIES-SPECIFIC

The following species-specific sections presents key results which were further discussed for each species. Table 3 provides a quick, basic summary of findings for each species. Refer to the species-specific appendices for the full analyses, results, and figures.

### *Bowfin*

Although a small sample size of Bowfin were acoustically tagged (N = 4; Table B1), their general locations, habitat clusters, and depths used were relatively consistent within seasons over the years of available data (April 2016 - April 2020; Figures B1, B2, and B5; see Appendix B for a complete summary of Bowfin results). Bowfin were more likely to be detected during dawn, dusk and night than during the daytime, and detections did not vary based on moon phase (Figure B4). There have been relatively few studies of Bowfin habitat use; however, Bowfin are generally described as inhabiting shallow, warm, and highly vegetated habitats or areas with abundant cover (Scott and Crossman 1998; Midwood et al. 2018; Brownscombe et al. 2023). In the spring, Hamilton Harbour Bowfin were detected in areas of dense and sparse SAV, shallow depths, and lotic areas, which occurred at Grindstone Creek, at the entrance to Cootes Paradise Marsh and at the Ottawa St. Slip, using very shallow depths (1.9 ± 0.7 m; Figures B3, B6, and B7). In the summer, Bowfin were detected in areas of dense SAV, shallow waters and moderate SAV at moderate depths as they moved from the Grindstone Creek area to the harbour towards the north shore or in areas with slightly more vegetation (e.g. Macassa Bay) using shallow depths (1.8 ± 0.6 m; Figures B3, B6, and B7). Our findings align with the spring and summer habitat use of acoustically tagged Bowfin in Toronto Harbour, Ontario (i.e., shallow, vegetated waters; Midwood et al. 2018; Brownscombe et al. 2023); however, differences were observed in the fall and winter. In Hamilton Harbour, in the fall and winter, there appeared to be higher residency for areas of sparse and moderate SAV at moderate depths, and to a lesser extent for areas with no SAV in deep waters in the west end, near Piers 5-7, and towards the north shore (Figures B3 and B7). During this time, Bowfin were using deeper waters (fall: 3.6 ± 0.6 m, winter: 6.3 ± 0.6 m; Figure B6), and as such would be slightly offshore. In contrast, in Toronto Harbour, in the fall and winter most Bowfin were found in shallow habitats similar to their spring and summer habitats, with some movement to deeper areas in the fall (yet low detectability in winter; Midwood et al. 2018; Brownscombe et al. 2023). These variations in fall and winter habitat use of Bowfin could be related to differences in factors like ice cover, bathymetric depth, temperatures, wind exposure, and dissolved oxygen levels between these two systems. No Bowfin left Hamilton Harbour for the duration of the study.

During the spawning window (May 1 to June 30), Bowfin were at their shallowest depths (< 1 m; Figure B6) in shallow, vegetated areas but also moved into river environments (e.g., Grindstone Creek, which has many adjacent wetlands) to find spawning grounds (Figures B8 and B9). This coincides with the literature, that during spawning in spring, Bowfin move to shallow, vegetated water in lakes and rivers (Scott and Crossman 1998). One Bowfin was detected at the western end of Cootes Paradise Marsh in April 2020, just prior to the start of their spawning period. Bowfin are frequently captured and recaptured at the Cootes Paradise Fishway in the spring (Larocque et al. 2023; Rebalka et al. 2023), further suggesting Cootes Paradise Marsh is an important and repeatable spawning area for Bowfin. However, acoustically tagged Bowfin spatial use highlighted that Grindstone Creek (an area not monitored extensively for fish movements) may also be an important spawning area for this species.

### *Common Carp*

Acoustically tagged Common Carp (N = 27; Table C1) had relatively consistent general locations, habitat clusters, and depth use within seasons over the years of available data (Oct 2017- April 2020; Figures C1, C4, and C7; see Appendix C for a complete summary of Common Carp results). Common Carp were more likely to be detected during dawn and night, followed by dusk, and lastly daytime, and detections did not vary based on moon phase (Figure C6). There appeared to be increased residency in areas of sparse SAV at moderate depths in the west end year-round, as well as to a lesser extent areas with no SAV in deep waters in the fall and winter as waters cooled (Figures C5 and C9). During the fall and winter, Common Carp moved into deeper waters (fall: 6.0 ± 0.5 m; winter: 3.2 ± 0.5 m; Figure C8), and as such would be slightly offshore; however, in the fall there were larger movements than in winter and residency also included the north shore and central basin. In the spring, Common Carp were primarily resident in areas of sparse SAV at shallow depths, followed by sparse SAV at moderate depths, and lotic areas, which occurred in the west end towards Cootes Paradise Marsh and to a smaller extent the mouth of Grindstone Creek, using shallow depths (1.0 ± 0.5 m; Figures C5 and C9). The summer had similar habitat use as spring but without lotic areas and was slightly more spread out in the west end as depth use increased slightly (1.8 ± 0.5 m; Figures C5, C7 and C9). Acoustically tagged Common Carp in Hamilton Harbour showed similar seasonal habitat associations as has been previously documented. Generally, Common Carp inhabit shallow, vegetated areas in the spring for spawning, littoral habitats in the summer for feeding, and aggregate in deeper, offshore areas in the fall and winter to overwinter (Scott and Crossman 1998; García-Berthou 2001; Penne and Pierce 2008; Watkinson et al. 2021; Brownscombe et al. 2023). However, winter habitat associations can vary across regions as Common Carp in Lake Winnipeg used shallower depths at the mouth of the Winnipeg River during winter, as it may have had greater oxygenation (Rudolfsen et al. 2021; Watkinson et al. 2021).

Common Carp typically spawn in shallow, vegetated areas (Scott and Crossman 1998; Penne and Pierce 2008). Similarly, in Hamilton Harbour, during the spawning window (May 1 to July 31), Common Carp had increased residency in semi-vegetated areas at shallow or moderate depths in the west end but also towards Cootes Paradise Marsh and river environments (e.g., mouth of Grindstone Creek; Figure C10 and C11). The shallowest depth use for Common Carp (mean monthly depths were ~1.2 m; Figure C8) coincided with their spawning window.

Since 1997, Common Carp have been actively excluded from entering the Cootes Paradise Marsh at the fishway (Wilcox and Whillans 1999), and larger individuals are generally unable to access these habitats. Notably, seven (26%) Common Carp were detected within Cootes Paradise Marsh and were primarily entering or leaving in October or during the summer of 2018 and 2019 (Figure C1). This movement into Cootes Paradise Marsh indicates that some fish were able to bypass the fishway, which may impact wetland recovery in this area. Water levels in 2019 were the highest in the past 50 years with some sections of the fishway being inundated; however, the fishway is also kept open at certain points in the year so Common Carp may be able to access the marsh at these times. The timing of Common Carp bypassing the fishway did not coincide with the spawning window so the driver of these movements is unclear.

Most Common Carp remained within Hamilton Harbour, however one individual left Hamilton Harbour five days after tagging and was later detected at the mouth of the Niagara River and in the Toronto Harbour, but never returned to Hamilton Harbour (Figure C3). Common Carp having high residency within Hamilton Harbour suggests they likely have all their habitat and food requirements in this area. In other studies, Common Carp populations have shown similarly high residency in their tagging area (Reynolds 1983; Stuart and Jones 2006), but more extensive movements (and thus lower residency) have also been documented (Watkinson et al. 2021), even in other Lake Ontario populations (Piczak et al. 2023), suggesting Common Carp mobility likely varies among populations.

***Freshwater Drum***

Acoustically tagged Freshwater Drum (N = 13; Table D1) had relatively consistent general locations, habitat clusters, and depth use within seasons over the years of available data (July 2016 – April 2020; Figures D1, D3, and D6; see Appendix D for a complete summary of Freshwater Drum results). Freshwater Drum detections did not vary based on time of day or moon phase (Figure D5). In the winter, Freshwater Drum appeared to have increased residency in deeper areas (deep or moderate depth habitat clusters), when Freshwater Drum were further offshore at the west end and central basin using deeper waters (6.8 ± 0.5 m; Figures D4, D7, and D8). During the spring, Freshwater Drum resided in areas of sparse SAV in shallow waters or at moderate depths, closer to shore in the west end, using shallow depths (2.2 ± 0.5 m; Figures D4, D7, and D8). In the summer and fall, Freshwater Drum were mostly residing outside of Hamilton Harbour but some were also in areas of no SAV and deep depths in the harbour (Figures D4, D7, and D8). However, in the summer, Freshwater Drum were still using shallower depths (2.8 ± 0.5 m), while in the fall there were more detections throughout the harbour towards the deeper, central basin, which coincided with Freshwater Drum using to deeper depths (7.0 ± 0.5 m; Figure D7 and D8). Freshwater Drum did not enter Cootes Paradise Marsh or lotic areas. The limited literature available indicates Freshwater Drum are benthic feeders and seem to prefer waters < 20 m (Scott and Crossman 1998). In Lake Winnipeg, acoustically tagged Freshwater Drum were detected in areas of fine substrates and were dispersed throughout the lake in the summer, using broader depths (6 – 16 m), and moved to the southern basin in winter, at a narrower depth range (8 – 12 m; Rudolfsen et al. 2021), which was similar to the summer dispersal and winter aggregation of Hamilton Harbour Freshwater Drum. Generally, Freshwater Drum were less associated with habitat that had SAV and more associated with bathymetric depths that were similar to their depth use (i.e., shallow waters in spring and summer, moderate and deep depths in fall and winter). As benthic feeders, substrate is likely an important driver of habitat selection, but such associations were not assessed here.

The spawning habitat of Freshwater Drum is relatively unknown and could be at shallow depths (~2 m) over sandy substrate (Daiber 1953), but can occur over a variety of habitats as they are broadcast spawners with positively buoyant eggs (Lane et al. 1996). In Hamilton Harbour, during the spawning window (June 1 to July 31), Freshwater Drum generally went to areas of deeper depths with minimal vegetation (sparse SAV at moderate depths or no SAV at deep depths) in the west end and to a lesser extent along the north shore and east end (Figures D10 and D11). Freshwater Drum were also shallow in the water column (mean monthly depths used were ~2 m; Figure D7) while in these deeper 'offshore' waters (5 – 12 m), which could be related to ensuring eggs drift to an appropriate area for pelagic survival.

Hamilton Harbour Freshwater Drum showed long-range dispersal in the summer into Lake Ontario (max of ~180 km to Rochester, NY) and would return to the harbour in the fall or winter, with relatively high fidelity. When outside of Hamilton Harbour, they were along the south shore of Lake Ontario towards the Niagara River or further east, with some fish being detected along the north shore towards Toronto (Figures D2 and D9). While in Lake Ontario, they remained at relatively shallow depths (~2 – 6 m), presumably feeding along the nearshore, although they were also detected at deeper depths (20 – 34 m; tags maxed out at 34 m depths) in the summer (Figure D7). This repeated long-distance dispersal in the summer outside of Hamilton Harbour may be related to limited food resources in the benthos (e.g., benthic invertebrates, fish, molluscs, decapods; Scott and Crossman 1998), as low oxygen levels in the hypolimnion of the harbour can limit distribution and composition of the benthic invertebrate community (Dermott et al. 2007; Gertzen et al. 2016). Regardless, with such high mobility, Freshwater Drum populations may be intermixing across most of Lake Ontario.

### *Goldfish*

Goldfish have become a more prominent invasive species in Hamilton Harbour and are increasingly common in other freshwater systems and knowing more about their spatial ecology can assist with developing control measures (Boston et al. 2016; Beatty et al. 2017). Acoustically tagged Goldfish (N = 12; Table E1) had relatively consistent general locations, habitat clusters, and depth use within seasons over the years of available data (June 2017 - April 2020; Figures E1, E3, and E6; see Appendix E for a complete summary of Goldfish results). Goldfish were more likely to be detected during dawn and night, than dusk and day, and detections did not vary based on moon phase (Figure E5). In the fall and winter, Goldfish appeared to have a general affinity to deeper areas (deep or moderate depth habitat clusters), when Goldfish were further offshore at the west end and along the north shore towards the east end in the fall or at the west end and towards Piers 5-7 in the winter using slightly deeper waters (fall: 4.2 ± 1.0; winter: 3.9 ± 1.0 m; Figures E4, E7, and E8). These deeper, overwintering movements have not been documented before but are similarly presented in a more focused study of this species in Hamilton Harbour (Boston et al. 2024). During the spring, Goldfish resided in areas of sparse SAV in shallow or moderate depths but also in lotic areas, at the mouth of Grindstone Creek and closer to shore in the west end, using shallow depths (1.8 ± 1.0; Figures E4, E7, and E8). In the summer, Goldfish were mostly residing in areas of dense SAV shallow waters and to a lesser extent moderate or sparse SAV at moderate depths, in the west end, towards Macassa Bay and also along the north shore, using relatively shallow depths (1.9 ± 1.0 m; Figures E4, E7, and E8). Of the scant information on habitat use, Cadwallader (1979) indicated Goldfish inhabit slow-flowing areas associated with cover (e.g., trees, woody debris, vegetation, turbid waters). Our broader-scale habitat clusters cannot discern precise habitat use but generally matches with shallow, vegetated habitat associations in spring and summer. Beatty et al. (2017) found that adult Goldfish in the lower Vasse River of Australia were highly resident with small movements (average ~300 m/day), but were capable of longer distances migrations to off-channel wetlands to spawn. Hamilton Harbour Goldfish were similarly highly resident and remained within the harbour for the duration of the study, except for one fish that was detected briefly leaving (~5 km from the canal) and then returning to the harbour (Figure E2). Interestingly, no tagged Goldfish were detected in Cootes Paradise Marsh proper (beyond detections at the fishway), despite this species being frequently captured at the fishway (Rebalka et al. 2023; Boston et al. 2024).

Goldfish generally spawn in shallow waters (< 5 m) in areas of high SAV (Lane et al. 1996; Scott and Crossman 1998). Similarly, during the spawning window (May 1 to June 30), Hamilton Harbour Goldfish had mean monthly depth use of ~1 m (Figure E7) and were detected in semi-vegetated areas at shallow to moderate depths (< 12 m) and river environments (e.g., areas of sparse SAV at shallow and moderate depths, and to a lesser extent lotic areas and areas of moderate SAV at moderate depths; Figure E10). Spatially, Goldfish were in the west end, the mouth of Grindstone Creek, Macassa Bay and to a lesser extent along the north shore during the spawning window (Figures E9). While detected in lotic areas, Goldfish were likely moving to shallow wetlands to spawn as seen in Beatty et al. (2017). Hamilton Harbour Goldfish were not always found in dense SAV areas; however, our broad-scale habitat clusters may not always reflect what specific habitat Goldfish are using. Furthermore, during the spawning window Goldfish may be staging in nearby areas prior to spawning (Boston et al. 2024).

### ***Largemouth Bass***

Acoustically tagged Largemouth Bass (N = 25; Table F1) had relatively consistent depth use but slightly variable general locations and habitat clusters within seasons over the years of available data (April 2016 – April 2020; Figures F1, F3, and F6; see Appendix F for a complete summary of Largemouth Bass results). Inconsistency over the years may in part be related to the expanding array (Figure 1) and Largemouth Bass being detected at more nearshore locations as they were increasingly covered in the later years of the project. Largemouth Bass were more likely to be detected during dawn, then night, followed lastly by dusk and day, and detections did not vary based on moon phase (Figure F5). Largemouth Bass were generally in areas of sparse SAV at moderate depths, within the west end year-round (Figures F4 and F8). Given the shallow depth use of Largemouth Bass (mean monthly depth use < 3 m based on pressure sensors), the bathymetric depth preferences (e.g., moderate depths, 5 – 12 m) may be skewed from higher sample sizes of tagged fish (N = 11; Figure A3) when the array had less receiver coverage at shallow depths earlier in the study. Thus Hamilton Harbour bass were likely quite close to shore in more vegetated areas as their depth use suggests, as typically, Largemouth Bass inhabit shallow (< 3 m), warm waters, with soft substrates associated with cover like debris and vegetation along the shoreline (Winter 1977; Scott and Crossman 1998). Brownscombe et al. (2023) found similar habitat associations for Largemouth Bass in nearby Toronto Harbour, Ontario, with the use of shallow to moderate depth waters (3 – 7 m) and moderate to dense SAV, while in sheltered, low-wind exposure environments, areas similar to the west end of Hamilton Harbour. Hamilton Harbour Largemouth Bass showed some seasonal variation in habitat use. In the fall and winter, Largemouth Bass were slightly offshore at the west end in slightly deeper waters (fall: 0.9 ± 0.2 m; winter: 1.9 ± 0.2 m), and in late winter, Largemouth Bass residency in areas of dense SAV at shallow depths increased (Figures F4, F7, and F8). Movement to deeper waters in winter has been observed in other areas and may be attributed to Largemouth Bass seeking warmer waters (Karchesky and Bennett 2004) or avoiding shallower areas where ice may form first. During the spring, Largemouth Bass were in the west end, closer to shore and towards Macassa Bay using shallow depths (0.4 ± 0.2 m), and to a lesser extent found in areas of dense SAV at shallow depths (Figures F4, F7, and F8). In the summer, Largemouth Bass were still using shallows depths (0.4 ± 0.2 m) in the west end but with reduced residency in dense SAV shallow waters (Figures F4, F7, and F8).

Spawning generally occurs in shallow, soft substrate, sheltered areas with emergent vegetation (Nack et al. 1993; Scott and Crossman 1998). Similar to the literature, during the spawning window (May 1 to July 15), Largemouth Bass were quite shallow (mean monthly depths were ~0.5 m; Figure F7) and were primarily in areas of sparse SAV at moderate depths, specifically in the west end shallows, towards Macassa Bay and to a lesser extent along the north shore and in Cootes Paradise Marsh (areas sheltered from prevailing winds; Figures F9 and F10). Four Largemouth Bass entered Cootes Paradise Marsh during June and July (during the spawning window) before returning to the harbour. One fish repeatedly entered Cootes Paradise Marsh during this time of year. Note that habitat clusters during the spawning window were likely skewed due to larger sample sizes of Largemouth Bass in the earlier years and would more likely be associated with sparse SAV in shallow areas as opposed to moderate depths.

Largemouth Bass generally remained within the harbour year-round, with two fish being detected leaving the harbour, with one eventually returning (Figure F2). The Largemouth Bass that never returned went into Lake Ontario and was detected as far as Port Credit, ON, while the one that returned remained close (within ~5 km) to Hamilton Harbour. Largemouth Bass typically do not make extensive movements with primary home ranges being less than 0.5 ha (Winter 1977; Scott and Crossman 1998), which is consistent with highly localized residency in the west end of Hamilton Harbour. However, Largemouth Bass can move as far as 3 km to reach protected areas for spawning (Mesing and Wicker 1986).

### *Longnose Gar*

Acoustically tagged Longnose Gar (N = 13; Table G1) had relatively consistent general locations, habitat clusters, and depth use within seasons over the years of available data (June 2016 – April 2020; Figures G1, G3, and G6; see Appendix G for a complete summary of Longnose Gar results). Longnose Gar detections did not vary based on time of day or moon phase (Figure G5), although Longnose Gar are apparently more active at night (Scott and Crossman 1998). All Longnose Gar were tagged in the Ottawa St. Slip (an industrial slip with year-round warmwater outfall), which could skew habitat associations (Table G1). Generally, Longnose Gar inhabit warm, quiet, vegetated shallow lakes or large rivers, (Scott and Crossman 1998). Not much is known about Longnose Gar winter habitat use other than it may be in similar areas to summer and fall habitats (McGrath et al. 2012). Similar to the literature, in Hamilton Harbour, Longnose Gar primarily resided in shallow, warm, vegetated waters, specifically areas of sparse SAV in shallow waters, at the Ottawa St. Slip year-round. However, variation in spatial use did occur among Longnose Gar, particularly with those that left the harbour. In the winter, Longnose Gar that remained in the Ottawa St. Slip were consistently in shallow waters, while those in the harbour were typically further offshore at the west end using deeper waters (4.6 ± 0.5 m; Figures G4, G7, and G8). From spring through fall, Longnose Gar were either at the Ottawa St. Slip or outside of the harbour, using fairly shallow depths (spring: 0.2 ± 0.5 m; summer: 0.4 ± 0.4 m; fall: 2.1 ± 0.5 m); however, in the fall, returning Longnose Gar from Lake Ontario were resident throughout the harbour, using slightly deeper depths (Figures G4, G7, and G8). Tagged Longnose Gar did not enter Cootes Paradise Marsh or lotic areas.

Longnose Gar generally spawn in warm, shallow lakes or large streams, over SAV in which the adhesive eggs attach to the vegetation (Scott and Crossman 1998). In Hamilton Harbour, during the spawning window (May 1 to June 30), Longnose Gar were at their shallowest depth use (mean monthly depths were ~0.4 m; Figure G7). During this time, Longnose Gar were in areas of sparse SAV at shallow depths at the Ottawa St. Slip or outside the harbour (Figures G10 and G11). The main spawning location is likely in the same area of capture for most Longnose Gar, in the Ottawa St. Slip. Longnose Gar have been observed migrating towards spawning grounds (~50 km) and then dispersing post-spawning (Johnson and Noltie 1996), which may be a strategy some of the Hamilton Harbour Longnose Gar used.

The majority of Longnose Gar were not resident in Hamilton Harbour, and generally most Longnose Gar (N = 10; 77%) would leave Hamilton Harbour in the spring and summer to move along the south shore of Lake Ontario towards the Niagara River, as well as near Toronto in the fall, and typically return to the harbour by winter (Figure G2 and G9). Of the ten Longnose Gar that left the harbour, six returned, and four left and never returned. The three resident Longnose Gar remained in the Ottawa St. Slip for the duration of the study. More in-depth analyses by Croft-White et al. (2023) showed variable movement patterns of Longnose Gar with three distinct groups: migrants, sporadic migrants, and residents. Differences in movement patterns may be related to density dependence and resource limitations (e.g., food and habitat) within the Ottawa St. Slip, in which some gar remain and others disperse (Taylor et al. 2013). The dispersal and subsequent return of Longnose Gar to Hamilton Harbour could also be related to gar seeking overwintering habitat, staging in proximate to spawning grounds, or driven by other environmental factors (e.g., temperature, dissolved oxygen). As waters warm, movement out of the harbour in the summer may be in relation to anoxia below the thermocline (Polak and Haffner 1978; Gertzen et al. 2016; Hiriart-Baer et al. 2016), reducing available habitat. However, Longnose Gar are facultative air breathers (Scott and Crossman 1998) and may not be as affected by anoxia-related issues in the harbour as other fishes.

### ***Northern Pike***

Acoustically tagged Northern Pike (N = 24; Table H1) had relatively consistent depth use but slightly variable general locations and habitat clusters within seasons across the years of available data (April 2016 – April 2020; Figures H1, H2, and H5; see Appendix H for a complete summary of Northern Pike results). Inconsistency over the years may in part be related to the expanding array (Figure 1) and Northern Pike being detected in more specific areas (e.g., Piers 5-7 and Grindstone Creek) in the later years of the project. Northern Pike were more likely to be detected during night, then dawn and dusk, followed lastly by day, and detections did not vary based on moon phase (Figure H4). Generally, Northern Pike are associated with warm, nearshore, vegetated waters at shallow depths (<5 m; Diana et al. 1977; Cook and Bergersen 1988; Scott and Crossman 1998). Similar to the literature, Hamilton Harbour Northern Pike were generally in areas of sparse SAV at moderate depths within the west end and used shallow depths (mean monthly depths <4 m) year-round, with some seasonal variation (Figures H3, H6 and H7). In Toronto Harbour, Northern Pike were also associated with sparse SAV, at moderate bathymetric depths (Brownscombe et al. 2023). All acoustically tagged Northern Pike were large adults and likely resided in sparse SAV for better foraging opportunities, as larger Northern Pike tend to be found in less dense vegetation (Casselman and Lewis 1996). In winter, Northern Pike will move slightly deeper, and further offshore (Diana et al. 1977; Cook and Bergersen 1988), which was also seen in Hamilton Harbour. In the fall and winter, Hamilton Harbour Northern Pike were slightly offshore at the west end in slightly deeper waters (fall: 1.6 ± 0.3 m; winter: 2.5 ± 0.3 m) and were found in areas of moderate SAV at moderate depth and no SAV at deep depths (Figures H3, H5, H6, and H7). During the spring, Northern Pike were closer to shore in the west end and towards Macassa Bay, Cootes Paradise Marsh, and Grindstone Creek using shallow depths (0.6 ± 0.3 m), and to a lesser extent were found in areas of sparse and dense SAV at shallow depths (Figures H3, H5, H6, and H7). In the summer, Northern Pike used slightly deeper depths (1.8 ± 0.3 m) close to shore in the west end and towards Macassa Bay and Piers 5-7, and were detected less frequently in sparse SAV shallow waters (Figures H3, H5, H6, and H7). Unlike other tagged fishes, Northern Pike showed an increase in depth use during the summer (as well as winter), which is likely related to avoiding high temperatures (Scott and Crossman 1998).

Northern Pike are known to spawn in shallow, heavily vegetated floodplains of rivers, marshes, and bays of larger lakes (Scott and Crossman 1998), which were similar to habitats that Hamilton Harbour Northern Pike were found in during the spawning window (March 15 to April 30). During the spawning window, Northern Pike were quite shallow (mean monthly depths were ~0.7 m; Figure H6) and were primarily in areas of sparse SAV at moderate and shallow depths but would also use lotic areas (Figure H9). Vegetation at the exact location of spawning was likely higher than the mean values within the detection range of receivers and we did not include emergent vegetation in habitat clusters, which when flooded in the spring is often where Northern Pike spawn (Farrell et al. 2006). As such greater detections in areas of sparse SAV is likely misaligned with the true habitat use of Northern Pike during spawning, and incorporating the presence or areal coverage of emergent vegetation in future modelling efforts may help resolve this issue. Spatially, Northern Pike were in the west end shallows, towards Bayfront, and to a lesser extent along the north shore, in Grindstone Creek, and in Cootes Paradise Marsh (Figure H8). As wetlands in Grindstone Creek were only monitored later in the study (i.e.., 2019 and onward), Northern Pike detected in Grindstone Creek (lotic areas) in earlier years during the spawning window may potentially underestimate their wetland use (dense/sparse SAV, shallow areas) for spawning in this area. Grindstone Creek is likely more important for Northern Pike attempting to spawn, as they were historically observed spawning in this area (Leslie and Timmins 1992). Six (25%) tagged Northern Pike entered Cootes Paradise Marsh between March and June (during their spawning window) before returning to the harbour. Northern Pike have homing behaviours and will return to the same spawning area the following year (Vehanen et al. 2006), which was also observed with two of the tagged Northern Pike repeatedly leaving and returning to Cootes Paradise Marsh over multiple years. Similarly, Northern Pike have been captured and recaptured at the Cootes Paradise Fishway in the spring when entering Cootes Paradise Marsh (Larocque et al. 2023; Rebalka et al. 2023), further suggesting Cootes Paradise Marsh is an important and repeatable spawning area for Northern Pike.

Northern Pike were resident in Hamilton Harbour and remained in the harbour for the duration of the study. The high residency of Northern Pike primarily in the west end of Hamilton Harbour indicated small home ranges and movements, with no movements outside of the harbour. Diana et al. (1977) found that Northern Pike had no distinct home range but moved at random within a narrow zone around the edges of the lake. While Vehanen et al. (2006) found two movement groups of Northern Pike: sedentary and movers. Sedentary Northern Pike had less than 200 $m^2$ 95% home ranges while movers entered the river system to spawn and migrated to a lake post-spawning. Based on these groupings, Hamilton Harbour Northern Pike are relatively sedentary but there were short movements towards spawning areas (e.g., Cootes Paradise Marsh, Grindstone Creek wetlands) during the spring spawning window. A mark-recapture study in Hamilton Harbour by Larocque et al. (2023) indicated that boat electrofishing and the Cootes Paradise Fishway captured different components of the Northern Pike population, further indicating Northern Pike are relatively sedentary in Hamilton Harbour. An important part of the harbour not covered well by the telemetry array is Red Hill Creek, which flows into the southeastern corner of the harbour. Wetlands situated upstream in this creek have been identified as potentially suitable spawning and nursery habitat for Northern Pike (discussed in Budgell et al. 2024) and should Northern Pike telemetry studies be undertaken in the future, this area should receive greater attention.

### *Smallmouth Bass*

Acoustically tagged Smallmouth Bass (N = 6; Table I1) had relatively consistent depth use but locations and habitat cluster associations within seasons varied over the years (June 2017 – April 2020; Figures I1, I2, and I5; see Appendix I for a complete summary of Smallmouth Bass results). Variability over the years may in part be related to small sample sizes; there was nearly a full year (~June 2018 – April 2019) with only one active tag providing data. Smallmouth Bass were more likely to be detected during night, dawn, and dusk, than during the day, and detections did not vary based on moon phase (Figure I4). Generally, Smallmouth Bass inhabit moderately shallow waters in sandy and rocky areas, near rock shoals or submerged logs and are less associated with vegetation than Largemouth Bass (Lane et al. 1996; Scott and Crossman 1998). Similar to the literature, in Hamilton Harbour, Smallmouth Bass were detected in areas of sparse SAV at moderate depths, at the Piers 5-7 area (an area with a rocky break wall protected by winds) year-round, near their tagging location (Table I1, Figures I3, and I6). No Smallmouth Bass were detected in Cootes Paradise Marsh or in lotic areas. During the spring and summer, Smallmouth Bass primarily resided in areas of sparse SAV at moderate depths and to a lesser extent areas of dense SAV at shallow depths, or areas with no SAV at deep depths, around Piers 5-7, using very shallow depths (spring: -0.3 ± 0.7 m; summer: -0.4 ± 0.7 m; note negative depths were model estimates and actual depths were still very shallow; Figures I3, I6, and I7). In the fall and winter, Smallmouth Bass were found in deeper areas (deep or moderate depth habitat clusters), further offshore at the west end and along the north shore and towards Piers 5-7 while using deeper waters (fall: 1.8 ± 0.7 m; winter: 6.5 ± 0.7 m; Figures I3, I6, and I7). Such selection of deeper waters for overwintering has been previously documented (e.g., Suski and Ridgway 2009) and Smallmouth Bass are thought to aggregate at depth, near bottom, under the ice (Scott and Crossman 1998).

Spawning generally occurs in shallow (0.5 – 6 m) waters with sandy, rocky or gravel substrate, usually avoiding dense vegetation where Smallmouth Bass build and guard nests (Lane et al. 1996; Scott and Crossman 1998). Spawning success of Smallmouth

Bass is also greater in sheltered, wind-protected, areas (Goff 1985). Similar to the literature, during the spawning window (May 1 to July 15), Hamilton Harbour Smallmouth Bass were quite shallow (mean monthly depths were ~0.2 m; Figure I6), in areas of sparse SAV at moderate depths and at the Piers 5-7 areas (Figures I8 and I9). Although Smallmouth Bass had high residency in areas of sparse SAV at moderate depths, there is a protected, rocky break wall in the Piers 5-7 area, and although the array cannot determine the exact location of Smallmouth Bass, it is likely they were along this rocky reach for spawning. Field surveys during the spawning period should be undertaken to confirm their selection of this habitat.

In Hamilton Harbour, Smallmouth Bass remained within the harbour and had highly localized residency in the Piers 5-7 area where they were originally tagged, with small movements to nearby, deeper waters during winter. Generally, Smallmouth Bass move more than Largemouth Bass and can move almost 500 m/day on average during summer, which is likely related to abiotic factors (e.g., water temperature) and prey availability (Kaemingk et al. 2011; Carter et al. 2012). Mean core home ranges of 7.8 ha have been documented (Kaemingk et al. 2011); however, home range sizes can be variable. For example, in eastern Lake Ontario, Smallmouth Bass were found to have small home ranges with movements < 3 linear km (Rupnik 2018), similar to Hamilton Harbour. The small movements of Smallmouth Bass in Hamilton Harbour suggest water temperatures and prey availability are suitable in the limited area they frequent and spawning and overwintering habitats are similarly proximate. A mark-recapture study in Hamilton Harbour indicated that Smallmouth Bass had a small, localized population (Larocque et al. 2023), matching our acoustic telemetry results. Notably, fish community electrofishing surveys catch most Smallmouth Bass near Bayfront, Macassa Bay and in the Piers 5-7 areas (C. Boston *unpublished data*), where tagged bass inhabited. Rocky habitat associated with these areas might be limited in the harbour and prevent Smallmouth Bass population expansion. Removal of aggregate materials from the harbour was one of the key sources of habitat loss that the AOC has experienced, with some remaining shoals buried under fine sediments (Holmes 1988). Habitat creation or remediation efforts that can increase or improve the amount of habitat suitable for spawning by Smallmouth Bass could facilitate in their range expansion within the harbour.

### ***Walleye***

Walleye are part of both commercial and recreational fisheries in the Great Lakes and as such their spatial distribution and habitat use have been extensively studied, including in Hamilton Harbour. Efforts to reintroduce Walleye into Hamilton Harbour have occurred over the past two decades to help increase piscivore populations and boost recreational fishing (Brooks et al. 2019; OMNRF 2019). To inform reintroduction efforts, it is important to understand the habitat use of Walleye in the area. Acoustically tagged Walleye (N = 37; Table J1) had relatively consistent general location, habitat cluster, and depth use within seasons over the years of available data (April 2016- April

2020; Figures J1, J3, and J6; see Appendix J for a complete summary of Walleye results). Hamilton Harbour Walleye were more likely to be detected during dawn and night, followed by dusk, and lastly during the day (Figure J5A). Also, Walleye were the only species that showed difference in detections among moon phases with proportionally more detections during the waning and new moon phases compared to the full moon (Figure J5B). Both time of day and moon phase results suggest greater activity of Walleye during lower light conditions, likely related to light sensitivity. Walleye are sensitive to bright daylight and will associate with cover like boulders, logs, and sparse vegetation during the daytime to avoid the sun and be more active in low light (Scott and Crossman 1998; Bozek et al. 2011).

Walleye are generally demersal and thrive in large, shallow, turbid lakes but can also inhabit deeper waters of clear lakes as well as rivers (Scott and Crossman 1998; Bozek et al. 2011). Overall, Hamilton Harbour Walleye were more resident in deeper areas (deep or moderate depth habitat clusters) with less SAV and sunlight, and were detected broadly throughout the harbour in the west end, central basin, north shore, and east end, as well as outside of the Harbour (Figures J4 and J8). Similarly, in Toronto Harbour, Walleye were associated with lower SAV in deeper waters, and would generally disperse during the summer (Brownscombe et al. 2023). In Hamilton Harbour, there was slight seasonal variation in Walleye habitat use. In the winter, Walleye had higher residency at the north shore, central basin, and west end, when Walleye were using deeper waters, further offshore (9.4 ± 0.5 m; Figures J4, J7, and J8). During the spring, Walleye were in the same areas (north shore, west end, and central basin) but slightly closer to shore as seasonal depth use was shallower (3.8 ± 0.5 m; Figures J4, J7, and J8). In the summer, Walleye were mostly residing outside of Hamilton Harbour and to a lesser extent also closer to the east end of the harbour, still using relatively shallow depths (3.2 ± 0.5 m; Figures J4, J7, and J8). In the fall, Walleye were still outside of Hamilton Harbour but there was increased residency throughout the harbour at the west end, north shore, east end, and central basin (Figure J8), at this time Walleye moved to deeper depths (6.2 ± 0.5 m; Figure J7).

Walleye are known to spawn in rivers but also in areas with boulders, cobble or coarse-gravel shoals of lakes (Scott and Crossman 1998), specifically over clean, windswept gravel, cobble, and rubble substrate shorelines (Johnson 1961; Bozek et al. 2011). During the spawning window (March 15 to May 15), Hamilton Harbour Walleye were found in areas with greater fetch/windswept substrate (e.g., north shore and east end) but also the central basin and west end, and did not go to Cootes Paradise Marsh or any lotic systems (Figure J10). Spring electrofishing-based surveys have similarly documented Walleye along shorelines throughout the harbour in areas with suitable substrates (J. Midwood, *unpublished data*) and collectively these results suggest Hamilton Harbour Walleye are shoal spawners. In Hamilton Harbour, during the spawning window, Walleye were not at their shallowest depths (mean monthly depths were ~5 m; Figure J7). Although we did not have substrate data, Walleye were also resident in areas of deeper depths with minimal vegetation (no SAV at deep depths or sparse and moderate SAV at moderate depths) but also sometimes dense SAV in shallow areas (Figures J11). Deeper habitat use could be related to Walleye, particularly females, staying further offshore when staging, prior to the act of spawning in shallower waters at night (Ellis and Giles 1965; Scott and Crossman 1998). We did not have information on the sex of tagged Walleye (tagged outside of the spawning period) to assess differences in habitat use across sexes, but electrofishing surveys are highly biased towards male Walleye, which further aligns with offshore staging by females.

Most Walleye were not fully resident to Hamilton Harbour. The majority of Walleye (N = 27; 73%) left the harbour during the study, usually with repeated emigration in the summer and returning to the harbour by winter (Figure J2). When Walleye were in Lake Ontario, KUD home ranges were generally along the south shore of Lake Ontario towards the Niagara River for all seasons; however, in winter, the home ranges were mostly in Hamilton Harbour (Figure J9). In other systems, Walleye conduct long-distance migrations after spawning which has been attributed to finding areas of optimal temperature and/or prey availability (Bowlby and Hoyle 2011; Raby et al. 2018). Walleye outmigration in Hamilton Harbour could be related to temperature, prey availability, hypolimnetic anoxia (Polak and Haffner 1978; Gertzen et al. 2016; Hiriart-Baer et al. 2016) or, more likely, a combination of these factors. For example, Walleye will actively avoid upwellings of anoxic waters (Brooks et al. 2022), but at some point the resulting habitat compression may prove to be too restrictive for both Walleye and their prey (Brooks et al. *in review*). Walleye then return to Hamilton Harbour once abiotic conditions improve after the fall turnover and mixing event, which suggests the harbour meets their habitat requirements for parts of the year. However, Walleye will also move long-distances to spawning grounds (Hayden et al. 2014) and returning to Hamilton Harbour could be in preparation for spawning as opposed to selection of overwintering habitats or improved abiotic conditions.

### ***White Sucker***

Acoustically tagged White Sucker (N = 8; Table K1) had relatively consistent use of the same general locations, habitat clusters, and depths within seasons over years of available data (June 2016 – April 2020; Figures K1, K3, and K6; see Appendix K for a complete summary of White Sucker results). White Suckers were more likely to be detected during dusk compared to daytime, and detections did not vary based on moon phase (Figure K5). Generally, White Sucker are demersal, bottom feeders, and inhabit warmer, shallow lakes or bays, and tributary rivers of larger lakes (Scott and Crossman 1998). White Sucker predominately feed on chironomid larvae among other invertebrates (Scott and Crossman 1998), and because chironomid larvae have a preference for soft sediments (fines/sands/gravel; Pinder 1986), the habitat of White Sucker is likely comprised of similar substrates, sparse SAV, and shallow waters. In Hamilton Harbour, outside of the spring spawning window, White Sucker were generally found using deeper depths (mean monthly depth use range of 3.5 – 12.0 m; Figures K6 and K7) with no or sparse SAV (Figure K4), presumably in areas with suitable substrate to forage more effectively. Brownscombe et al. (2023) found White Sucker in Toronto Harbour to also be associated with a range of deeper waters and sparse SAV. In Hamilton Harbour, White Sucker was the only species assessed in our study that used deeper depths in the summer rather than winter (Figures K6 and K7), although Northern Pike also used deeper depths in summer but not as deep as winter. In the winter, White Sucker had the highest residency in areas of sparse SAV at moderate depths at the west end, and were closer to shore, using shallow depths (2.3 ± 1.0 m; Figures K4, K7, and K8). During the spring, White Sucker had increased residency in areas of moderate SAV at moderate depths, no SAV at deep depths, and dense SAV in shallow waters, at the west end and along the north shore when using shallow depths (2.0 ± 1.0 m; Figures K4, K7, and K8). White Sucker were detected in lotic areas in the Harbour during winter and spring only. In the summer, White Sucker had the highest residency outside Hamilton Harbour, followed by areas with no SAV at deep depths in the harbour, and generally White Sucker were at their deepest depths during this season (8.7 ± 1.0 m; Figures K4, K7, and K8). In the fall, some White Sucker were still outside of Hamilton Harbour or in areas with no SAV at deep depths in the harbour but there was an increase in residency at the west end of the harbour, using deep depths (4.7 ± 1.0 m; Figures K4, K7, and K8).

White Sucker will migrate into gravelly areas of streams to spawn in early spring but can also spawn on lake margins or quiet areas in the mouths of blocked streams (Scott and Crossman 1998). The spawning window for White Sucker (April 1 to May 31) coincided with when White Sucker were at their shallowest depths (mean monthly depths were ~2 m; Figure K7). During spawning, White Sucker were present at all habitat clusters but to a lesser extent in areas of sparse SAV in shallow waters and lotic areas. White Sucker were spatially located in the west end, near Bayfront, but also along the north shore of Hamilton Harbour (lake margins) and at the mouths of Grindstone Creek and Cootes Paradise Marsh (Figures K10 and K11). One tagged White Sucker was detected in Cootes Paradise Marsh near Spencer Creek during the spawning window for two successive years. White Sucker are also frequently captured at the Cootes Paradise Fishway each spring (Rebalka et al. 2023) and the area (including Spencer Creek) is likely of importance for spawning. Lower residency in lotic areas may indicate that White Sucker were passing by river mouths or through lotic areas (e.g., Grindstone Creek) to reach spawning habitat, yet it was unclear if they were targeting a specific habitat cluster for spawning. Without substrate information, it is difficult to determine if White Sucker were using gravel areas, but they were in shallower depths, and it is likely they found pockets of gravel substrate in the streams and lake margins to spawn.

White Sucker were not resident to Hamilton Harbour and most White Sucker left Hamilton Harbour (N = 7; 88%) in the summer and returned by winter (Figure K2). While in Lake Ontario, home ranges indicated White Sucker remained relatively close to the harbour but one individual was detected as far as Jordan Harbour (~40 km) along the south shore of Lake Ontario in summer (Figure K9). Aside from the spawning migration, larger White Sucker have a tendency to move offshore, potentially due to temperature (Scott and Crossman 1998); however, it could also be related to food availability as food density is correlated to growth of White Sucker (Chen and Harvey 1995). As noted, hypolimnetic anoxia (Polak and Haffner 1978; Gertzen et al. 2016; Hiriart-Baer et al. 2016) can limit the availability of benthic invertebrates in Hamilton Harbour (Dermott et al. 2007) and documented upwellings of hypolimnetic anoxic waters (Flood et al. 2021) could potentially further reduce suitability of foraging habitats for this demersal species. Dissolved oxygen levels, temperatures, and food availability could all contribute to White Sucker leaving Hamilton Harbour for a portion of the year.

***Yellow Perch***

Yellow Perch (N = 10; Table L1) were tagged with smaller tags with no depth sensors and had less than one year of data from early in the study (July 2016 – April 2017; Figures L1, L2, and L5; see Appendix L for a complete summary of Yellow Perch results). Coverage did not include some habitat clusters that Yellow Perch may frequent due to the limited array at the time and therefore results may be skewed for habitat and spatial use. Yellow Perch were more likely to be detected during dawn compared to dusk and daytime, and detections did not vary based on moon phase (Figure L4).

Yellow Perch can inhabit a variety of warm to cooler environments including large lakes, ponds, and quiet rivers (Scott and Crossman 1998). They can be found in shallow, clear waters with moderate or dense vegetation, and are associated with fines, sand, or gravel substrate (Fish and Savitz 1983; Lane et al. 1996; Scott and Crossman 1998; Matley et al. 2022b). Generally, Hamilton Harbour Yellow Perch were detected year-round in the west end in areas with sparse SAV at moderate depths, or areas with no SAV at deep depths. Residency in these less vegetated, deeper areas were likely artificially inflated from the reduced array earlier in the study (Figure A3), yet similar to the literature, there was still an indication (likely an underestimation) of Yellow Perch being detected in shallow areas with dense SAV or moderate depths with moderate SAV in the west end towards the shoreline (Figure L2, L3 and L5). Spatially, Yellow Perch have relatively small home ranges (0.005 – 0.022 $km^2$; Fish and Savitz 1983) but can undertake larger movements. Yellow Perch can have spring migratory movements associated with spawning, and seasonal movements into deeper waters in the fall to overwinter in response to temperature and food availability (Wang and Eckmann 1994; Scott and Crossman 1998; Radabaugh et al. 2010). In the winter, Hamilton Harbour Yellow Perch were detected further offshore in the west end, in areas of no SAV at deep depths (Figures L3 and L5) yet without data after the array expansion into Piers 5-7, we have reduced accuracy in spatial positioning of Yellow Perch (Figure 1). Although there was no depth use data, Yellow Perch were detected on receivers further offshore in winter, supporting the movement to deeper waters as temperatures declined. m home ranges and high residency in the harbour.

During the spawning window (April 1 to May 31), Yellow Perch were in areas of no SAV at deep depths (likely artificially inflated because of array constraints), areas of sparse SAV at shallow depths, and moderate SAV at moderate depths in Hamilton Harbour. These areas were in the west end, towards Bayfront and Cootes Paradise Marsh but also along the north shore (Figures L6 and L7). The spatial areas of Yellow Perch were all areas with aquatic vegetation or submerged structure (e.g., brush, logs, debris) that provide more shelter, which is consistent with their noted spawning preference, especially as their egg masses adhere to submerged vegetation or, at times, bottom and can easily be dislodged by wind and waves (Scott and Crossman 1998). However, we cannot verify if Yellow Perch were using that specific habitat during spawning with our coarse-scale habitat clusters. Two Yellow Perch entered Cootes Paradise Marsh in April and returned to Hamilton Harbour that same month. Since 2016, very few (< 15) Yellow Perch have been captured annually in the spring at the Cootes Paradise Fishway (Rebalka et al. 2023); however, Yellow Perch can pass between the barrier mesh, and may be moving into Cootes Paradise undetected at the fishway. Lotic areas were not well monitored when Yellow Perch data were available, yet some fish were detected at the mouth of Grindstone Creek and could also be using these lotic areas to reach spawning sites.

## SYNTHESIS

We assessed basic seasonal and spawning window-related spatial and physical habitat associations of 11 species of acoustically tagged fish in Hamilton Harbour and environs. The spatial and habitat information broadly indicates species-specific associations within the harbour and reveals similar trends among the tagged fish community. An important caveat noted previously is that the array slowly expanded and covered additional areas from 2016 to 2020, this resulted in changes in the number of receivers associated with each habitat cluster. A consequence of this is that fishes with only detection data in earlier years may have skewed habitat association patterns that may influence data interpretation. Yellow Perch are a good example since all detections of this species occurred prior to 2018. The array pre-2018 had limited receiver coverage of habitat clusters in shallow areas with sparse or dense SAV (Figure 3). As such, Yellow Perch habitat associations documented herein may be biased against these habitat clusters. Similarly, changes in detection efficiency across seasons and habitat types can influence results and this is discussed in more detail in the next section. Caveats aside, areas highly frequented by species at different times of year revealed dynamic habitat associations within this highly urbanized and degraded embayment. For managers focused on AOC recovery, determining fish habitat associations in this degraded system provides insights into the types of habitat that are important and when they are primarily utilized. If combined with a broader analysis of habitat distributions, results here can help determine whether fish populations are influenced or may be limited by specific habitat availability or overall supply. Such an integration can be used to direct ongoing and future restoration efforts in the Hamilton Harbour AOC.

### *Influences on detection efficiency*

It is important to understand and, when possible, incorporate changes in receiver detection efficiency to reduce collection biases and improve data interpretation. Variables such as seasonal water temperature or stratification, SAV (presence and seasonality), fish behaviour (e.g., benthic vs pelagic swimming), and a changing array design (as discussed above) may all alter detection efficiency of tagged fish and ultimately results and interpretation of the analyses. In Hamilton Harbour, detection range (and efficiency) is reduced in the stratified (~350 m) vs isothermal (~500 m) seasons and is further influenced by local seiche events (Wells et al. 2021). Thus, in winter, the isothermal conditions could increase the number of detections across more receivers and the true location of a fish would be more difficult to discern. Although we attempted to account for this change in detection range by using only the first detection for every acoustic tag ping, there were still more detections occurring during winter. Increased winter detections could also be related to reduced SAV (seasonal related die offs), and less obstructions between fish and receivers as fish were generally further offshore and deeper in winter and thus likely to be detected on multiple receivers compared to summer. For example, Weinz et al. (2021) found highly reduced detection efficiency in areas of high SAV in the Detroit River; however, it also meant when fish were detected in summer they were likely closer to those receivers and their locations more accurate. In addition to SAV, fish can have reduced detection efficiency if behind rocks, logs or other debris, particularly in the warmer months when inhabiting the shallows. Species behaviour may also influence detections, for example, Bowfin and White Sucker are demersal and could more easily go undetected when swimming near the bottom, especially amongst large rocks and logs or in areas of variable bathymetry. Given the extensive array coverage, we accounted for periods of absences of tagged fish in our Hamilton Harbour residency calculation by giving a daily position at the last receiver where they were detected. Such an approach can help account for seasonal changes in detection efficiency, but the noted limitations are something to be aware of when interpreting acoustic telemetry data and derived habitat associations.

### *Commonalities within Hamilton Harbour fishes*

By assessing the habitat associations of 11 different species, we revealed some community-wide trends in habitat associations, movements, and depths, which can not only help us understand habitat selection but also where fish productivity is the greatest seasonally in the harbour. Even considering just these brief analyses of habitat associations, the west end of Hamilton Harbour was of importance for all tagged fish species for at least one, if not all seasons. Hydroacoustic surveys in Hamilton Harbour show a similar trend of greater fish density and biomass in the west end of the harbour compared to other areas (Midwood et al. 2019). Increased use by tagged fishes at the west end of the harbour could be related to increased productivity, more sheltered or warmer areas, and its proximity to rivers/marshes. Additionally, it could be related to being an area with more heterogenous habitat (all six habitat clusters were within this area), and potentially increased cover from logs and debris as well as SAV. While here we explored habitat selection based on general habitat clusters, determining the specific habitat features that fish are associated with would be beneficial to study. Machine learning modelling with resource selection functions can help tease apart if fish are selecting for specific habitat variables within the harbour and how this selection compares across species (Brownscombe et al. 2021; Griffin et al. 2021). These variables can include static layers (e.g., bathymetric depth) and time-matched variable layers (e.g., surface water temperature). Modelled habitat selection results could then be used to estimate the amount of those selected habitat features in the harbour and how it compares to the amount of spatial area fish use. These comparisons can give insight on population sizes and growth potential, and may help explain why the west end has increased fish use compared to the rest of the harbour.

Seasonal depth use generally followed the same trends across all tagged species. Typically, fish used shallower depths in spring and summer, and deeper depths in fall and winter with movements further offshore. This seasonality across species is likely related to changes in temperature, water quality, foraging and food availability, and/or spawning. As is typical of most eutrophic lentic systems in temperate regions, the water column in Hamilton Harbour can become stratified on a seasonal basis. In summer, water temperatures warm, a thermocline develops, and the hypolimnion in Hamilton Harbour can experience anoxia and deeper waters become less habitable for fish (Gertzen et al. 2016; Hiriart-Baer et al. 2016; Midwood et al. 2019). During this time, options for fish are limited and they must tolerate low dissolved oxygen conditions at deeper depths, move into shallower, warmer waters (potentially above their thermal optima), or leave the harbour. Stratification can also occur in winter months and with ice cover reducing the surface water and air interface, reduced dissolved oxygen can become a problem for fish. In Hamilton Harbour, winter dissolved oxygen levels in the main basin generally remained above 6 mg/L (with short periods of low dissolved oxygen in months of February or March) and is thus mostly suitable for fish (Gertzen et al. 2016). With shorelines subject to freezing, and bottom waters being warmer (~ 4°C), temperatures are likely driving fish to move deeper and further offshore in the winter. The tagged species in this study all generally spawn in shallow waters (Scott and Crossman 1998), which could be driving the start of the shallow depth use seen during the spring and summer, especially during the period prior to thermocline establishment. As ice cover recedes and nearshore waters warm up, it also stimulates photosynthesis and prey move into the area. Piscivores, like Lake Trout (*Salvelinus namaycush*), have been found to track their prey into nearshore areas to forage (Guzzo et al. 2017), and other piscivorous fishes tracked in the current study may use similar tactics to acquire prey in shallow, nearshore waters during the spring. Feeding strategies are also likely why White Sucker were found at deeper depths in the summer (contrary to the trends seen across species), as they may have left the harbour to feed benthically in Lake Ontario where it was not hypoxic and thus likely had greater food availability. Although tagged fish were found at deeper depths in the winter, future research directly comparing the vertical and horizontal spatial use within the fish community, particularly piscivores, would determine if they are segregating or overlapping spatial niches and whether such habitat partitioning changes seasonally or is affected by benthic anoxia. Overlapping spatially may increase interspecific competition and potentially limit growth of some fish populations.

Another commonality among some species was outmigration during the summer months and return to the harbour during the fall to overwinter in the harbour. Although the distances traversed varied, Walleye, White Sucker, Longnose Gar, and Freshwater Drum underwent migrations around the same time of year. As previously indicated with White Sucker, these migrations out of the harbour could be related to foraging as the timing did not coincide with spawning for any of these species. Outside of the spawning migration, larger White Sucker have a tendency to move offshore and movements can be related to temperature (Scott and Crossman 1998). As White Sucker remained relatively close to the harbour, it could also be an innate tendency to move further offshore, for foraging and temperature related reasons. Long distance forays of Freshwater Drum in the summer time have also been observed in Lake Winnipeg, with a return to a small area in the south basin for winter (Rudolfsen et al. 2021). Adult Walleye in the Bay of Quinte were also observed to emigrate into Lake Ontario during the summer and return during the fall, presumably to move to cooler waters and feed on alewife (Bowlby and Hoyle 2011), and a similar migration occurs in Lake Erie (Raby et al. 2018) and Lake Huron (Hayden et al. 2014). The movement patterns by these species may be part of their natural history within large lakes for reasons such as feeding and temperature preferences, and returning to Hamilton Harbour may be related to the preparation to spawn. Future research on whether environmental variables such as water temperature or dissolved oxygen drive species movement in or out of Hamilton Harbour and the synchronicity of timing across individuals and species can help indicate if there are mass migrations across species related to water quality or other factors.

### *Habitat associations and impacts to harbour recovery*

Acoustic telemetry enabled us to understand long-term habitat associations of different fish species in Hamilton Harbour. As habitat mapping in the harbour continues to improve, we will be able to determine the amount of different habitat features available in the harbour and compare this to what acoustically tagged fish are associated with across different seasons or life stages as adults (e.g., spawning, overwintering, foraging). Habitat selection is complex and hierarchical at times, and including seasonal or dynamic habitat info could discern if and when fish are selecting for more dynamic features, such as water temperature, compared to static features like substrate. When fish habitat use of a habitat feature completely overlays its availability (i.e., fish are using all available habitat of that type), it may indicate that a specific habitat feature is limiting population sizes in the harbour due to habitat saturation. Alternatively, if fish are using a fraction of the available habitat, fish may be limited to expanding to other similar habitats due to poor habitat connectivity or the habitat may be of lower quality due to other variables like low dissolved oxygen, limited prey availability, or interspecific competition. Similarly, differences in habitat use in a degraded system like Hamilton Harbour relative to what has been documented in less disturbed areas may indicate selection of less optimal habitat; however, in most instances fish-habitat associations outlined in the present work are consistent with previous studies. One exception is fall and winter habitat associations for Bowfin, a species that was found to use deeper, more exposed waters in Hamilton Harbour compared to the shallow, sheltered habitats noted in nearby Toronto Harbour (Midwood et al. 2018). Both systems are degraded (i.e., Great Lakes AOCs), so the suitability of Toronto Harbour as a reference area is questionable. That being said, pervasive issues with anoxia in Hamilton Harbour may make shallow, sheltered habitats in the system less suitable for overwintering, particularly in the winter once ice is established. Discerning habitat quality may be complex, particularly in a degraded system, but indicating if habitat associations and availability match or are in discord can help define management goals to improve fish habitat and populations in Hamilton Harbour.

Given Hamilton Harbour's status as a Great Lake AOC and assessed impairment of fish habitat within the system, caution should be taken in transferring the fish habitat associations documented herein into other, less degraded areas. As noted, Hamilton Harbour has a long history of habitat loss that has included infilling of coastal wetlands and river mouths (Whillans 1982). Remaining habitats are also degraded, with the few remaining spawning shoals largely covered by mud, silt, and clay (Holmes and Whillans 1984), contaminants in benthic substrate limiting macroinvertebrates (Milani and Grapentine 2017), and hypolimnetic anoxia reducing habitat suitability (Flood et al. 2021). As a result of the loss and degradation of habitat, fish in the harbour may not be selecting their optimal habitat, but rather surviving by using the types of habitat that remain in the system. Similarly, associations with habitats now reduced in availability (e.g., wetlands or spawning shoals) may appear muted since they would be less likely to occur within the detection range of receivers. A risk from these limitations is that guidance on what habitats to restore based on observations of current use may be biased and point towards the need for creating more of the remaining sub-optimal habitat types rather potentially more suitable lost habitats. Fish habitat managers should therefore be cautious when applying the findings of the present work without fully understanding the historical context of habitat losses in the system.

Barring the caveats outlined in the previous paragraph, habitat associations of acoustically tagged fish can still help inform and focus efforts to improve Hamilton Harbour. With regards to BUI #14 (Loss of fish habitat), as noted above, fish habitat associations can be compared to what is available in the system to help inform what kinds of habitat creation projects (and locations) may be effective. The high residency across most tagged species in the west end (at some point in the year, particularly in winter) highlights the importance of this area and its potential habitat suitability. Habitat creation efforts may therefore be better focused on other areas of the harbour, such as the eastern end of the harbour where sheltered habitats are thought to be limiting

(Maynard et al. 2022). Alternately, efforts to improve the quality of existing habitats (especially if deemed limited in the harbour) such as spawning areas in Cootes Paradise Marsh or Grindstone Creek, may help to increase the productive capacity of these areas of the harbour. Improving access to limited habitats should also be considered. The west end likely has greater fish presence due to it containing areas that are shallower and more protected but it is also proximate to areas with higher habitat heterogeneity, which can support a more diverse fish community. Exploring the extent of connectedness among habitat types within the Hamilton Harbour AOC and fishes propensity to move among habitats can help identify parts of the harbour and habitat types therein that are comparatively isolated.

Incorporating acoustically tagged fish behaviour and spatial use, as well as conspecific capture rates in monitoring surveys can help improve population trend estimates and the assessment of BUI #3 (Loss of fish populations). For example, Smallmouth Bass had very small home ranges so if unmarked individuals are captured elsewhere in the harbour over time, it could indicate population growth or range expansion. Adjusting sampling strategies to avoid periods when a species leaves the harbour or when they are using water depths greater than can be accessed by a specific gear can be useful in population monitoring since it can maximize capture rates of the focal species. Similarly, species that leave the harbour, their duration in Lake Ontario, and other areas in the system where they are resident are important pieces of information for understanding contaminate loads (Visha et al. 2021); restricting contaminant analyses to resident species only may be prudent (potentially in support of BUI#1 - restrictions on fish and wildlife consumption). From an AIS perspective, based on the general locations and depth use of Common Carp and Goldfish, there may be opportunities to target their removal when congregating prior to and during spawning (Boston et al. 2024), with Carrol's Bay as a potential focal area. More focused studies of these and other AIS (e.g., Rudd (*Scardinius erythrophthalmus*)) are underway in the harbour and will hopefully lead to management solutions to help control populations of these fishes.

## CONCLUSION

To conclude, we used acoustic telemetry to assess the spatial ecology of 11 species of fish across multiple seasons and years. That alone is rather novel and has yielded remarkable understanding of the ecology of fishes in an embayment on Lake Ontario. The specific embayment we studied (Hamilton Harbour) is not unlike many others in the Laurentian Great Lakes where there are legacy effects arising from the industrial revolution and other human activities that have impaired the structure and function of freshwater systems. Data such as we present here can be used to assess the extent to which these habitats are recovering and being used by fish. Moreover, these data can be used to inform future restoration efforts in Hamilton Harbour to improve fish habitat and populations. As other systems that are "pristine", impaired and in the process of recovering are studied across the Great Lakes and beyond it should be possible to identify general characteristics of fish space use and behaviour that are transferable and can be extrapolated to the management and restoration of other water bodies in the Great Lakes and beyond. Previous fish-related indicators have tended to focus on presence-absence or abundance-based point-in-time sampling. The approach used here is unique in that it provides continuous spatio-temporal sampling at various scales and thus provides a more nuanced understanding of fish-habitat relationships.

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## TABLES

**Table 1.** Summary of habitat conditions at each of the six groups that were identified through Principal Component Analyses and k-means cluster analysis. Mean values (with standard deviation) for each environmental metric are presented as are a general description of the typical habitat conditions therein.

| | **SAV Cover (%)** | | **Weighted Fetch (m)** | | **Depth (m)** | | |
|---|---|---|---|---|---|---|---|
| **Groups** | **Mean** | **General** | **Mean** | **General** | **Mean** | **General** | **Notes** |
| Dense SAV/shallow | 55 ± 15 | High > 40 % | 8 ± 9 | None < 25 m | 2.2 ± 1.9 | Shallow <5 m | |
| Sparse SAV/shallow | 7 ± 7 | Low 0-20 % | 8 ± 8 | None < 25 m | 1 ± 0.5 | Shallow <2 m | |
| No SAV/shallow/lotic | 0 ± 0 | None 0 % | 10 ± 20 | Low 0-50 m | 0.8 ± 0.5 | Shallow <2 m | Sites in river |
| Mod SAV/mod depth | 18 ± 10 | Mod 5-40 % | 53 ± 15 | Mod 25-75 m | 8.1 ± 2.6 | Mod 5-12 m | |
| Sparse SAV/mod depth | 3 ± 3 | Low <7 % | 17 ± 14 | Low 0-50 m | 7.9 ± 2 | Mod 5-12 m | |
| No SAV/deep | 1 ± 2 | None <5 % | 60 ± 14 | Mod 25-80 m | 15.2 ± 4.2 | Deep 9-23 m | |

**Table 2.** Summary of the number (N) and size of acoustically tagged individuals of each species, their detection date range and estimated spawning window in Hamilton Harbour.

| Species | N | Length (mm) Range | Mass (g) Range | Detection Date Range | | | Spawning Window |
|---|---|---|---|---|---|---|---|
| Bowfin | 4 | 488 – 608 | 1180 - 2620 | 4/30/2016 | - | 4/24/2020 | May 1 to June 30 |
| Common Carp | 27 | 445 – 727 | 1330 - 7694 | 10/5/2017 | - | 4/25/2020 | May 1 to July 31 |
| Freshwater Drum | 13 | 451 – 637 | 1430 - 4450 | 6/15/2016 | - | 4/25/2020 | June 1 to July 31 |
| Goldfish | 12 | 300 – 340$^{F}$ | 850 - 1218 | 6/27/2017 | - | 4/25/2020 | May 1 to June 30 |
| Largemouth Bass | 25 | 346 – 515 | 670 - 2700 | 4/30/2016 | - | 4/25/2020 | May 1 to July 15 |
| Longnose Gar | 13 | 680 – 978 | 680 - 2370 | 6/29/2016 | - | 4/12/2020 | May 1 to June 30 |
| Northern Pike | 24 | 548 – 923$^{F}$ | 1250 - 4850 | 4/30/2016 | - | 4/25/2020 | March 15 to April 30 |
| Smallmouth Bass | 6 | 411 – 453 | 1140 - 1590 | 6/28/2017 | - | 4/25/2020 | May 1 to July 15 |
| Walleye | 37 | 430 – 700 | 1463 - 3150 | 4/30/2016 | - | 4/25/2020 | March 15 to May 15 |
| White Sucker | 8 | 392 – 495$^{F}$ | 810 - 1500 | 6/18/2016 | - | 4/25/2020 | April 1 to May 31 |
| Yellow Perch | 10 | 175 – 295 | 51 - 359 | 7/21/2016 | - | 4/23/2017 | April 1 to May 31 |

Note: Length was total length unless indicated with an $^{F}$ for fork length.

**Table 3.** Summary of seasonal and spawning window depth use and habitat associations, and activity patterns for each acoustically tagged species in Hamilton Harbour.

| | Species | Bowfin | Common Carp | Freshwater Drum | Goldfish | Largemouth Bass | Longnose Gar | Northern Pike | Smallmouth Bass | Walleye | White Sucker | Yellow Perch |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Spring** | Depth (m) | 1.9 ± 0.7 | 1.0 ± 0.5 | 2.2 ± 0.5 | 1.8 ± 1.0 | 0.4 ± 0.2 | 0.2 ± 0.5 | 0.6 ± 0.3 | -0.3 ± 0.7 | 3.8 ± 0.5 | 2.0 ± 1.0 | - |
| | Habitat | S SAV/ Shallow | S SAV/ Shallow | S SAV/ M depth | S SAV/ Shallow | S SAV/ M depth | S SAV/ Shallow | S SAV/ M depth | S SAV/ M depth | No SAV/ Deep | M SAV/ M depth | No SAV/ Deep |
| | Location | GC | GC, CP, W | W | GC, W | W | OSS, Out | W, GC, CP | W | N, C, W | W, N | W, CP, N |
| **Summer** | Depth (m) | 1.8 ± 0.6 | 1.8 ± 0.5 | 2.8 ± 0.5 | 1.9 ± 1.0 | 0.4 ± 0.2 | 0.4 ± 0.4 | 1.8 ± 0.3 | -0.4 ± 0.7 | 3.2 ± 0.5 | 8.7 ± 1.0 | - |
| | Habitat | D SAV/ Shallow | S SAV/ Shallow | No SAV/ Deep | D SAV/ Shallow | S SAV/ M depth | S SAV/ Shallow | S SAV/ M depth | S SAV/ M depth | No SAV/ Deep | No SAV/ Deep | S SAV/ M depth |
| | Location | GC, N | CP, W | Out | W, N | W | OSS, Out | W | W | Out, E | Out | W |
| **Fall** | Depth (m) | 3.6 ± 0.6 | 6.0 ± 0.5 | 7.0 ± 0.5 | 4.2 ± 1.0 | 0.9 ± 0.2 | 2.1 ± 0.5 | 1.6 ± 0.3 | 1.8 ± 0.7 | 6.2 ± 0.5 | 4.7 ± 1.0 | - |
| | Habitat | M SAV/ M depth | S SAV/ M depth | No SAV/ Deep | M SAV/ M depth | S SAV/ M depth | S SAV/ Shallow | S SAV/ M depth | S SAV/ M depth | No SAV/ Deep | No SAV/ Deep | No SAV/ Deep |
| | Location | W, N | W, C, N | Out, W, C, N | W, N, C | W | OSS, Out | W | W, N | Out, N, C, W, E | Out, W | W |
| **Winter** | Depth (m) | 6.3 ± 0.6 | 3.2 ± 0.5 | 6.8 ± 0.5 | 3.9 ± 1.0 | 1.9 ± 0.2 | 4.6 ± 0.5 | 2.5 ± 0.3 | 6.5 ± 0.7 | 9.4 ± 0.5 | 2.3 ± 1.0 | - |
| | Habitat | S SAV/ M depth | S SAV/ M depth | S SAV/ M depth | S SAV/ M depth | S SAV/ M depth | S SAV/ Shallow | S SAV/ M depth | S SAV/ M depth | No SAV/ Deep | S SAV/ M depth | No SAV/ Deep |
| | Location | W | W | W, Out | W, N | W | OSS, W, Out | W | W, N | N, C, W | W, Out | W |
| **Spawning Window** | Depth (m) | < 0.6 | 1.2 | 2.1 | 1.0 | 0.5 | 0.4 | 0.7 | 0.2 | 5.0 | 2.0 | - |
| | Habitat | S SAV/ Shallow | S SAV/ Shallow | S SAV/ M depth | S SAV/ Shallow | S SAV/ M depth | S SAV/ Shallow | S SAV/ M depth | S SAV/ M depth | No SAV/ Deep | S SAV/ M depth | No SAV/ Deep |
| | Location | GC, W, OSS | GC, CP, W | W | GC, W, N | W, CP, N | OSS, Out | W, GC, CP | W | N, C, W, E | W, N, GC, CP | W, CP, N |
| | When | May 1 - June 30 | May 1 - July 31 | June 1 - July 31 | May 1 - June 30 | May 1 - July 15 | May 1 - June 30 | March 15 - April 30 | May 1 - July 15 | March 15 - May 15 | April 1 - May 31 | April 1 - May 31 |
| **Activity** | Time of Day | dawn/ night/ dusk > day | dawn/night > dusk > day | NS | dawn/ night > dusk/ day | dawn > night > dusk/day | NS | night > dawn/ dusk > day | dawn/ night/ dusk > day | dawn/ night > dusk > day | dusk > day | dawn > dusk/day |
| | Moon Phase | NS | NS | NS | NS | NS | NS | NS | NS | waning/ new > full | NS | NS |
| | Residency | Resident | Resident | Migrant | Resident | Resident | Migrant | Resident | Resident | Migrant | Migrant | Resident |

Note: Seasonal depth use (mean ± SE) are from modeled results while spawning window depth use is the approximate mean depth over the specified time period (N.B. Yellow Perch were not tagged with depth sensors and Smallmouth Bass had some seasonal model estimates at negative depths while actual depths were still very shallow). Habitat clusters are colour coordinated similar to Figures 2 & 3 and only the cluster with maximum mean residency was indicated, even if multiple clusters were similar or if results were likely skewed by a limited array. Location in the harbour was based on the most prominent areas identified in residency index maps. S = sparse; M = moderate; D = dense; NS = non significant; GC = Grindstone Creek; CP = Cootes Paradise Marsh; W = West end; N = North shore; C = central basin; OSS = Ottawa St. Slip; Out = outside harbour; E = East end.

## FIGURES

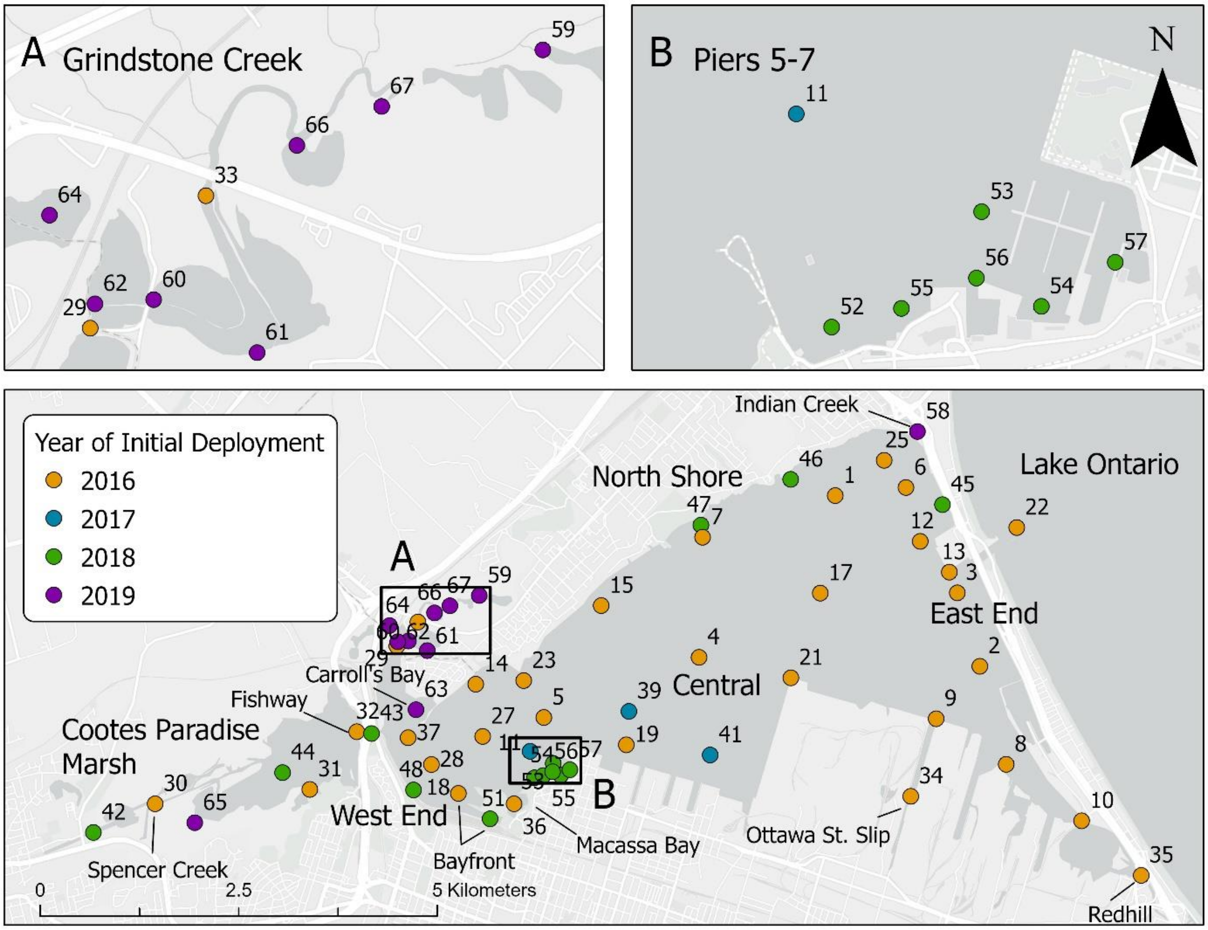


**Figure 1.** Receiver locations in Hamilton Harbour and the expansion of the array over time based on initial year of deployment, with close-ups at Grindstone Creek (inset A) and Piers 5-7 (inset B). Numbers indicate the station number.

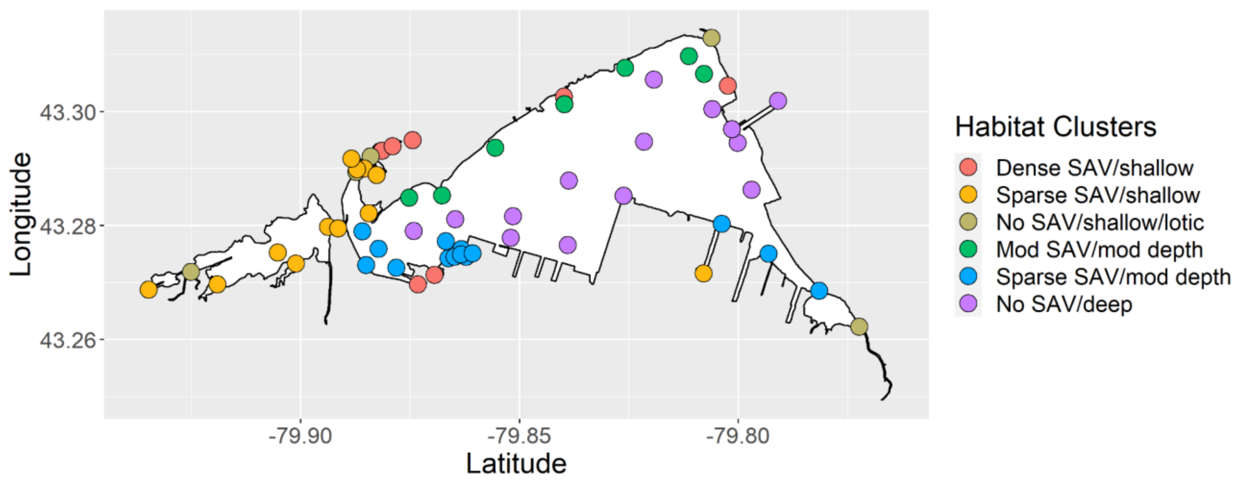


**Figure 2.** Habitat clusters associated with receivers within the Hamilton Harbour telemetry array. See Table 1 for more details related to each habitat cluster.

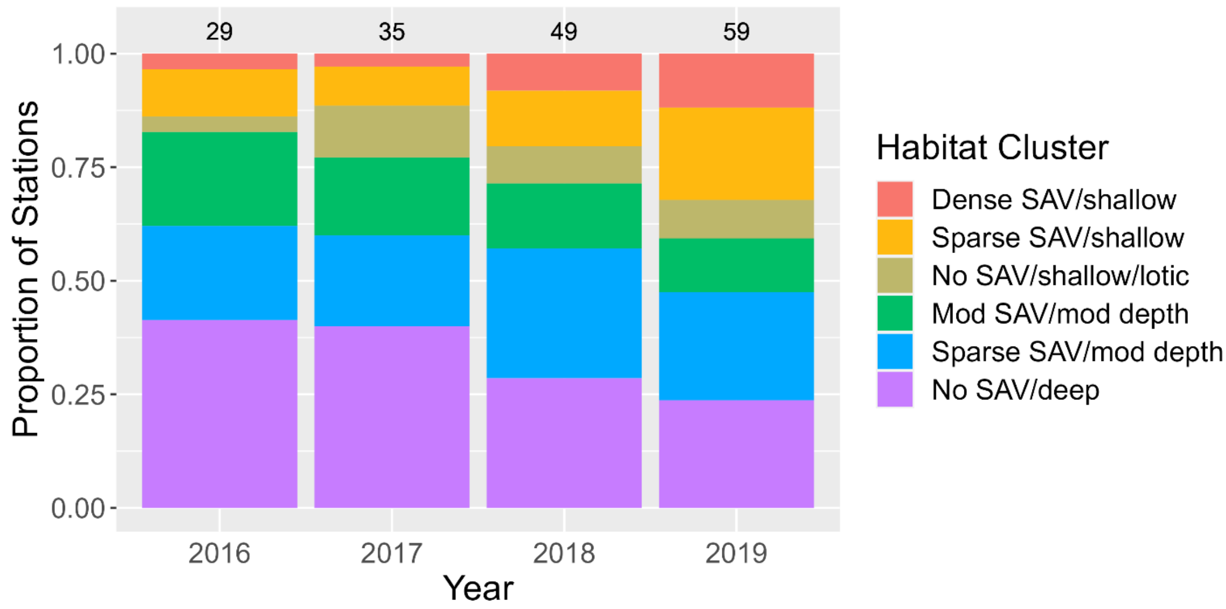


**Figure 3.** The proportion of receiver stations associated with each habitat cluster from 2016 to 2019 within the Hamilton Harbour acoustic telemetry array. Numbers above each bar are the total number of receiver stations for that year.

## APPENDIX A: ADDITIONAL STUDY DETAILS AND METHODOLOGY

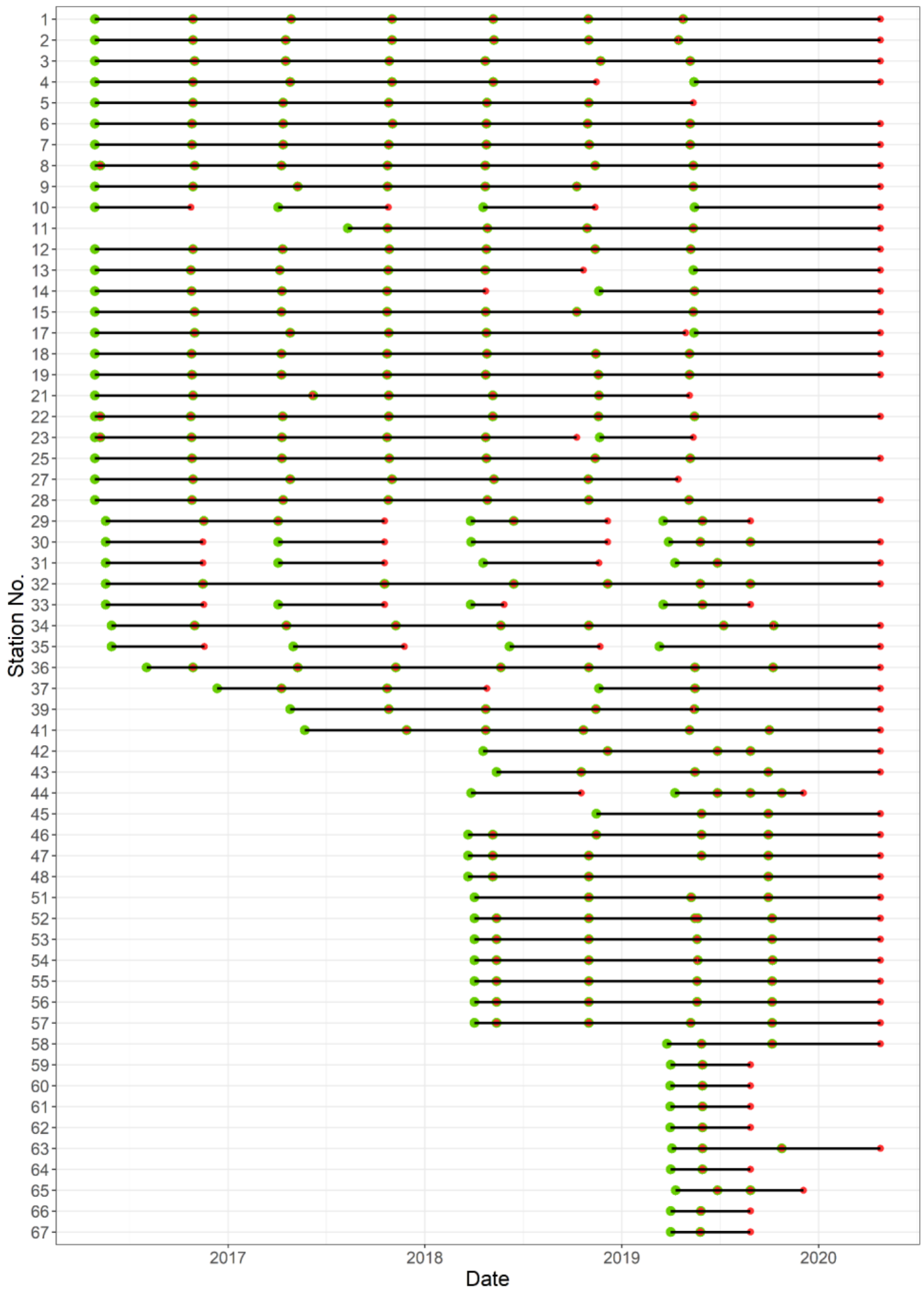


**Figure A1**. Hamilton Harbour receiver station deployment timeline. Green dots indicate time of deployment and smaller red dots indicate time of retrievals. Note that some locations have been decommissioned or are seasonally deployed.

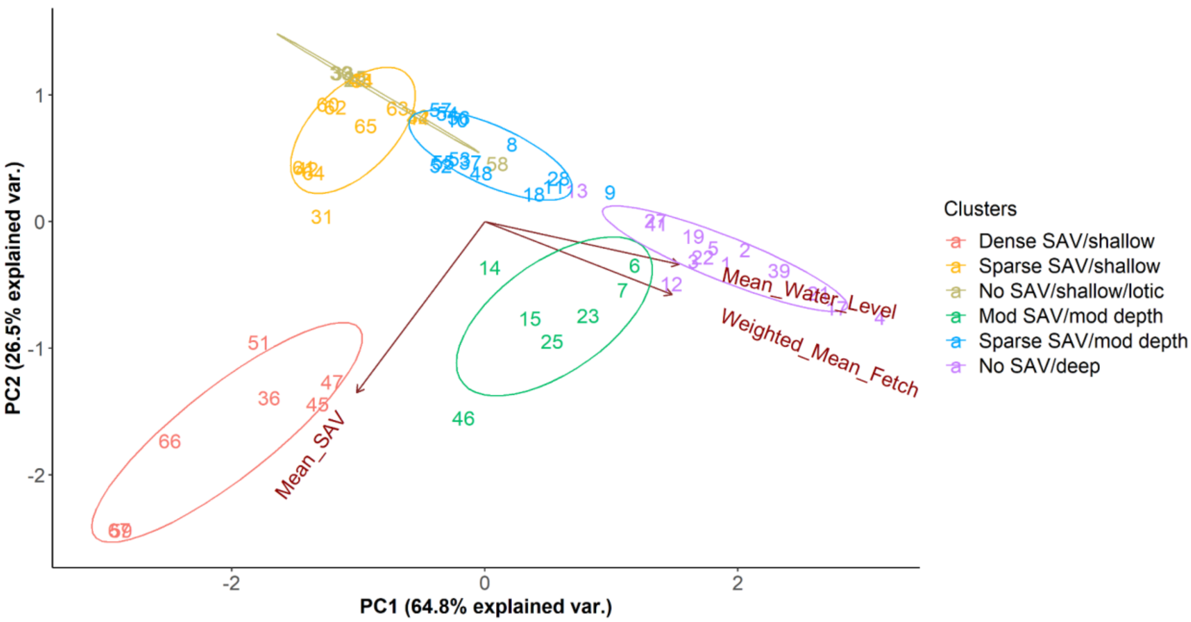


**Figure A2.** A principal components analysis showing the seven habitat clusters that receivers represent as determined using k-means cluster analysis and manually adding the lotic cluster. Numbers indicate the receiver station number – receiver locations are shown in Figure 1.


**Figure A3.** Duration of detections of fish tagged in Hamilton Harbour. First detections are green points and last detections are red points. Data were available from spring 2016 until spring 2020.

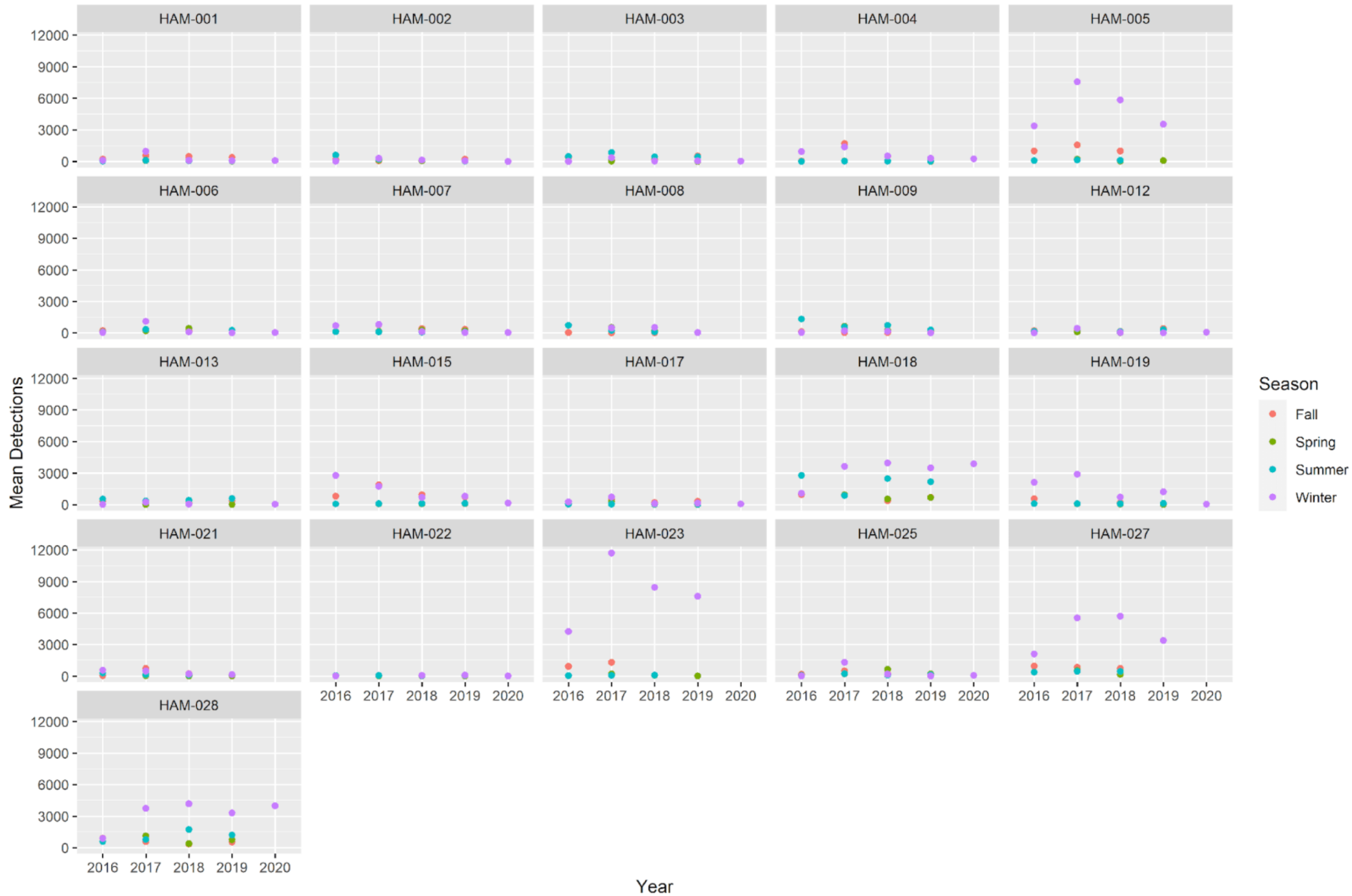


**Figure A4**. Mean number of raw detections from individual Freshwater Drum across years and seasons at receiver stations that were deployed for the majority of the study duration in Hamilton Harbour. Note that although the array expanded over time, the number of detections at stations rarely changed from year to year within seasons. Winter had the largest change, likely related to increased detection range.

## APPENDIX B: BOWFIN

### DETECTIONS AND HABITAT USE

Four Bowfin (*Amia calva*) were acoustically tagged and monitored in Hamilton Harbour from April 2016 to April 2020 (**Table B1**). Based on mean monthly detections, there appears to be an increase in detections during the fall and winter seasons relative to spring and summer over the four years of detection data (**Figure B1**). Of these detections, based on general groupings within the harbour there appears to be some affinity towards the Piers 5-7 area and north shore in the winter and Grindstone Creek area and Cootes Paradise Marsh in the spring and early summer of 2019 (**Figure B1**). No Bowfin left the harbour for the duration of the study.

Based on the habitat clusters, Bowfin were primarily detected in areas of sparse or moderate SAV/moderate depths and areas with no SAV and deep during the fall and winter seasons, while in 2019 there was an indication of being in areas of sparse SAV in shallow waters in the spring, and areas with dense SAV in shallow waters and moderate SAV at moderate depths in the summer (**Figure B2**). These trends were also seen when assessed based on seasonal residency by habitat clusters (**Figure B3**). However, seasonal residency more clearly showed that Bowfin also resided in lotic waters along with dense and sparse SAV in shallow waters in spring.

There was an increase in detections during dusk, night, and dawn compared to detections during the day (relative to the duration of time of each daylight category; $\chi^2_3$ = 20.670, p <0.001); but no change in the relative number of detections based on moon phase ($\chi^2_3$ = 1.730, p = 0.630; **Figure B4**).

### DEPTH USE

The depth use of Bowfin also appears to be seasonally cyclical (**Figure B5**) in which Bowfin were shallowest in summer (seasonal modelled mean ± SE = 1.8 ± 0.6 m) and spring (1.9 ± 0.7 m), followed by fall (3.7 ± 0.6 m), and lastly winter (6.3 ± 0.6 m; $X_3$ = 566.69, p < 0.001). Monthly, there was increased depth use from November until February (mean ± SD depth ranged from 5.2 ± 2.5 m to 7.8 ± 3.0 m) and shallower depth use from May until August (mean ± SD depth ranged from 0.4 ± 0.9 m to 0.8 ± 0.9 m; **Figure B6**). The greatest depth use was in late winter (April) in the central basin (max = 20.0 m).

### RESIDENCY

Spatially, Bowfin had increased residency at Grindstone Creek, at the mouth of Cootes Paradise Marsh and in the Ottawa St. Slip in the spring (**Figure B7**). This affinity for Grindstone Creek still occurred in summer but also with more movement along the north shore (**Figure B7**). In fall, Bowfin had greater residency use in both the west end, including Piers 5-7, and to a lesser extent along the north shore towards the east end

(**Figure B7**). By winter, residency was greatest in the west end in slightly deeper waters near Piers 5-7 and towards the northern shore (**Figure B7**), as the Bowfin were also residing at deeper depths (5-8 m; **Figure B6**).

### SPAWNING

May 1 to June 30 was estimated to be the spawning window for Bowfin (**Table 2**), during which time Bowfin were in very shallow depths (mean monthly depths were < 0.6 m) (**Figure B6**). As such, the shallow waters used in the spring and summer may be attributed to when bowfin were spawning. Based on the residency index, during the spawning window, Bowfin appear to primarily be in Grindstone Creek, especially the upstream ponds (**Figure B8**). However, Bowfin were also seen entering Cootes Paradise, and spending some time in the Ottawa St. Slip (**Figure B8**). The Cootes Paradise Fishway also captures lots of Bowfin at this time of year (J. Bowman, pers. comm.), suggesting that Bowfin are entering Cootes Paradise Marsh for spawning but it is unknown where they are going within the marsh after this point. However, one Bowfin in April 2020 was detected at the western end of Cootes Paradise Marsh where it could later have potentially spawned. Habitat-associated residency of Bowfin during the spawning window was greater in areas of dense and sparse SAV in shallow waters and to a lesser extent lotic areas with no SAV and shallow (**Figure B9**) indicating that Bowfin generally seem to go to shallow, vegetated areas for spawning but will also move into river environments (e.g., Grindstone Creek) to find these areas.

**Table B1.** Tagging and detection summary of acoustically tagged Bowfin (*Amia calva*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, or AD = Alive and later died, based on the detection/depth profiles.

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 53 | 564 | - | 10/26/2015 | West End | V13P-1L | TRUE | A | 4/30/2016 | 9/25/2017 | 513 | 31110 | 257 |
| 14189 | 608 | 2620 | 10/10/2018 | East End | V13P-1L | TRUE | A | 10/11/2018 | 4/21/2020 | 558 | 102101 | 511 |
| 14192 | 488 | 1180 | 10/9/2018 | North Shore | V13P-1L | TRUE | A | 10/10/2018 | 4/6/2020 | 544 | 41515 | 388 |
| 14193 | 555 | 1720 | 10/9/2018 | North Shore | V13P-1L | TRUE | A | 10/11/2018 | 4/24/2020 | 561 | 57385 | 392 |

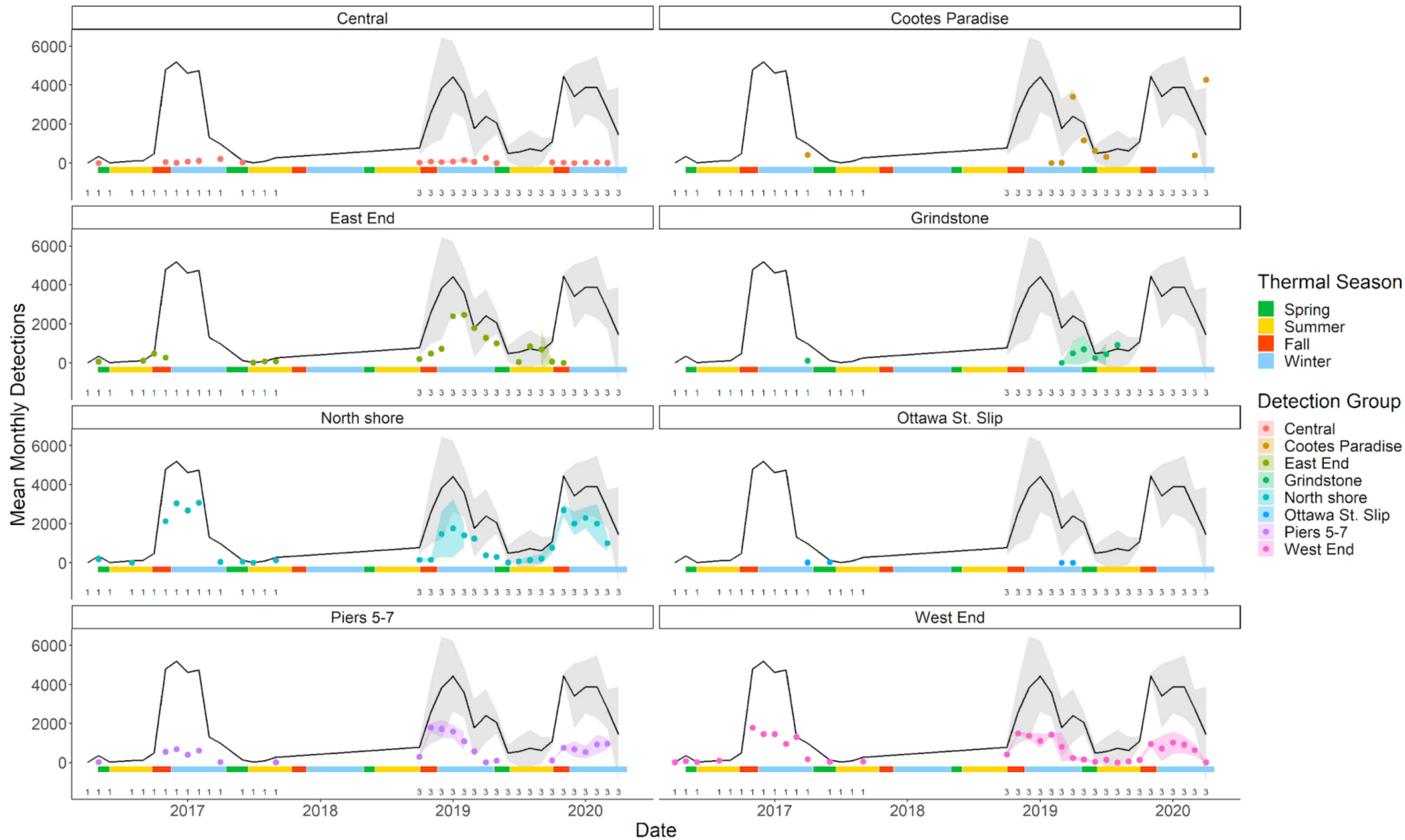


**Figure B1.** Mean (± SD) monthly detections of acoustically tagged Bowfin at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Bowfin at that time.

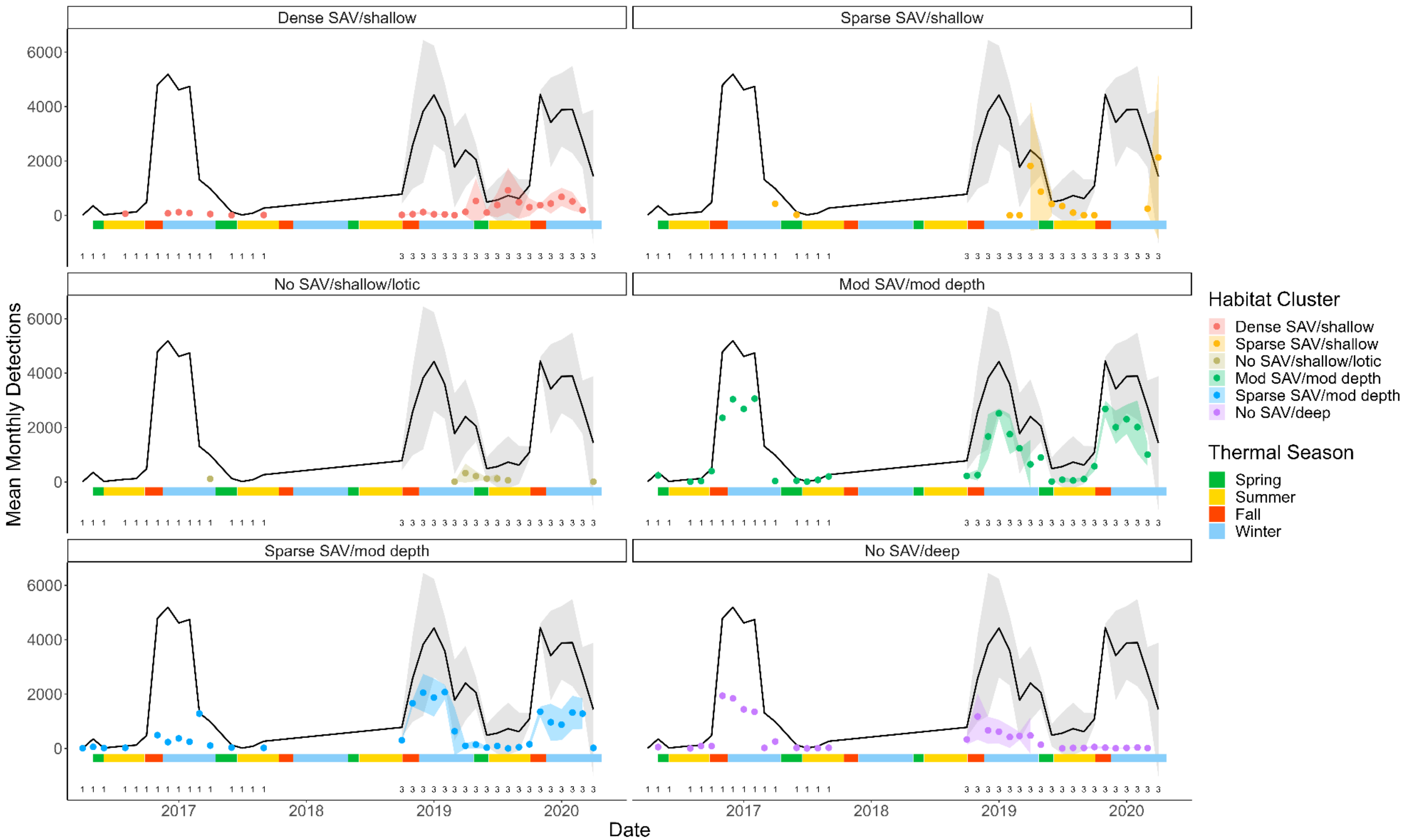


**Figure B2**. Mean (± SD) monthly detections of acoustically tagged Bowfin at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Bowfin.

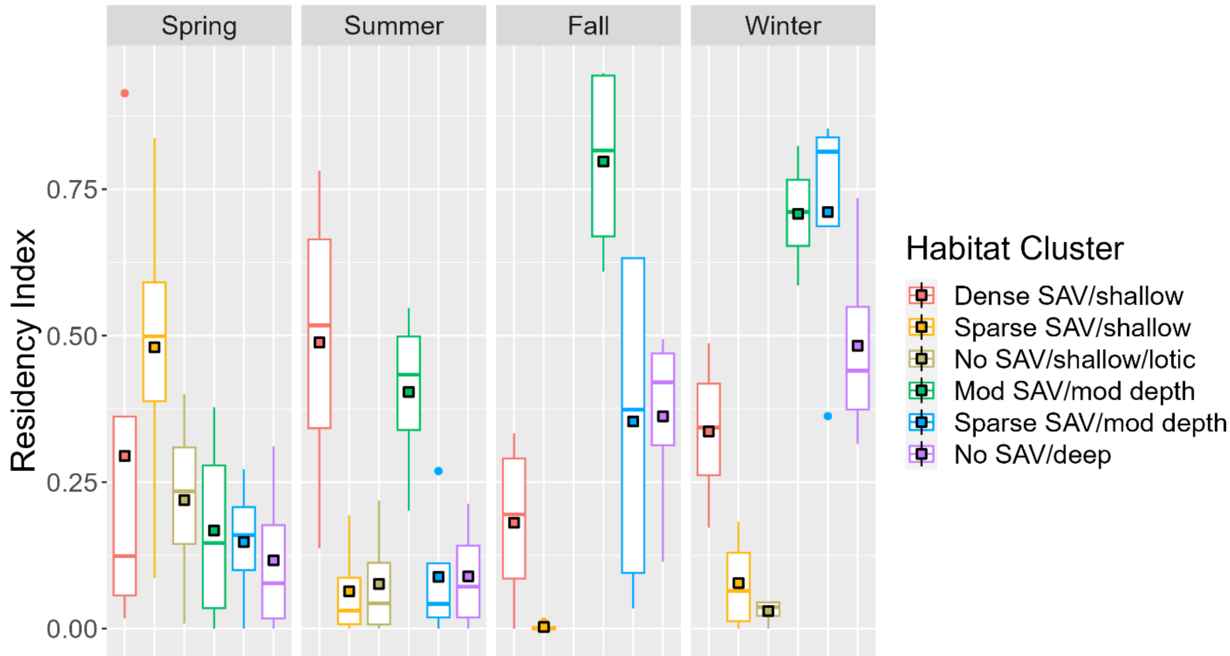


**Figure B3.** Boxplot of individual tagged Bowfin residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

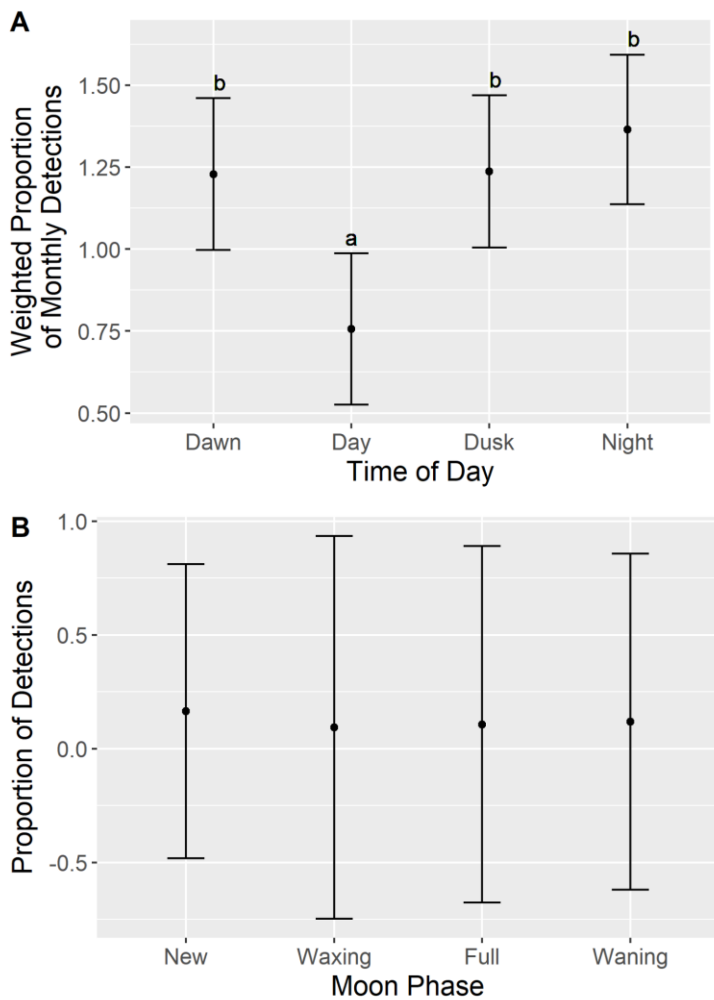


**Figure B4**. A) Mean (± SE) proportion of monthly detections of Bowfin at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Bowfin detections occurring at different moon phases within Hamilton Harbour, 2016 – 2020.

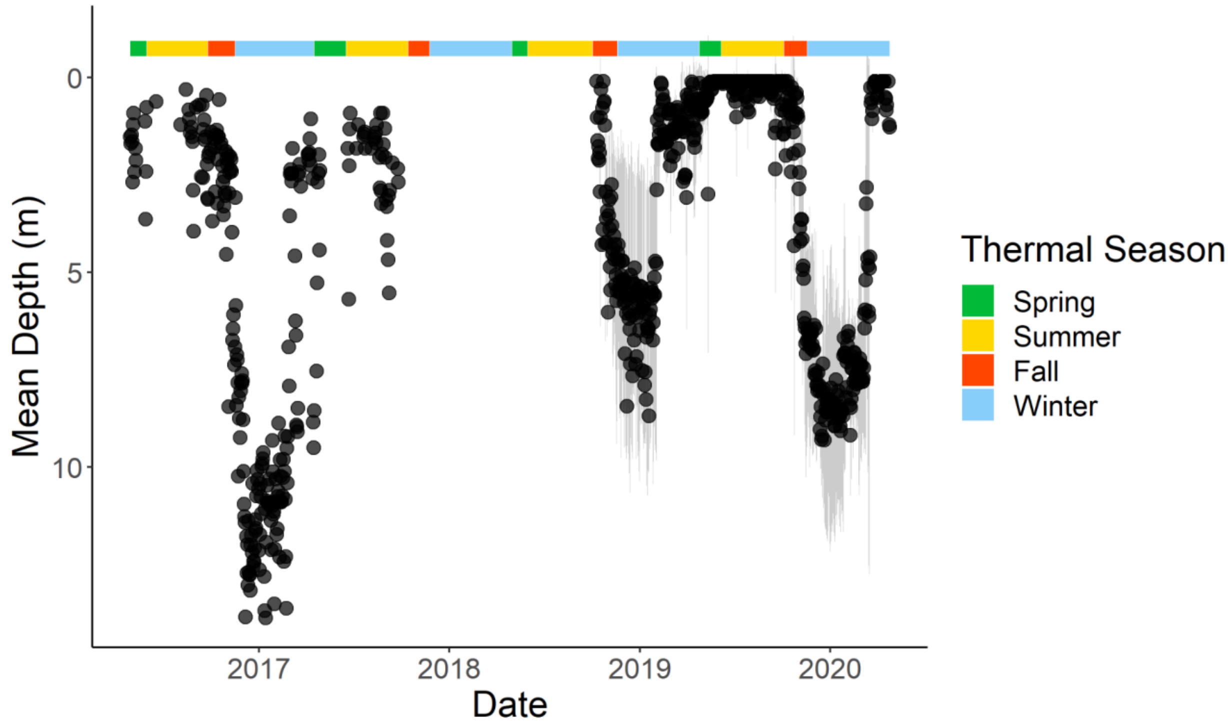


**Figure B5**. Mean (± SD) daily depth use of acoustically tagged Bowfin in Hamilton Harbour over time. The coloured bar indicates the season over time. There are no error bars for 2017 because there was only one individual tagged at that time.

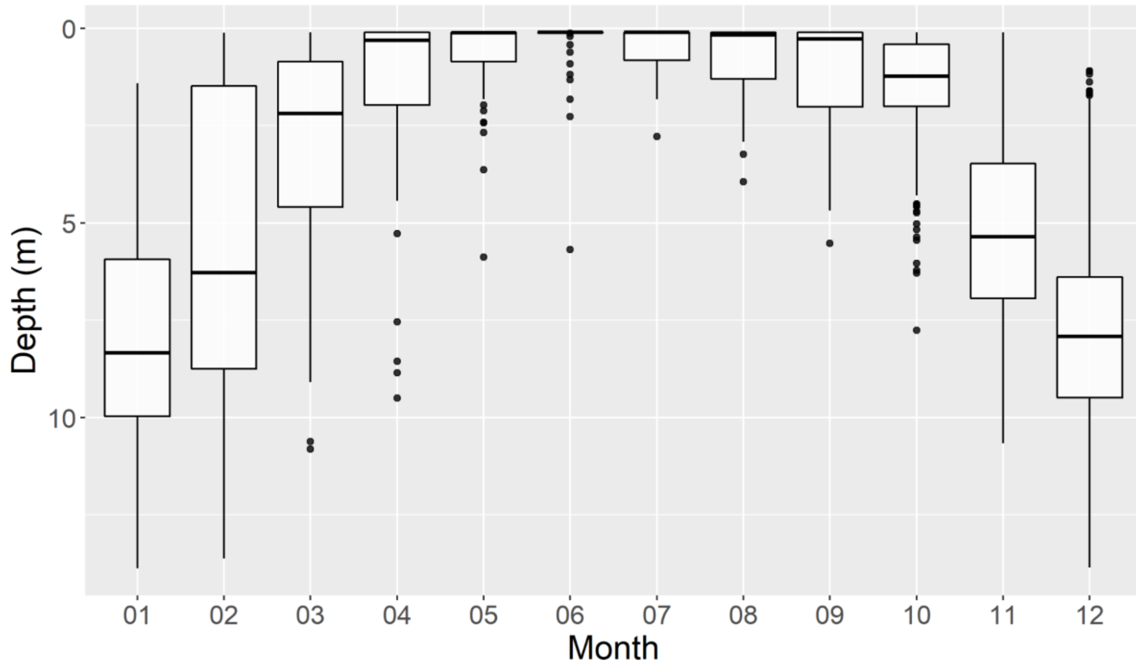


**Figure B6.** Boxplot of monthly depth use based on mean daily depths of acoustically tagged Bowfin in Hamilton Harbour, 2016 – 2020.

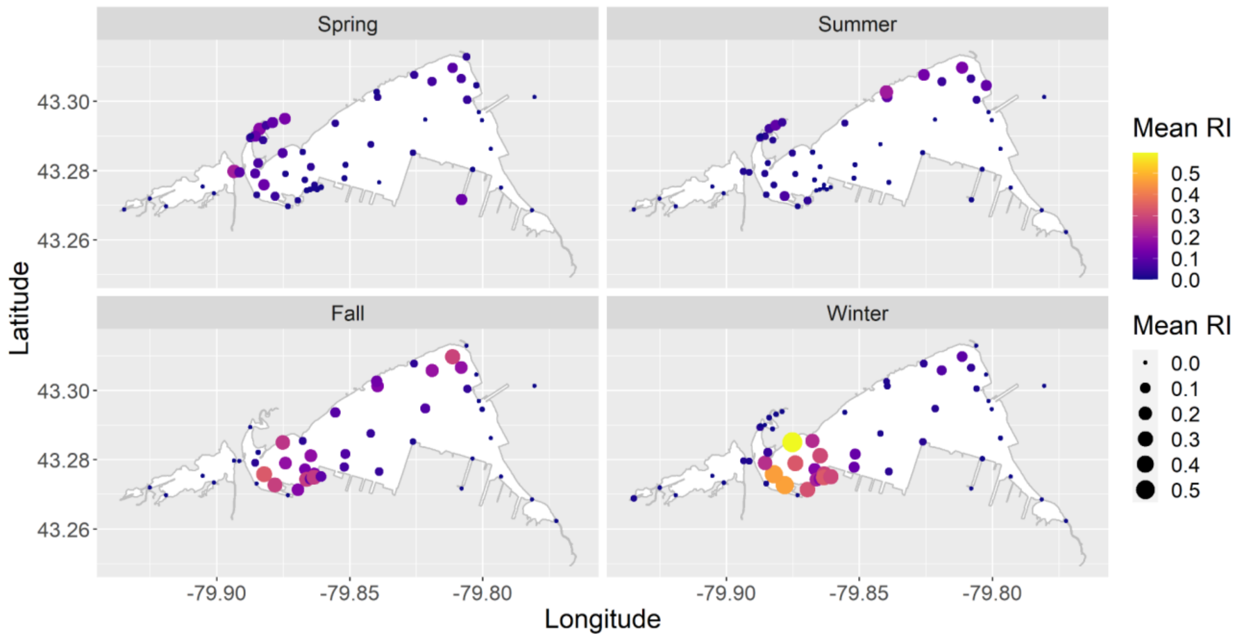


**Figure B7.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Bowfin (N = 4). Size increases and colours are brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

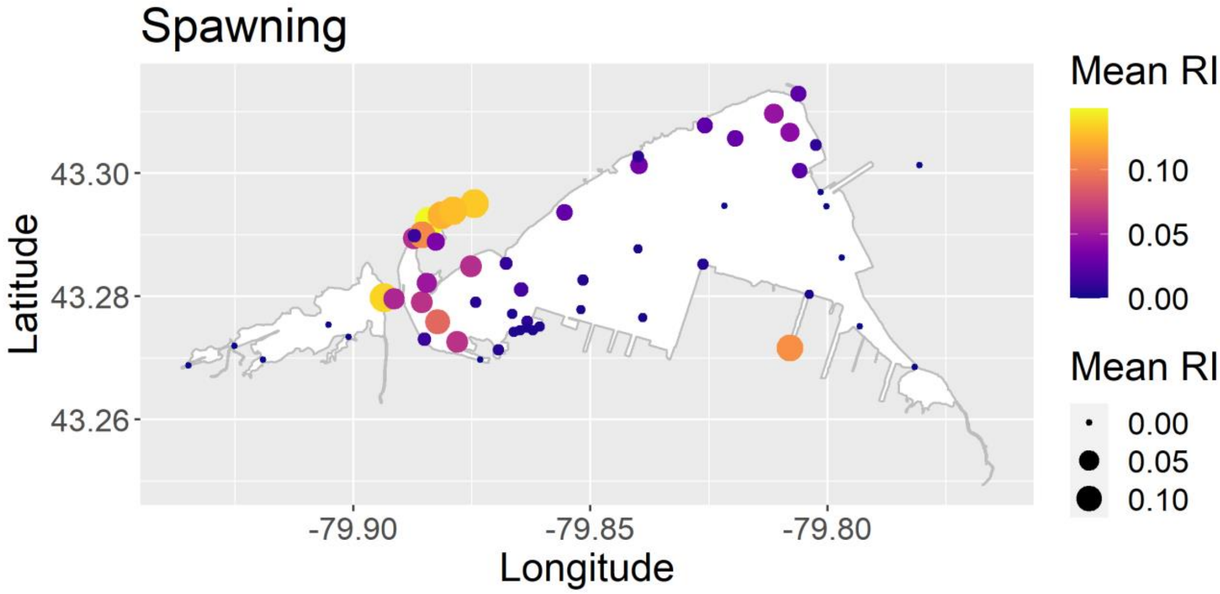


**Figure B8.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Bowfin (N = 4) during their spawning season (May 1 to June 30). Size increases and colours are brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

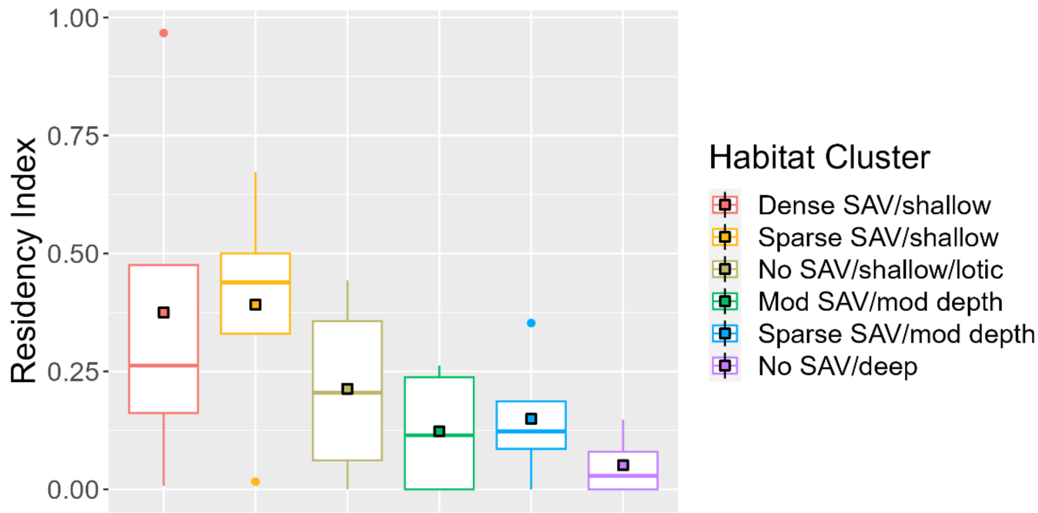


**Figure B9**. Boxplot of individual tagged Bowfin residency during the spawning window (May 1 to June 30) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX C: COMMON CARP

## DETECTIONS AND HABITAT USE

Twenty-seven Common Carp (*Cyprinus carpio*) were acoustically tagged and monitored in Hamilton Harbour from October 2017 to April 2020 (**Table C1**). Based on mean monthly detections, there appears to be no seasonal distinction in the number of detections with a general affinity towards the West End with the odd foray towards the East End and North shore in winter (**Figure C1**). Although the fishway at the entrance to Cootes Paradise Marsh should exclude any Common Carp from entering, some tagged carp found their way into Cootes Paradise Marsh (**Figure C1**). Further investigation revealed seven Common Carp detected across four locations of Cootes Paradise Marsh (all sites excluding the entrance to Spencer Creek - Station 30; this did not include fish detected at the fishway - Station 32 and 43). Common Carp were detected at all times of the year but primarily were entering or leaving Cootes Paradise Marsh in October or during the summer. One Common Carp left Hamilton Harbour five days after tagging and was later detected at the mouth of the Niagara River and in Toronto Harbour, but never returned to Hamilton Harbour; otherwise all other carp remained in the harbour for the duration of the study (**Figure C2 and C3**).

Based on the habitat clusters, Common Carp were primarily detected in areas of sparse SAV at moderate depths year-round, however, in the fall there was an increase in mean monthly detections in areas with no SAV at deep depths and in the spring and early summer there was an increase of detections in areas of sparse SAV in shallow waters (**Figure C4**). Habitat trends were fairly similar when assessed based on seasonal residency by habitat clusters (**Figure C5**). Seasonal residency more clearly showed that Common Carp were located in sparse SAV at moderate depths year-round, particularly in fall and winter. However, Common Carp were also using lotic areas in the spring, potentially to reach the sparse SAV and shallow areas, such as those located adjacent to Grindstone Creek that fish were highly resident to in both spring and summer. With only associated wetlands of Grindstone Creek being deployed in 2019, it could have reduced the residency within these areas by combining years for each seasonal residency. Deeper waters were used in fall, with sparse SAV at moderate depths and no SAV deep waters with the highest habitat-associated residency in Common Carp.

There was an increase in detections during dawn and night, followed by dusk, and lastly daytime had the fewest detections (relative to the duration of time of each daylight category; $\chi^2_3 = 242.690$, $p < 0.001$); there was no change in the relative number of detections based on moon phase ($\chi^2_3 = 3.604$, $p = 0.308$; **Figure C6**).

## DEPTH USE

The depth use of Common Carp appears to be seasonally cyclical (**Figure C7**) with shallowest depths during the spring (seasonal modelled mean ± SE = 1.0 ± 0.5 m), followed by summer (1.8 ± 0.5 m), then winter (3.2 ± 0.5 m) and lastly fall (6.0 ± 0.5 m; $X^2_3 = 2516.4$, $p < 0.001$). From a monthly perspective, Common Carp had increased depth use from October until February (mean ± SD depth ranged from 4.1 ± 1.8 m to 6.3 ± 5.5 m) and shallower depth use from April until August (mean ± SD depth ranged from 1.2 ± 0.9 m to 1.9 ± 1.6 m; **Figure C8**). The greatest depth use was during November in the central basin (max = 24.6 m).

**RESIDENCY**

Spatially, Common Carp had increased residency at the mouth of Grindstone Creek, at the mouth of Cootes Paradise Marsh and west end in the spring (**Figure C9**). This affinity for the mouth of Cootes Paradise Marsh and west end still occurred in summer but also with more movement throughout the harbour (**Figure C9**). In fall, Common Carp had greater residency use in both the west end and towards the north shore and central basin, as well as the Ottawa St. Slip (**Figure C9**), when Common Carp moved to their deepest mean monthly depths (~6 m; **Figure C8**). By winter, residency was greatest in the west end in slightly deeper waters and towards Piers 5-7 and surrounding area (**Figure C9**), as Common Carp were still residing at deeper depths (4-6 m; **Figure C8**).

**SPAWNING**

May 1 to July 31 was the spawning window used for Common Carp (**Table 2**), during which Common Carp were at their shallowest depths (mean monthly depths were ~1.2 m) (**Figure C8**).

The shallow waters used in the spring and summer may be attributed to when Common Carp were spawning. Based on the residency index, during the spawning window, Common Carp appear to be primarily at the mouth of Cootes Paradise Marsh (the fishway) and in the west end, with lesser affinity towards Piers 5-7 and the mouth of Grindstone Creek (**Figure C10**). The fishway is supposed to prevent Common Carp from entering Cootes Paradise, and based on the residency it appears many tagged fish were attempting to enter Cootes Paradise Marsh during the spawning window (of which a few were successful). Habitat-associated residency of Common Carp during the spawning window was greater in areas of sparse SAV in shallow waters and to a lesser extent sparse SAV at moderate depths (**Figure C11**) indicating that Common Carp generally seem to go to semi-vegetated areas, typically at shallow depths for spawning. Note that Common Carp spawning habitat may be skewed due to restricted access into Cootes Paradise Marsh by the fishway.

**Table C1.** Tagging and detection summary of acoustically tagged Common Carp (*Cyprinus carpio*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, or AD = Alive and later died, based on the detection/depth profiles. Dash indicates no data recorded.

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14515 | 445 | 1330 | 5/24/2018 | HH45 | V13P-1L | TRUE | AD | 5/25/2018 | 6/28/2018 | 34 | 4818 | 35 |
| 14522 | 685 | 5630 | 5/24/2018 | HH43B | V13P-1L | TRUE | A | 5/25/2018 | 4/25/2020 | 701 | 141868 | 651 |
| 14511 | 650 | 4810 | 5/24/2018 | HH44 | V13P-1L | TRUE | A | 5/25/2018 | 4/25/2020 | 701 | 200288 | 632 |
| 14518 | 558 | 3560 | 10/9/2018 | Lasalle | V13P-1L | TRUE | A | 10/10/2018 | 5/28/2019 | 230 | 42670 | 216 |
| 14520 | 684 | 4450 | 5/24/2018 | HH42B | V13P-1L | TRUE | A | 5/24/2018 | 4/25/2020 | 702 | 192249 | 689 |
| 14521 | 660 | 4280 | 5/24/2018 | HH43B | V13P-1L | TRUE | A | 5/25/2018 | 4/24/2020 | 700 | 83221 | 566 |
| 14525 | - | 5200 | 5/23/2018 | HH36 | V13P-1L | TRUE | A | 5/24/2018 | 4/18/2020 | 695 | 88047 | 638 |
| 14526 | 617 | 3580 | 5/24/2018 | HH42B | V13P-1L | TRUE | A | 5/24/2018 | 7/25/2019 | 427 | 69048 | 420 |
| 14797 | 623 | 4780 | 10/9/2018 | Lasalle | V13P-1L | TRUE | A | 10/10/2018 | 12/12/2018 | 63 | 12575 | 63 |
| 14808 | 625 | 4360 | 5/24/2018 | HH42B | V13P-1L | TRUE | A | 5/24/2018 | 4/25/2020 | 702 | 160742 | 665 |
| 15835 | 590 | 3400 | 10/20/2017 | Bayfront launch | V13P-1L | TRUE | A | 10/20/2017 | 4/19/2020 | 912 | 128314 | 800 |
| 15839 | 678 | 5505 | 10/5/2017 | Bayfront east shore | V13P-1L | TRUE | A | 10/5/2017 | 4/25/2020 | 933 | 182183 | 892 |
| 15840 | 663 | 5360 | 10/5/2017 | Bayfront east shore | V13P-1L | TRUE | A | 10/6/2017 | 4/21/2020 | 928 | 121177 | 847 |
| 15841 | 727 | 7694 | 10/5/2017 | Bayfront east shore | V13P-1L | TRUE | A | 10/5/2017 | 4/25/2020 | 933 | 77750 | 753 |
| 15847 | 453 | 1500 | 10/5/2017 | Ottawa Slip | V13P-1L | TRUE | A | 10/5/2017 | 8/21/2019 | 685 | 22002 | 232 |
| 15852 | 510 | 2170 | 10/5/2017 | Ottawa Slip | V13P-1L | TRUE | A | 10/5/2017 | 3/28/2020 | 905 | 53444 | 676 |
| 25129 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/19/2018 | 1/19/2020 | 487 | 17857 | 373 |
| 25130 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/19/2018 | 6/9/2019 | 263 | 52705 | 262 |
| 25131 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/19/2018 | 12/28/2019 | 465 | 24337 | 382 |
| 25132 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 4/11/2020 | 562 | 43267 | 456 |
| 25133 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 11/28/2019 | 427 | 18567 | 314 |
| 25134 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 4/20/2020 | 571 | 77147 | 554 |
| 25135 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 5/29/2019 | 244 | 32602 | 233 |

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 25136 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 6/5/2019 | 251 | 27971 | 142 |
| 25137 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 11/20/2019 | 419 | 89047 | 411 |
| 25141 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 7/18/2019 | 294 | 20468 | 200 |
| 25142 | - | - | 9/19/2018 | Unknown | V13 | FALSE | A | 9/27/2018 | 4/16/2020 | 567 | 6907 | 266 |

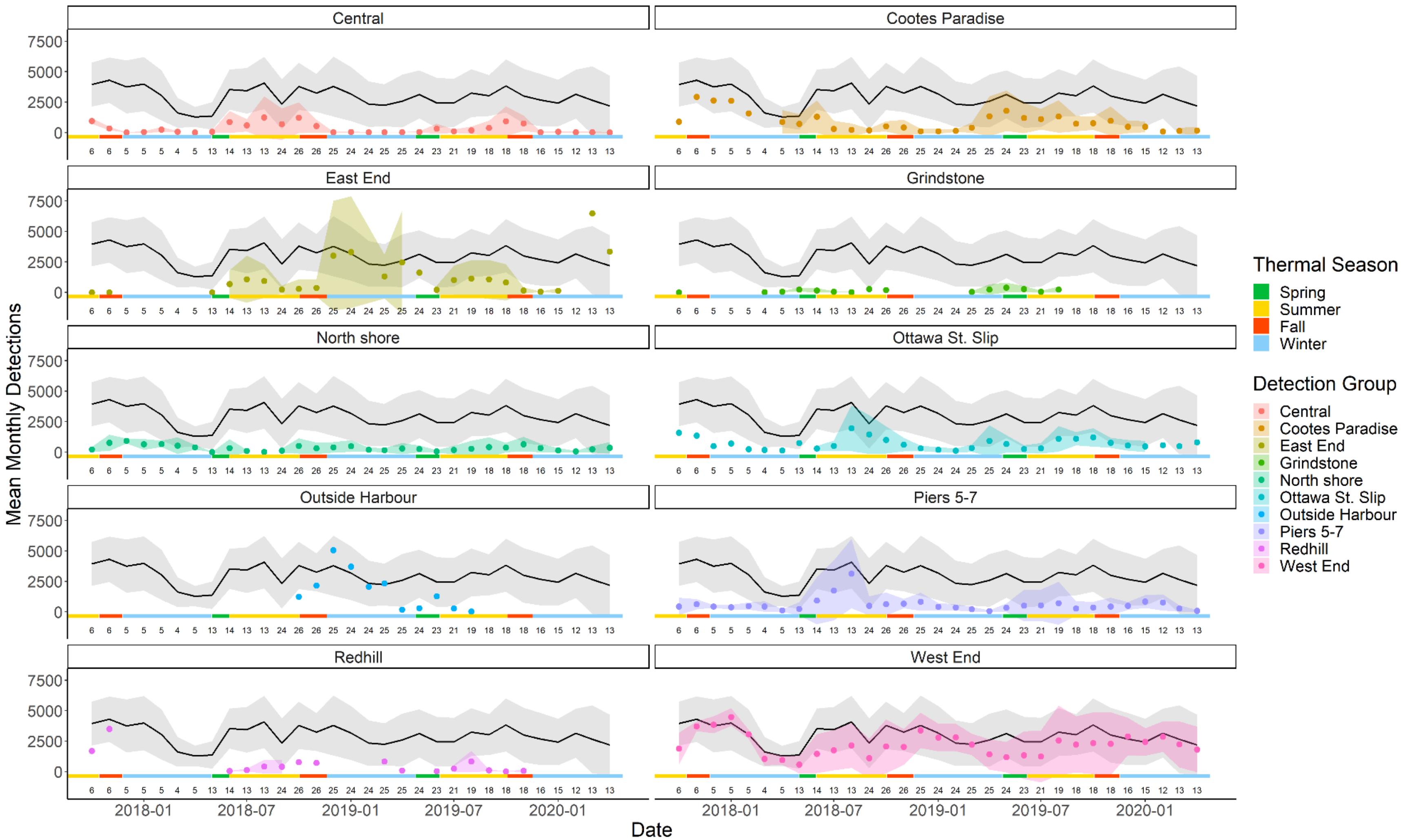


**Figure C1.** Mean (± SD) monthly detections of acoustically tagged Common Carp at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Common Carp at that time.

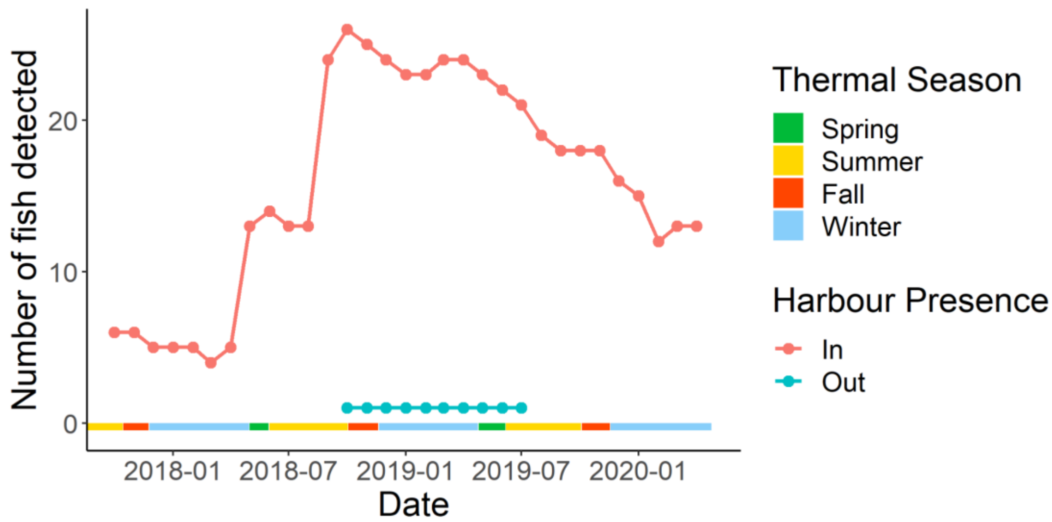


**Figure C2.** Monthly total of acoustically tagged Common Carp detected in or out of Hamilton Harbour over time. The coloured bar indicates the season over time.

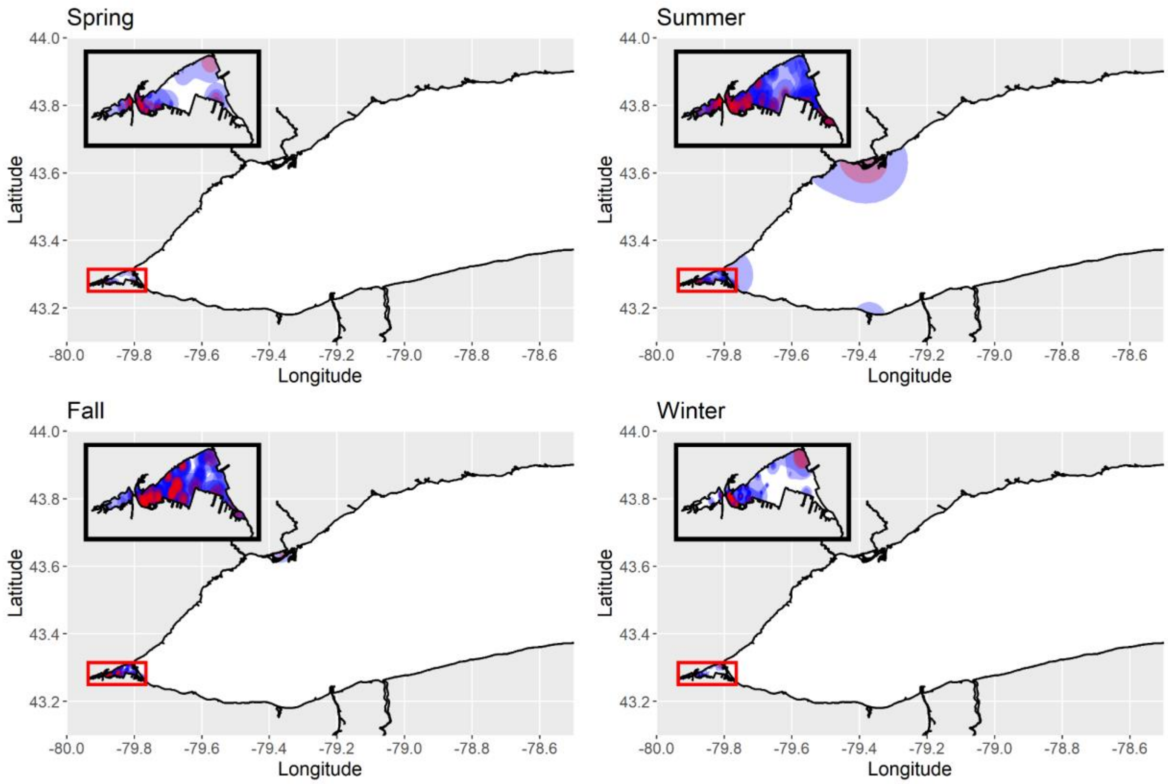


**Figure C3**. Seasonal 50% (red) and 95% (blue) home ranges (via kernel utilization distribution) of individual Common Carp tagged in Hamilton Harbour, 2016 – 2020. Darker colours indicate overlapping home ranges of individuals. One Common Carp left the harbour and its lake-wide home range can be seen in Summer and Fall.

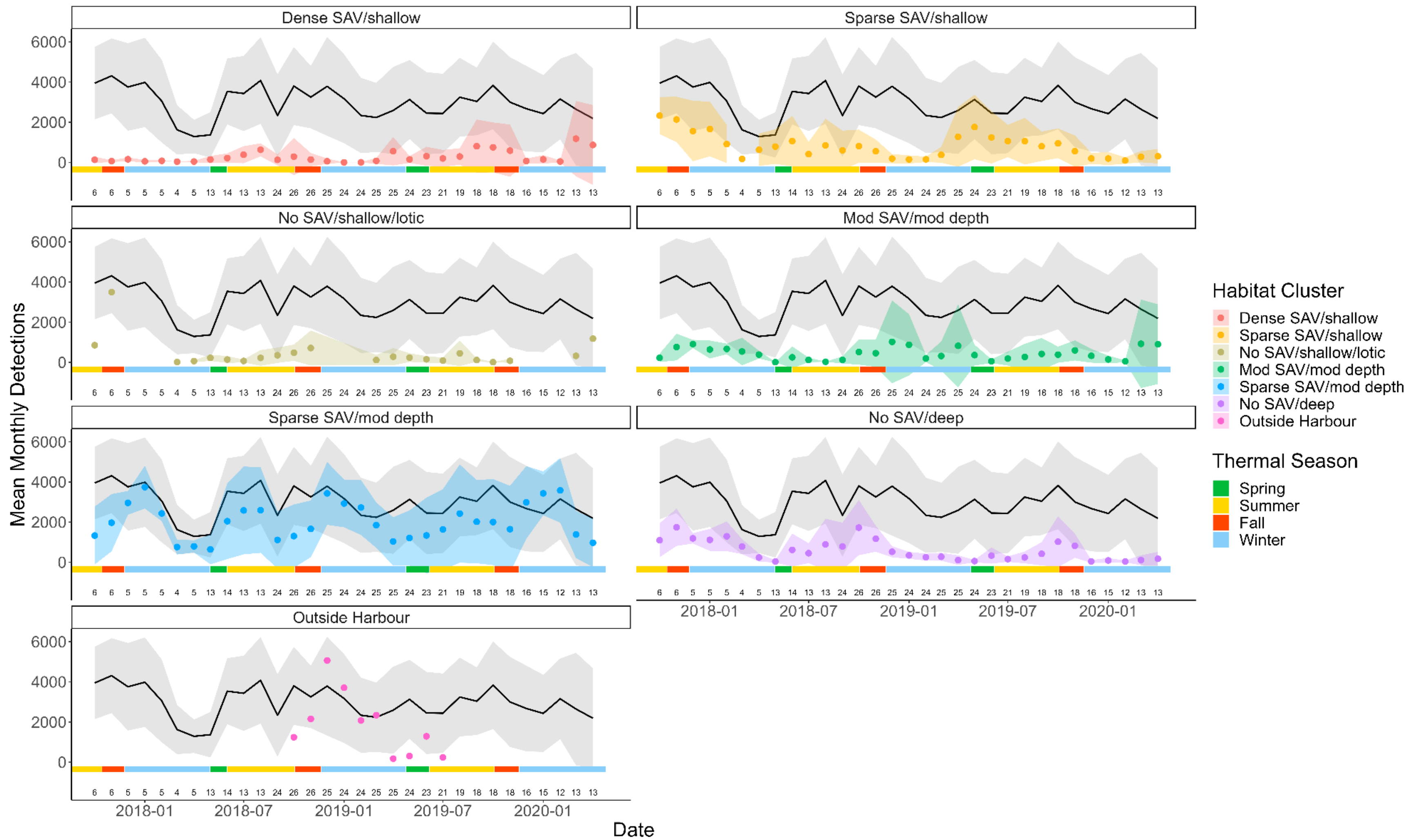


**Figure C4**. Mean (± SD) monthly detections of acoustically tagged Common Carp at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Common Carp.

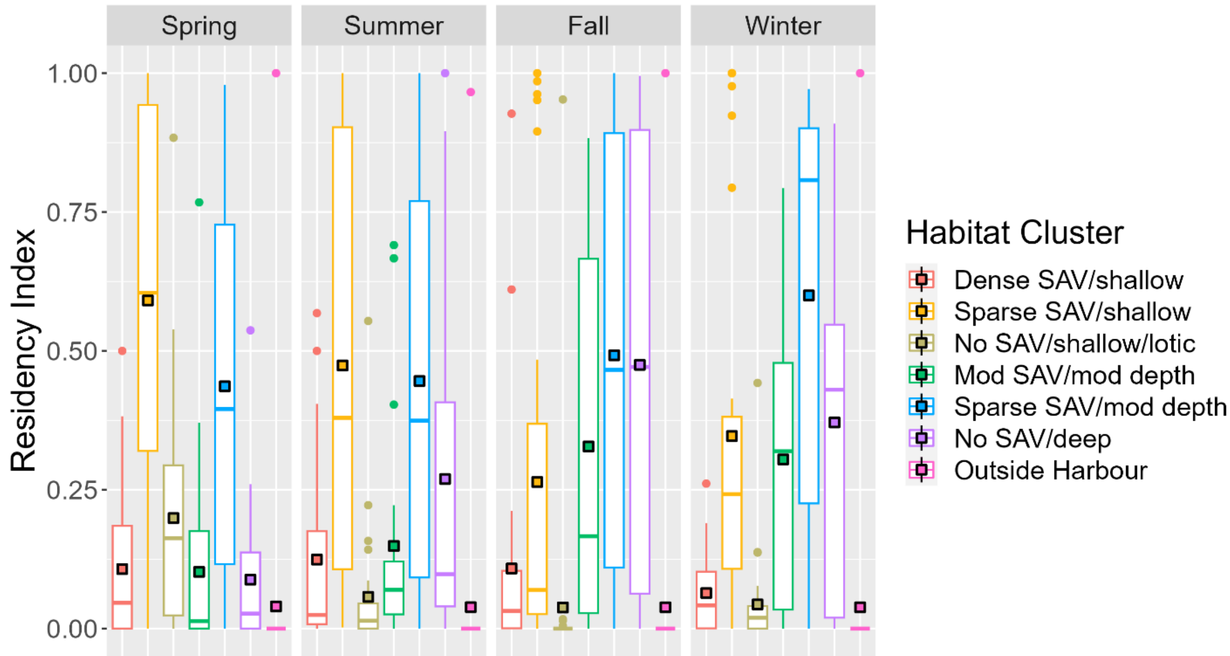


**Figure C5.** Boxplot of individual tagged Common Carp residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

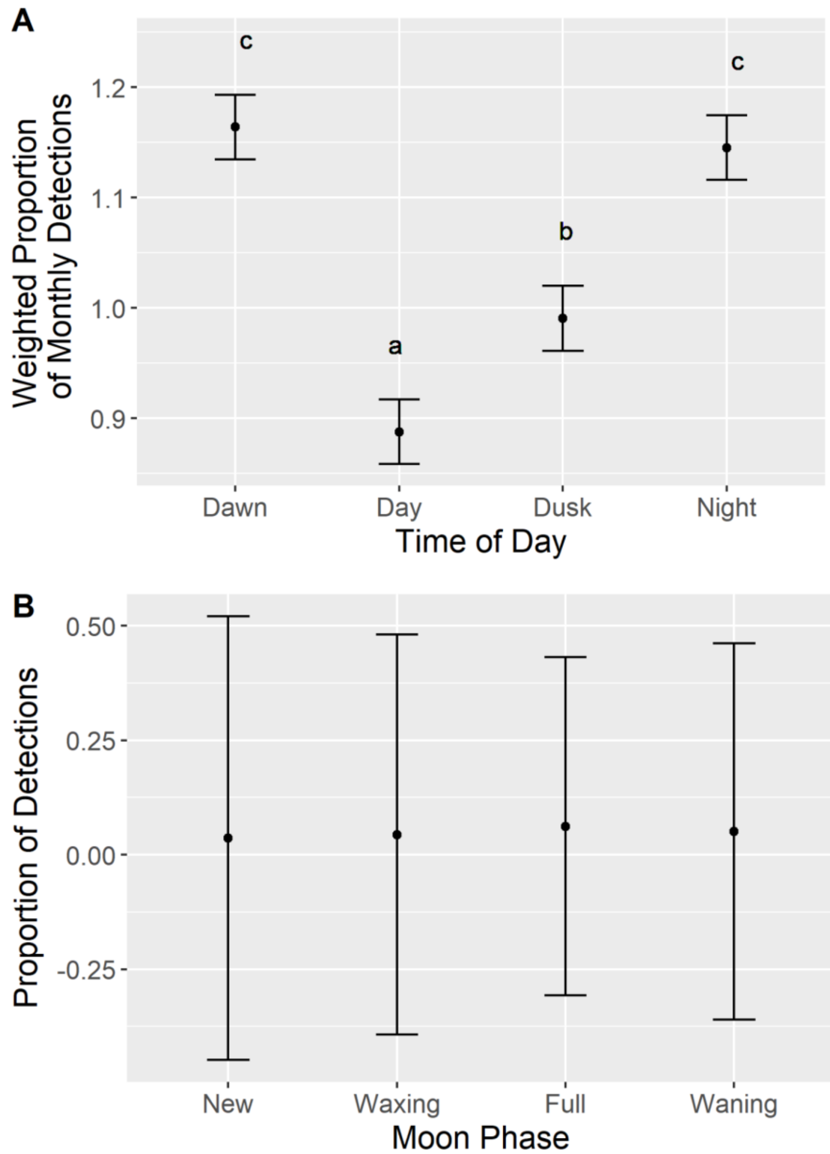


**Figure C6**. A) Mean (± SE) proportion of monthly detections of Common Carp at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Common Carp detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

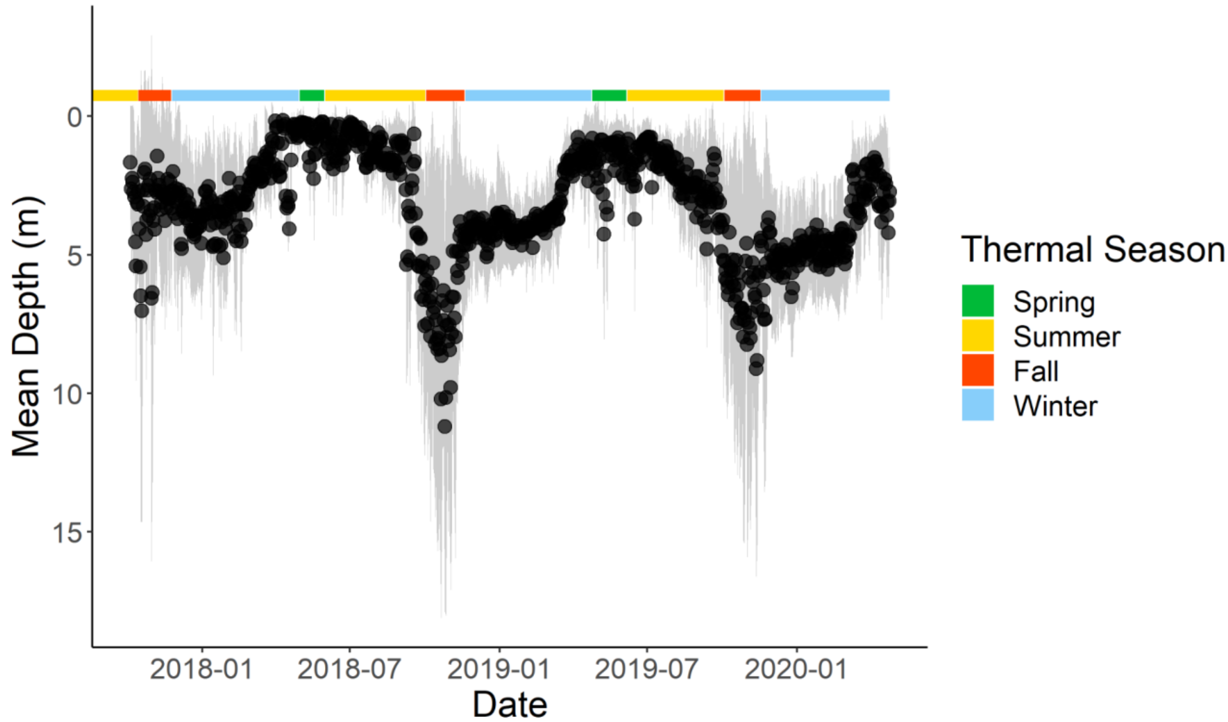


**Figure C7**. Mean (± SD) daily depth use of acoustically tagged Common Carp in Hamilton Harbour over time. The coloured bar indicates the season over time.

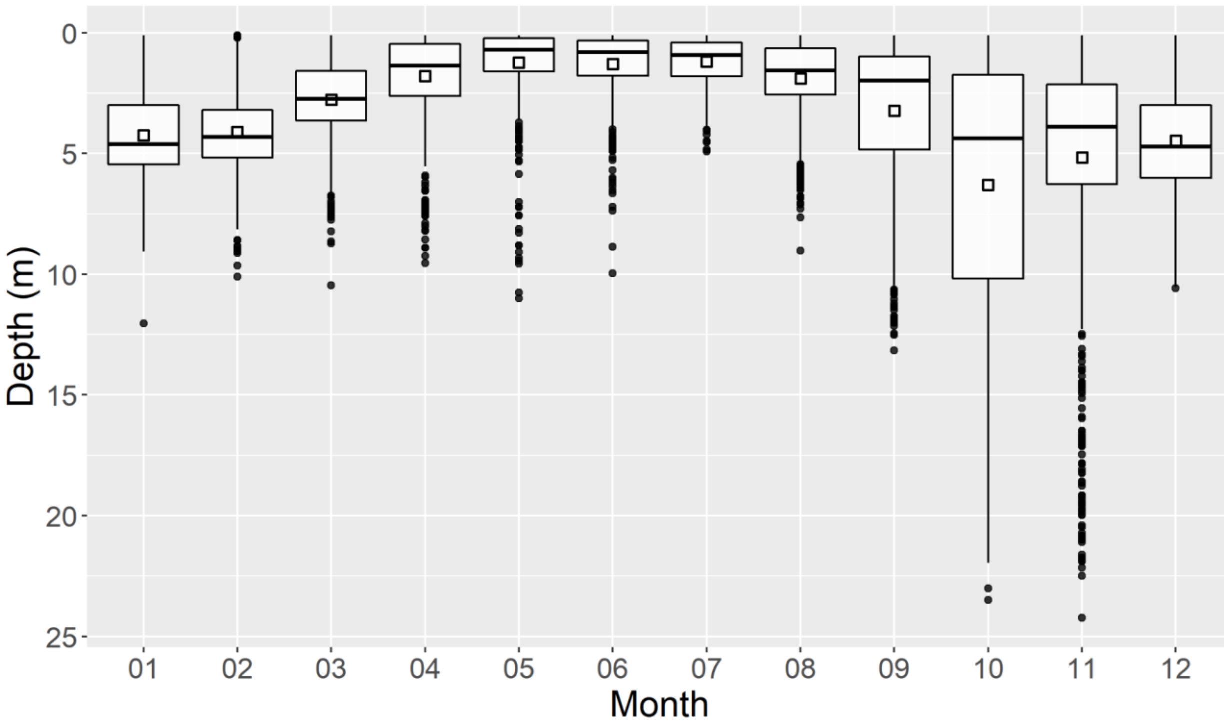


**Figure C8.** Boxplot of monthly depth use based on mean daily depths of acoustically tagged Common Carp in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

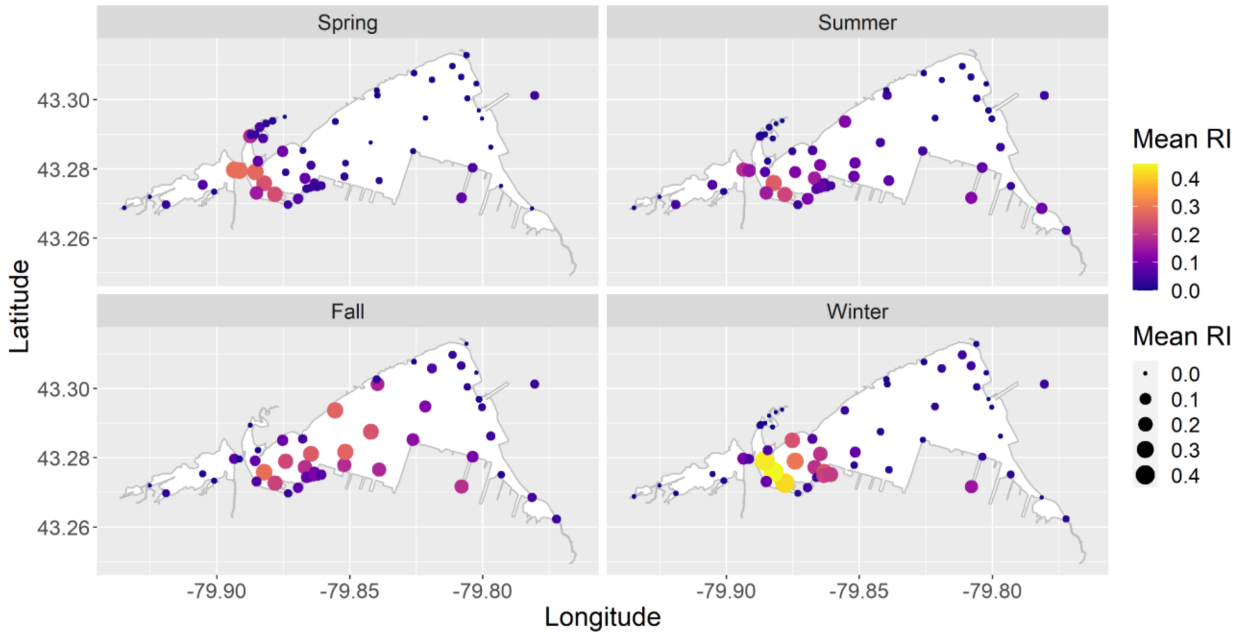


**Figure C9.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Common Carp (N = 27). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

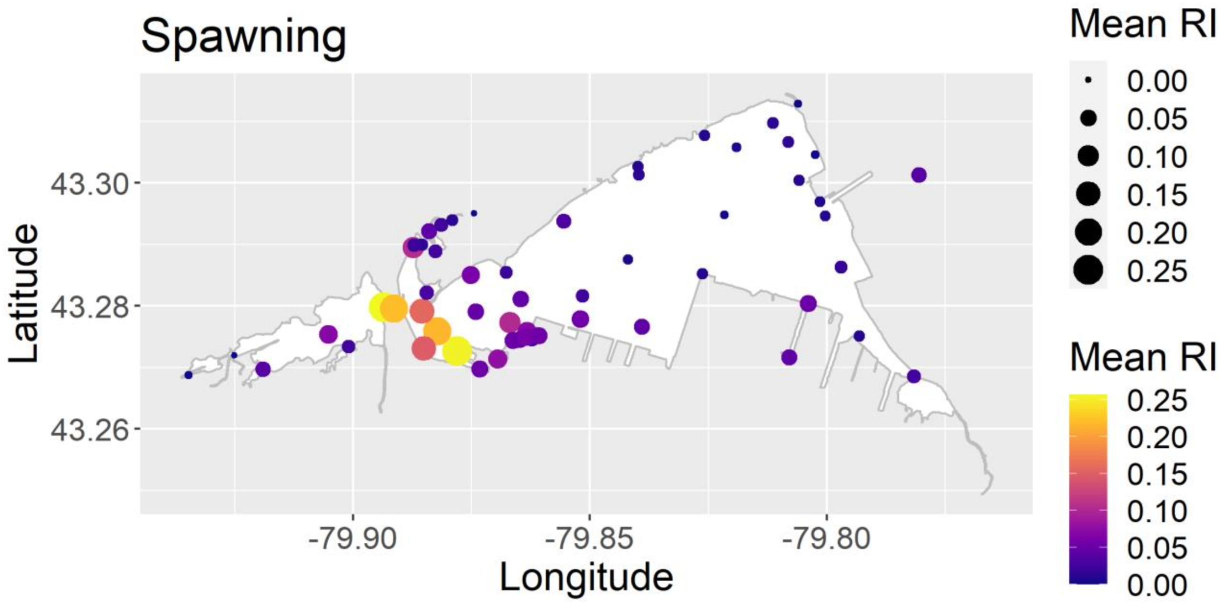


**Figure C10.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Common Carp (N = 27) during their spawning window (May 1 to July 31). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

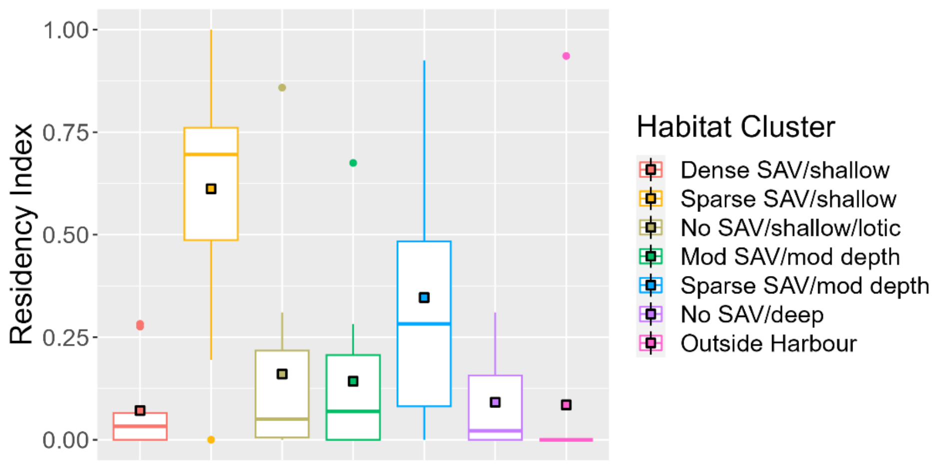


**Figure C11**. Boxplot of individual tagged Common Carp residency during the spawning window (May 1 to July 31) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX D: FRESHWATER DRUM

## DETECTIONS AND HABITAT USE

Thirteen Freshwater Drum (*Aplodinotus grunniens*) were acoustically tagged and monitored in Hamilton Harbour from July 2016 to April 2020 (**Table D1**). Based on mean monthly detections, there appeared to be overall detections in the winter and fewer in the summer, with a general affinity towards the west end with some time spent at the north shore and Piers 5-7 in the winter and near Cootes Paradise Marsh in the spring (**Figure D1**). Although Freshwater Drum were detected at Cootes Paradise Marsh receivers it was only at the receivers at the entrance to Cootes Paradise Marsh near the fishway and no Freshwater Drum were detected in Cootes Paradise. It appears that Freshwater Drum generally leave Hamilton Harbour in the summer and return to the harbour in the fall and winter (**Figure D2**), and at some point all Freshwater Drum were detected outside of Hamilton Harbour. However, the duration and extent of movements into Lake Ontario varied by individuals.

Based on the habitat clusters, Freshwater Drum were primarily detected in areas of no SAV and deep depths and either sparse or moderate SAV at moderate depths in the fall and winter (**Figure D3**). In the spring, there was an increase of detections in areas of sparse SAV in shallow waters, while in the summer detections were primarily in areas of sparse SAV in shallow waters or at moderate depths (**Figure D3**). Habitat trends were slightly different when assessed based on seasonal residency by habitat clusters (**Figure D4**). Seasonal residency indicated that Freshwater Drum were located in areas of sparse SAV in shallow waters or at moderate depths in the spring, and in areas of no SAV and deep depths or outside of the harbour in summer and fall (**Figure D4**). In winter, Freshwater Drum had highest residency in areas with sparse SAV at moderate depths, followed by no SAV at deep depths and moderate SAV at moderate depths. Freshwater Drum did not use lotic areas in the harbour.

The number of detections were similar at different times of day (relative to the duration of time of each daylight category; $\chi^2_3 = 4.972$, $p = 0.174$), and there was no change in the relative number of detections based on moon phase ($\chi^2_3 = 1.594$, $p = 0.661$; **Figure D5**).

## DEPTH USE

The depth use of Freshwater Drum appears to be seasonally cyclical (**Figure D6**) with shallowest depths during the spring (seasonal modelled mean ± SE = 2.2 ± 0.5 m), followed by summer (2.8 ± 0.5 m), and deepest depths in the fall (7.0 ± 0.5 m) and winter (6.8 ± 0.5 m; $X^2_3 = 7012.6$, $p < 0.001$). From a monthly perspective, Freshwater Drum had increased depth use from September until March (mean ± SD depth ranged from 6.2 ± 2.2 m to 7.6 ± 2.8 m) and shallower depth use from May until August (mean ± SD depth ranged from 2.0 ± 1.3 m to 2.9 ± 2.1 m; **Figure D7**). The greatest depth use was during the late summer (September) in Lake Ontario (max = 34.1 m). Although, this depth is the maximum depth the tag could detect and Freshwater Drum might be using deeper waters, it is unlikely as 34 m detected depths were quite rare (N = 2 detections) and generally deeper depths were observed between 20 – 30 m.

### RESIDENCY

Spatially, Freshwater Drum had increased residency at the west end in the spring (**Figure D8**). This affinity for the west end still occurred in summer but greater residency was seen outside of the harbour. In the fall, residency was still high outside of the harbour but also with more movement throughout the harbour towards the deeper, central basin (**Figure D8**), at the time when Freshwater Drum moved to deeper depths (~7 m; **Figure D7**). By winter, residency was greatest in the west end in slightly deeper waters and towards Piers 5-7 and surrounding area, as well as outside of the harbour for some fish (**Figure D8**), at which time Freshwater Drum were still residing at deeper depths (~7 m; **Figure D7**). Generally, Hamilton Harbour Freshwater Drum showed long-range dispersal in the summer into Lake Ontario (max of ~180 km to Rochester, NY) and would return to the harbour in the fall or winter, with relatively high fidelity. When Freshwater Drum were outside of Hamilton Harbour, the KUD home ranges were generally along the south shore of Lake Ontario towards the Niagara River for all seasons (**Figure D9**). However, in the summer general home ranges were along the north shore of Lake Ontario towards Toronto, as well as along the south shore beyond Niagara River (**Figure D9**).

### SPAWNING

June 1 to July 31 was the spawning window used for Freshwater Drum (**Table 2**), during which Freshwater Drum were at their shallowest depths (mean monthly depths were ~2.1 m; **Figure D7**). The shallow waters used in the spring and summer may be attributed to when Freshwater Drum were spawning. Based on the residency index, during the spawning window, Freshwater Drum appear to be in the west end and to a lesser extent along the north shore and east end (**Figure D10**). Habitat-associated residency of Freshwater Drum during the spawning window was greater in areas of sparse SAV at moderate depths and to a lesser extent no SAV at deep depths (**Figure D11**) indicating that Freshwater Drum generally seem to go to moderate to deep depths with minimal vegetation for spawning.

**Table D1.** Tagging and detection summary of acoustically tagged Freshwater Drum (*Aplodinotus grunniens*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, or AD = Alive and later died, based on the detection/depth profiles. Dash indicates no data recorded.

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15196 | 499 | 1605 | 7/21/2016 | Bayfront Beach | V13P-1L | TRUE | A | 7/21/2016 | 4/25/2020 | 1374 | 402878 | 1262 |
| 15197 | 570 | 3430 | 7/21/2016 | South Shore Is | V13P-1L | TRUE | A | 7/21/2016 | 4/25/2020 | 1374 | 311587 | 1077 |
| 15216 | 609 | 3010 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 7/23/2018 | 754 | 168479 | 569 |
| 15218 | 637 | 3650 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 7/25/2019 | 1121 | 42153 | 615 |
| 15244 | 510 | 1780 | 7/26/2016 | H26 | V13P-1L | TRUE | A | 7/26/2016 | 4/24/2020 | 1368 | 288602 | 1085 |
| 15247 | 554 | 2070 | 8/10/2016 | Desjardins West | V13P-1L | TRUE | A | 8/10/2016 | 4/25/2020 | 1354 | 354819 | 1226 |
| 15438 | - | - | 6/17/2016 | Bayfront West | V13P-1L | TRUE | A | 6/17/2016 | 4/12/2020 | 1395 | 274089 | 1073 |
| 15439 | - | 2310 | 6/15/2016 | Unknown | V13P-1L | TRUE | A | 6/15/2016 | 7/18/2018 | 763 | 138217 | 543 |
| 15856 | 620 | 4450 | 6/14/2017 | South of Canal | V13P-1L | TRUE | A | 6/15/2017 | 7/6/2018 | 386 | 12002 | 100 |
| 15857 | 593 | 2730 | 6/14/2017 | South of Canal | V13P-1L | TRUE | A | 6/15/2017 | 3/7/2020 | 996 | 32956 | 460 |
| 15867 | 451 | 1430 | 6/27/2017 | Bayfront Marina | V13P-1L | TRUE | A | 6/28/2017 | 4/25/2020 | 1032 | 56345 | 310 |
| 15871 | 512 | 2210 | 6/27/2017 | Bayfront | V13P-1L | TRUE | A | 6/28/2017 | 4/25/2020 | 1032 | 334424 | 749 |
| 15872 | 537 | 2020 | 6/26/2017 | Bayfront | V13P-1L | TRUE | A | 6/27/2017 | 8/20/2019 | 784 | 180566 | 725 |

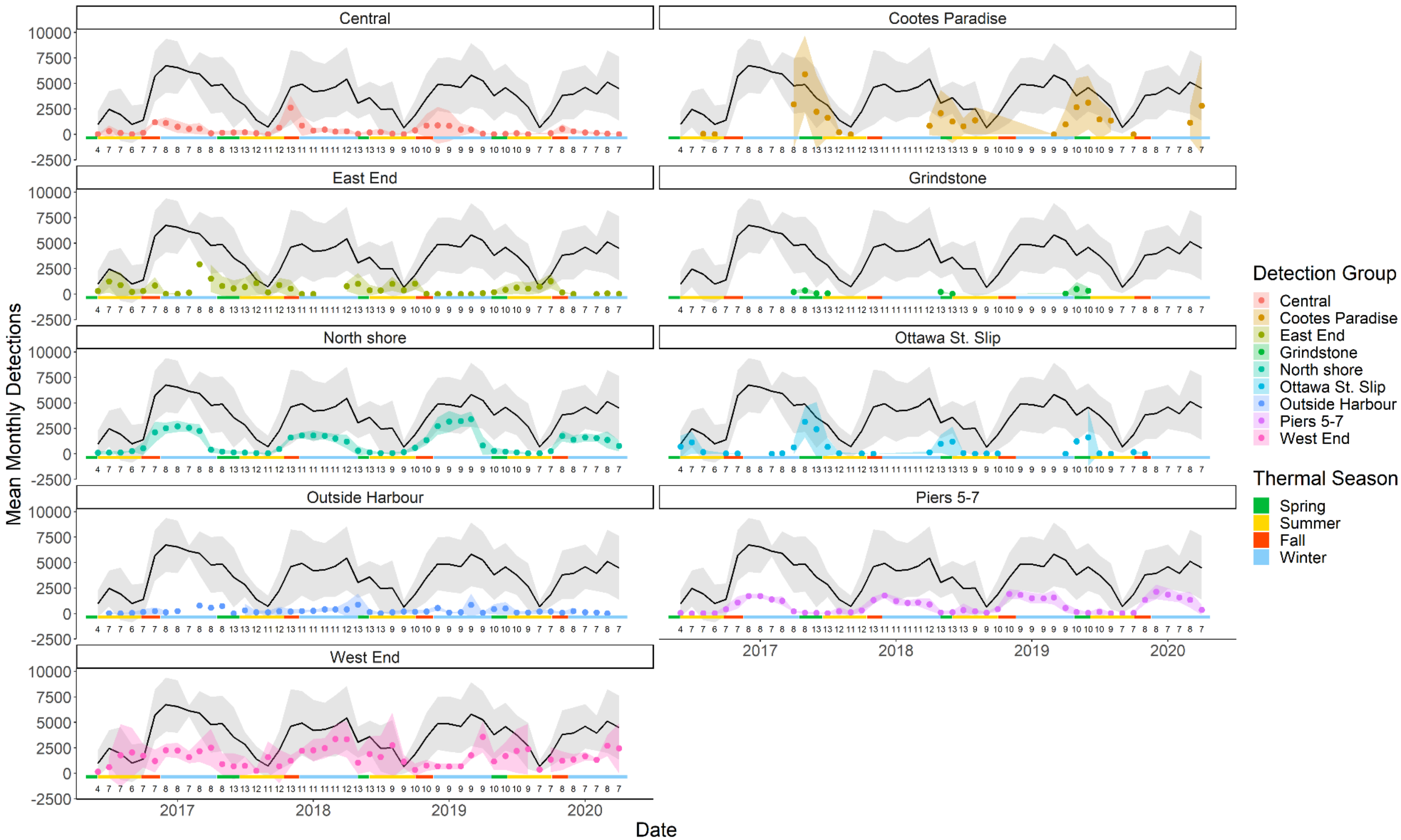


**Figure D1.** Mean (± SD) monthly detections of acoustically tagged Freshwater Drum at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Freshwater Drum at that time.

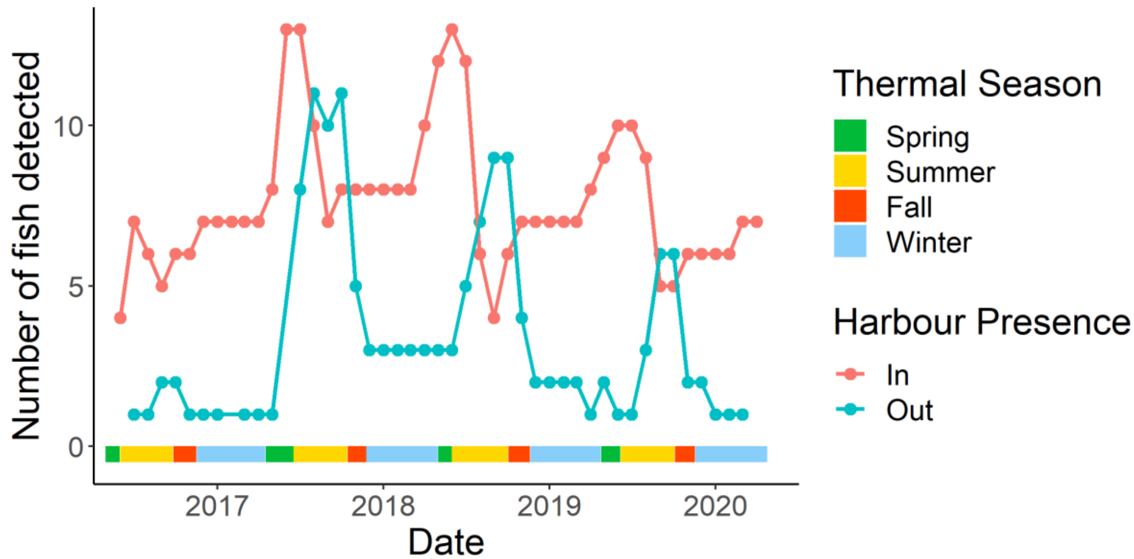


**Figure D2.** Monthly total of acoustically tagged Freshwater Drum detected in or out of Hamilton Harbour over time. The coloured bar indicates the season over time.

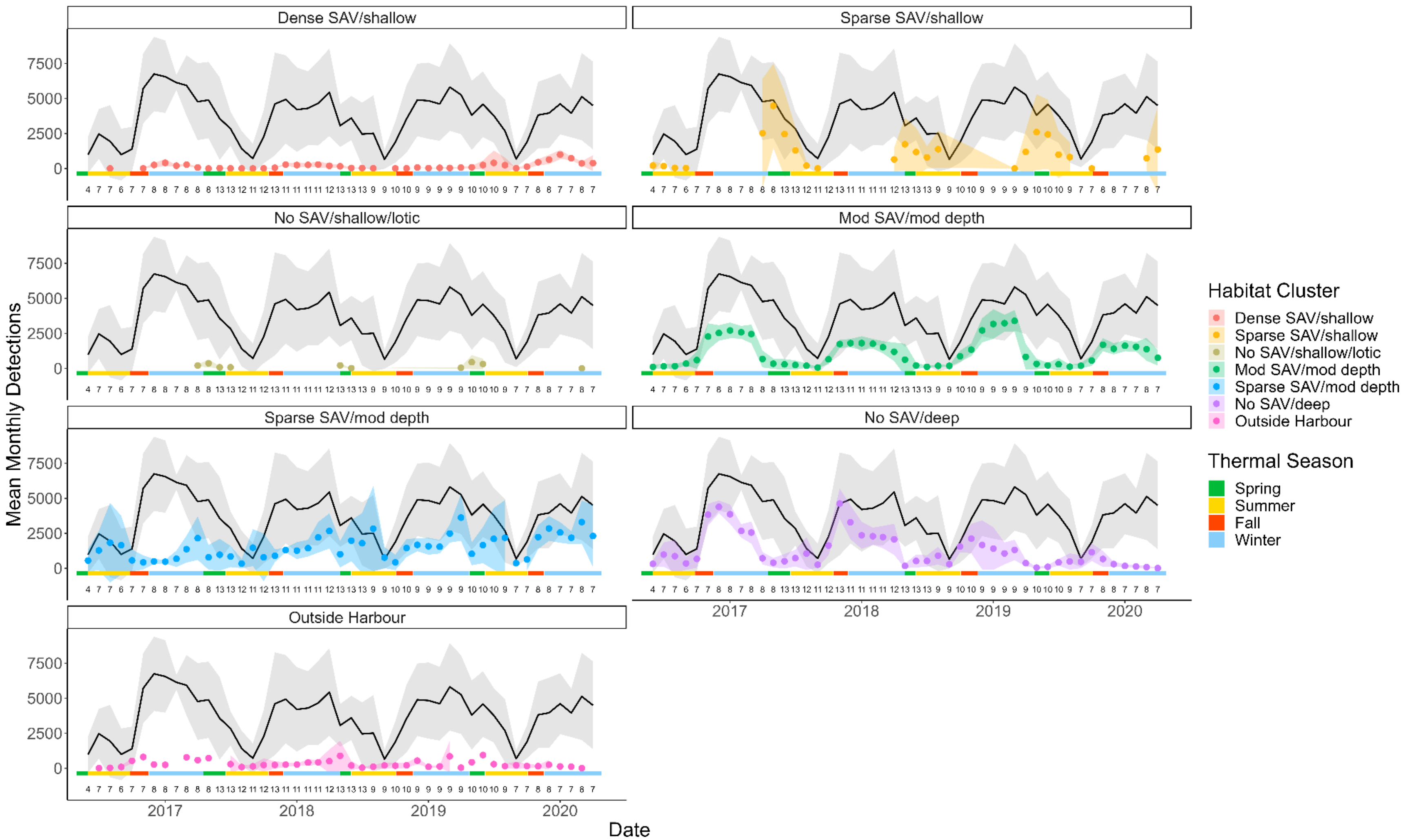


**Figure D3**. Mean (± SD) monthly detections of acoustically tagged Freshwater Drum at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Freshwater Drum.

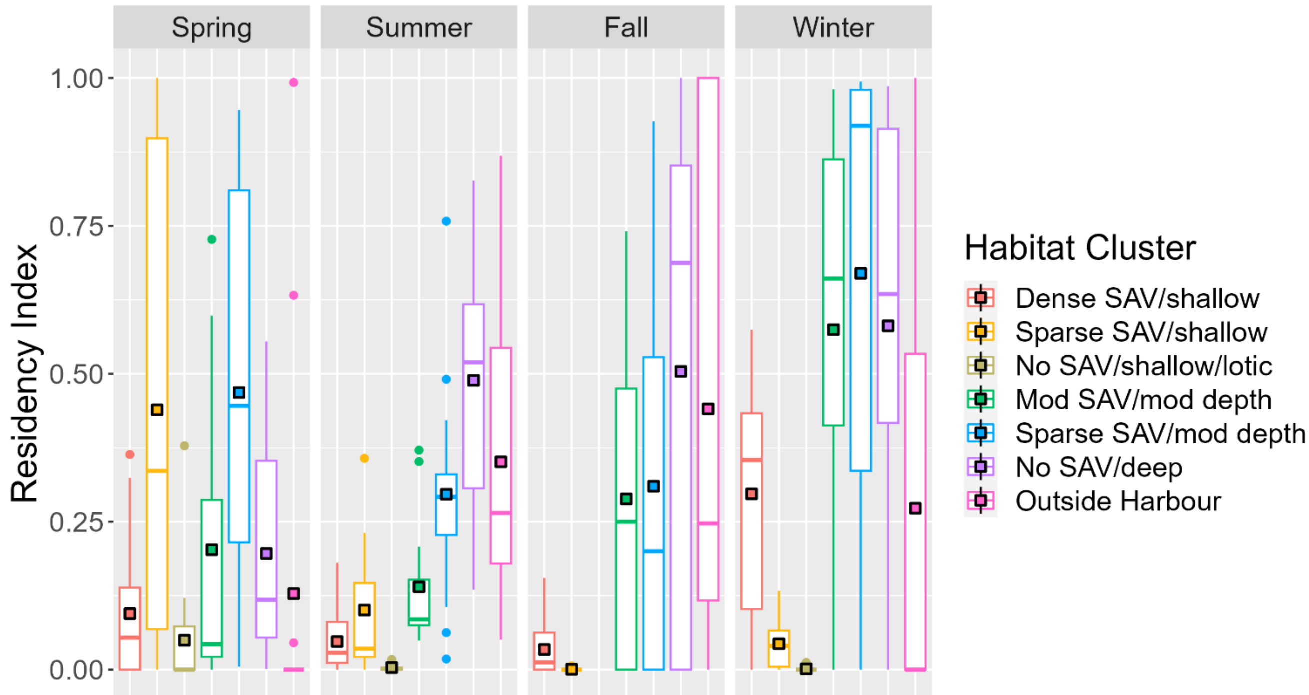


**Figure D4.** Boxplot of individual tagged Freshwater Drum residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

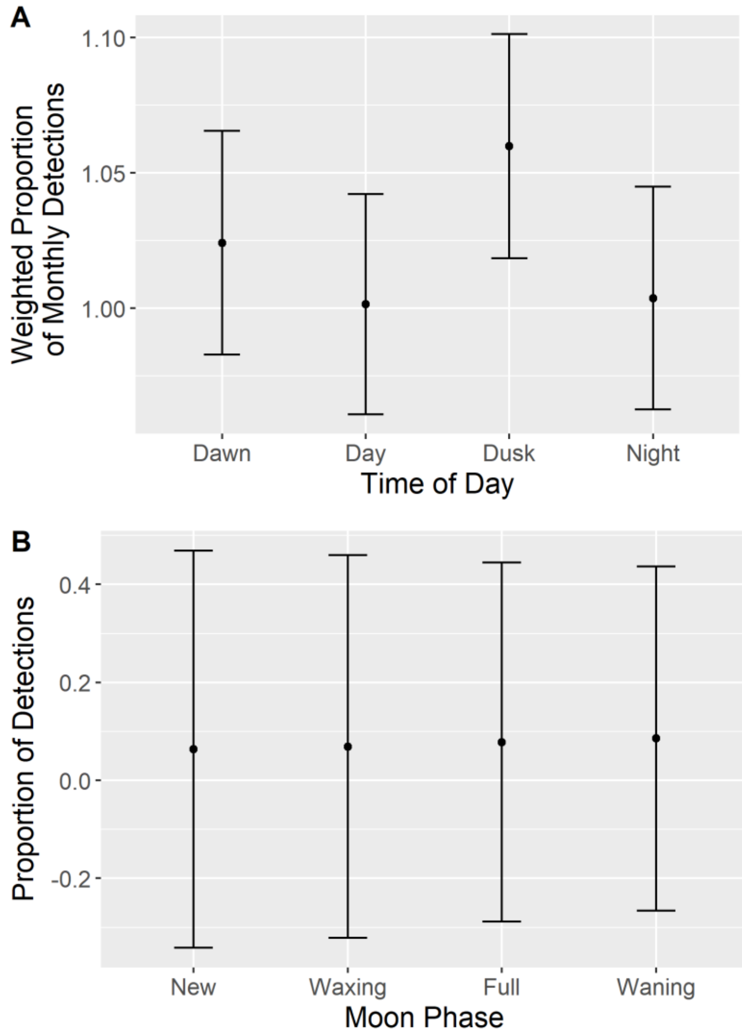


**Figure D5**. A) Mean (± SE) proportion of monthly detections of Freshwater Drum at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Freshwater Drum detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

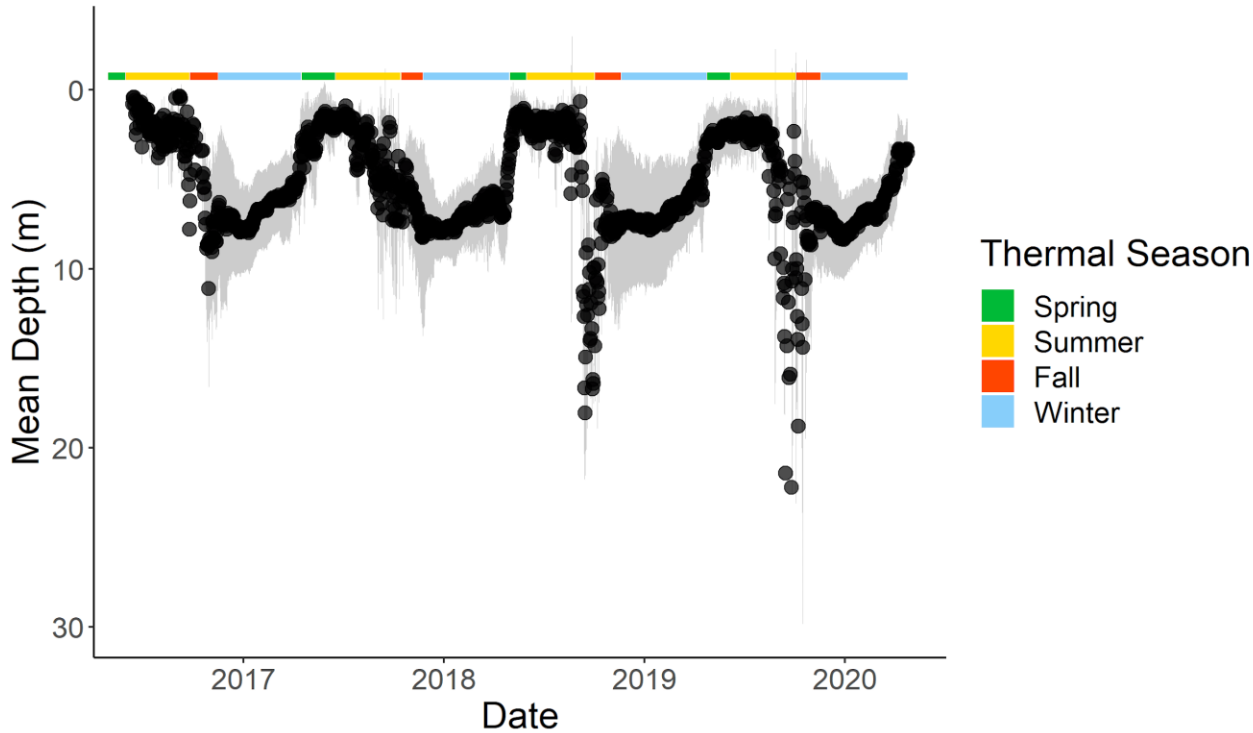


**Figure D6**. Mean (± SD) daily depth use of acoustically tagged Freshwater Drum in Hamilton Harbour over time. The coloured bar indicates the season over time.

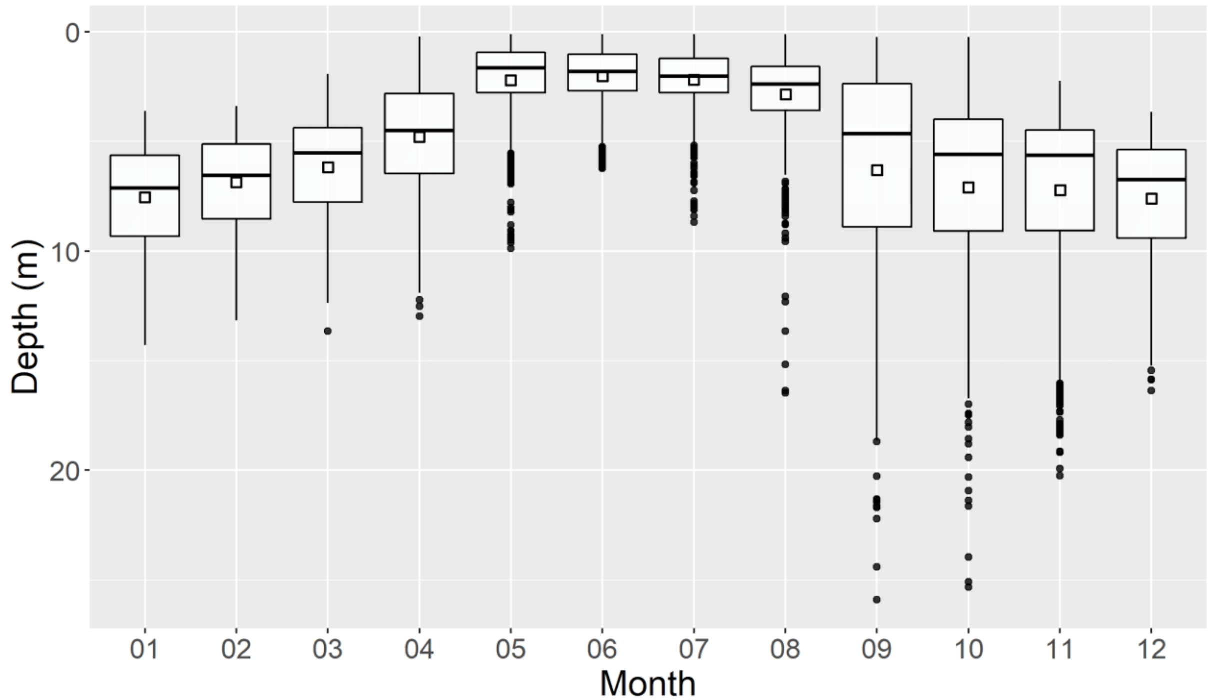


**Figure D7** Boxplot of monthly depth use based on mean daily depths of acoustically tagged Freshwater Drum in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

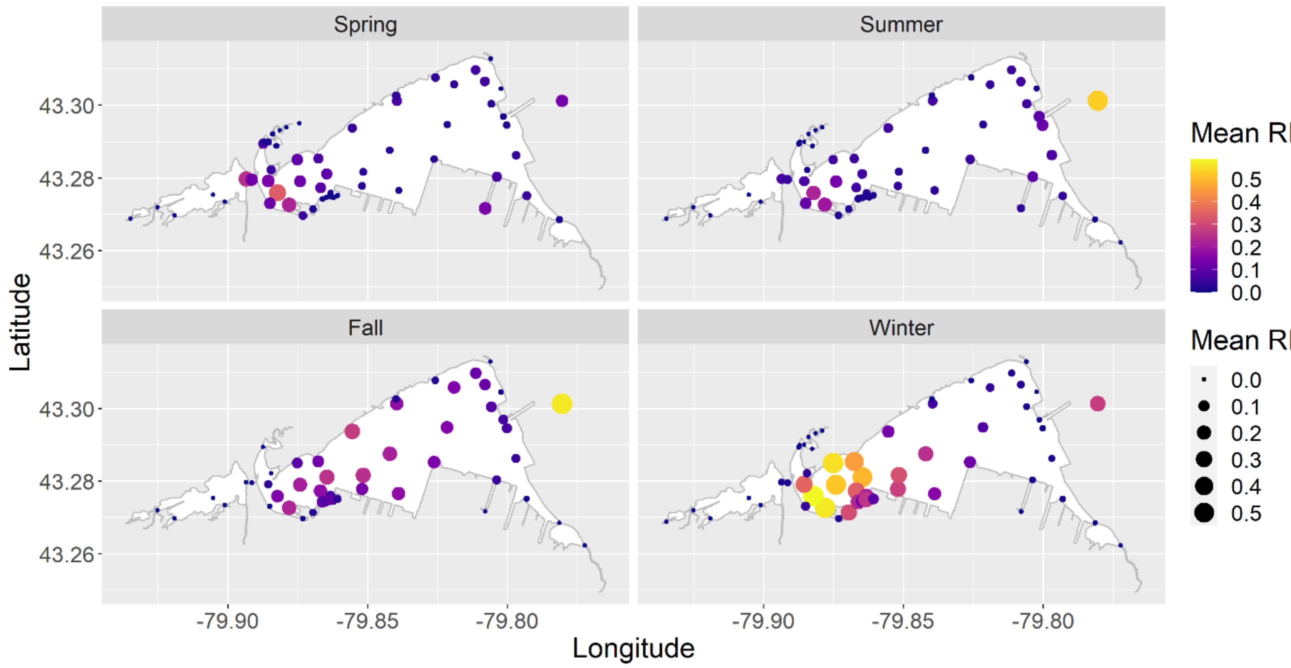


**Figure D8.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Freshwater Drum (N = 13). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

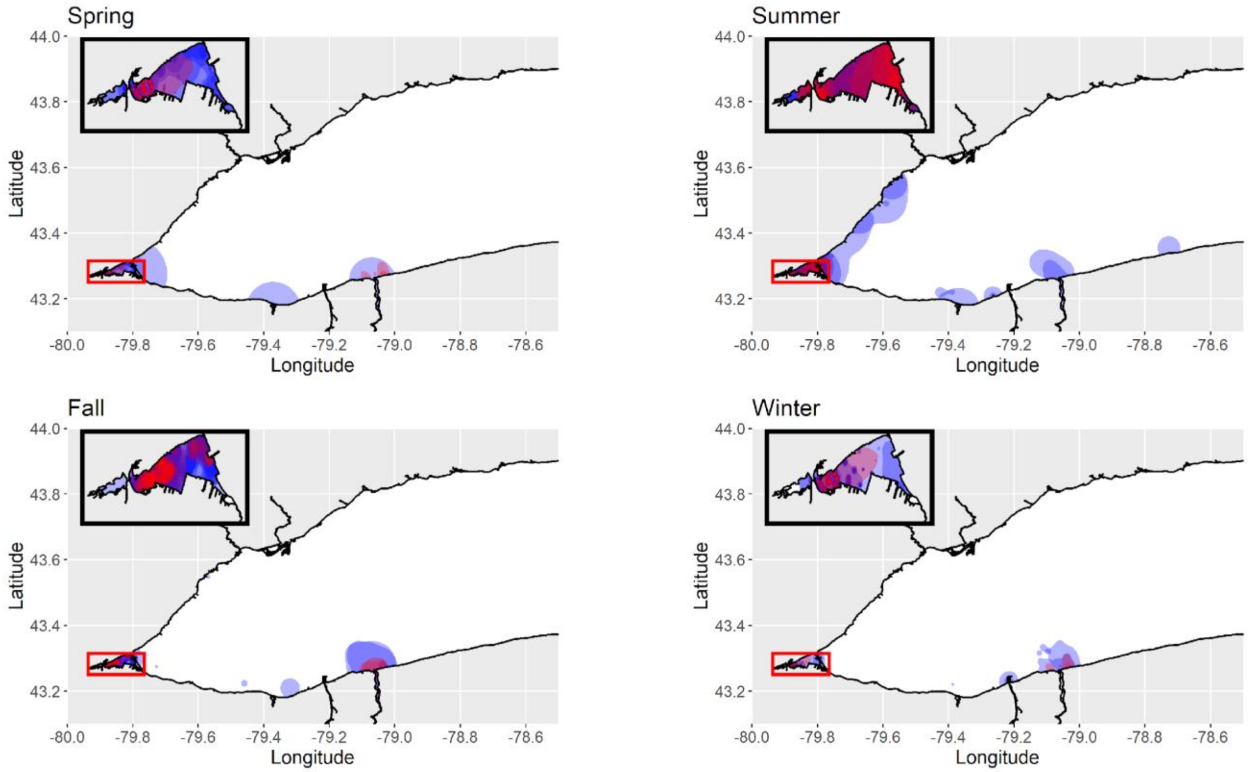


**Figure D9**. Seasonal 50% (red) and 95% (blue) home ranges (via kernel utilization distribution) of individual Freshwater Drum tagged in Hamilton Harbour, 2016 – 2020. Darker colours indicate overlapping home ranges of individuals. All Freshwater Drum left the harbour at some point during the study but the duration and distance varied.

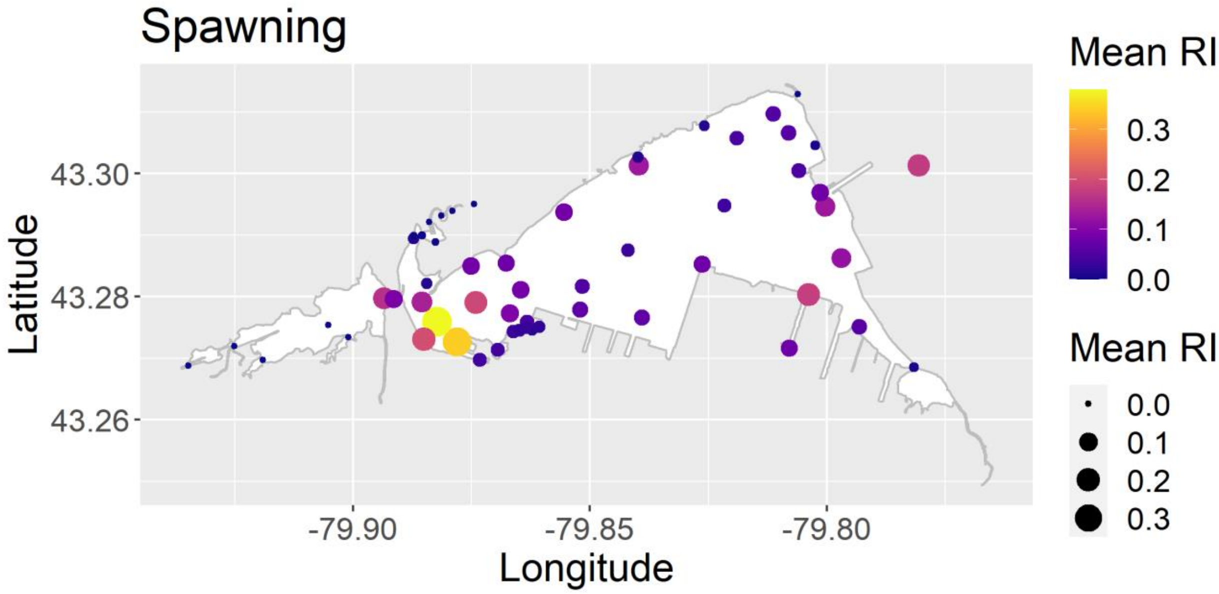


**Figure D10.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Freshwater Drum (N = 13) during their spawning window (June 1 to July 31). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

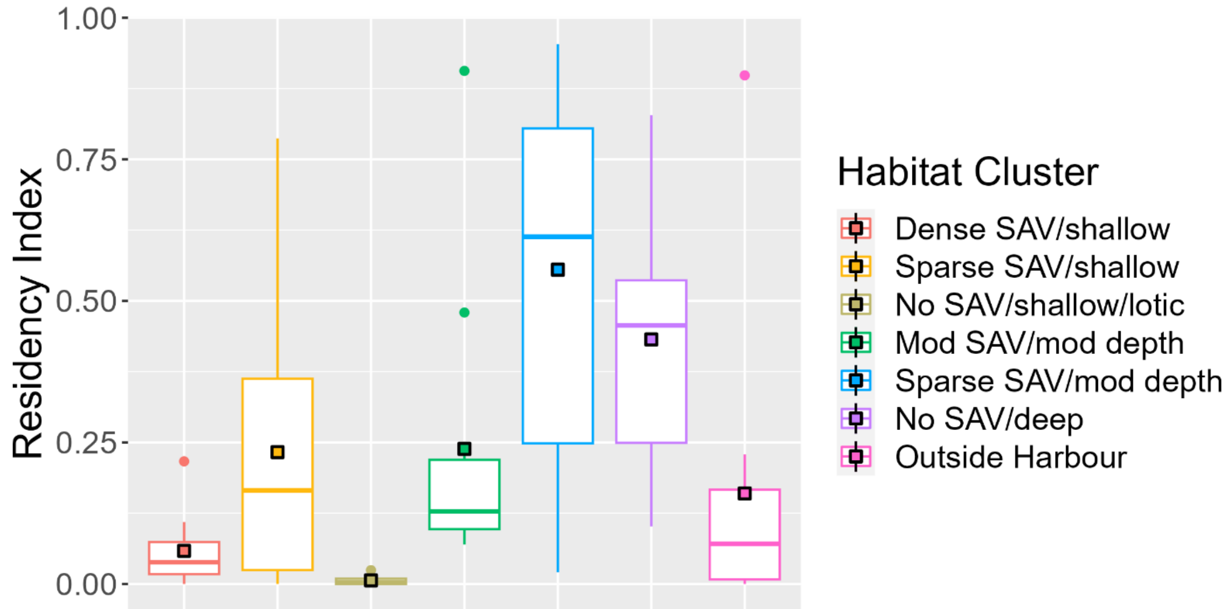


**Figure D11**. Boxplot of individual tagged Freshwater Drum residency during the spawning window (June 1 to July 31) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX E: GOLDFISH

## DETECTIONS AND HABITAT USE

Twelve Goldfish (*Carassius auratus*) were acoustically tagged and monitored in Hamilton Harbour from June 2017 to April 2020 (**Table E1**). Based on mean monthly detections, there appears to be more overall detections in the fall and fewer in the late winter and spring, with a general affinity towards the west end with some time spent at the north shore and Piers 5-7 in the winter and Grindstone Creek in the spring (**Figure E1**). Although Goldfish were detected at Cootes Paradise Marsh receivers it was only at the receivers at the entrance to Cootes Paradise Marsh near the fishway and no Goldfish were detected inside Cootes Paradise Marsh. Goldfish generally remained within the harbour year-round, with one fish being detected briefly leaving and then returning to the harbour (**Figure E2**). The Goldfish that went into Lake Ontario remained very close (~5 km) to the harbour.

Based on the habitat clusters, Goldfish were primarily detected in areas of sparse or moderate SAV at moderate depths, and no SAV at deeper depths in the fall and winter (**Figure E3**). In the spring, there was an increase of detections in areas of dense or sparse SAV in shallow waters, while in the summer detections were primarily in areas of dense SAV in shallow waters (**Figure E3**). Habitat trends were fairly similar when assessed based on seasonal residency by habitat clusters (**Figure E4**). Seasonal residency indicated that Goldfish were located in areas of sparse SAV in shallow waters but also in lotic areas and sparse SAV at moderate depths in the spring. In the summer, Goldfish were in areas of dense SAV shallow waters and to a lesser extent moderate or sparse SAV at moderate depths. In the fall and winter, Goldfish moved into deeper areas and were associated with moderate or sparse SAV at moderate depths, and no SAV at deep depths.

There was an increase in detections during dawn and night, compared to dusk and daytime (relative to the duration of time of each daylight category; $\chi^2_3 = 80.060$, $p < 0.001$); but no change in the relative number of detections based on moon phase ($\chi^2_3 = 2.520$, $p = 0.472$; **Figure E5**).

## DEPTH USE

The depth use of Goldfish appears to be seasonally cyclical (**Figure E6**) with shallowest depths during the spring (seasonal modelled mean ± SE = 1.8 ± 1.0 m) and summer (1.9 ± 1.0 m), and deeper depths in the fall (4.2 ± 1.0 m) and winter (3.9 ± 1.0 m; $X^2_3 = 1019.4$, $p < 0.001$). From a monthly perspective, Goldfish had increased depth use from October until February (mean ± SD depth ranged from 2.5 ± 3.4 m to 5.7 ± 3.1 m) and shallower depth use from April until August (mean ± SD depth ranged from 0.7 ± 0.7 m to 1.2 ± 1.4 m; **Figure E7**). The greatest depth use was during the fall and winter along the north shore and central basin (max = 20.6 m).

## RESIDENCY

Spatially, Goldfish had increased residency at the mouth of Grindstone Creek and the west end in the spring (**Figure E8**). This affinity for the west end still occurred in summer but shifted towards Macassa Bay and along the north shore. In the fall, higher residency occurred in slightly deeper waters in the west end and along the north shore towards the east end (**Figure E8**), at the time when Goldfish moved to deeper depths (~3 – 5 m; **Figure E7**). By winter, residency was greatest in the west end in slightly deeper waters and towards Piers 5-7 and surrounding area (**Figure E8**), at which time Goldfish were still residing at deeper depths (~3 – 5 m; **Figure E7**).

## SPAWNING

May 1 to June 30 was the spawning window used for Goldfish (**Table 2**), during which Goldfish were quite shallow (mean monthly depths were ~1 m) (**Figure E7**). The shallow waters used in the spring and summer may be attributed to when Goldfish were spawning. Based on the residency index, during the spawning window, Goldfish appear to be in the west end, towards Grindstone Creek, Macassa Bay and to a lesser extent along the north shore (**Figure E9**). Habitat-associated residency of Goldfish during the spawning window was greater in areas of sparse SAV at shallow and moderate depths, and to a lesser extent lotic areas and areas of moderate SAV at moderate depths (**Figure E10**). Habitat residency indicates that Goldfish generally seem to go to vegetated areas for spawning but will also move into river environments (e.g., Grindstone Creek) to find these areas.

**Table E1.** Tagging and detection summary of acoustically tagged Goldfish (*Carassius auratus*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, or AD = Alive and later died, based on the detection/depth profiles.

| Tag ID | Fork Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14188 | 322 | 850 | 10/10/2018 | Wildlife Islands | V13P-1L | TRUE | AD | 10/11/2018 | 2/18/2019 | 130 | 28321 | 131 |
| 14523 | 340 | 1218 | 5/29/2018 | MB06 | V13P-1L | TRUE | AD | 5/29/2018 | 7/3/2018 | 35 | 2675 | 33 |
| 15851 | 332 | 1090 | 10/3/2017 | Bayfront | V13P-1L | TRUE | AD | 10/3/2017 | 5/26/2019 | 600 | 51888 | 494 |
| 14186 | 330 | 880 | 10/10/2018 | Wildlife Islands | V13P-1L | TRUE | A | 10/11/2018 | 4/25/2020 | 562 | 119796 | 505 |
| 14187 | 328 | 1030 | 10/10/2018 | Wildlife Islands | V13P-1L | TRUE | A | 10/11/2018 | 4/25/2020 | 562 | 117228 | 500 |
| 14190 | 325 | 860 | 10/9/2018 | Lasalle | V13P-1L | TRUE | A | 10/10/2018 | 4/25/2020 | 563 | 146399 | 476 |
| 14191 | 320 | 920 | 10/9/2018 | Lasalle | V13P-1L | TRUE | A | 10/11/2018 | 4/25/2020 | 562 | 68236 | 485 |
| 14513 | 323 | 1010 | 10/9/2018 | Lasalle | V13P-1L | TRUE | A | 10/11/2018 | 10/18/2019 | 372 | 25645 | 287 |
| 15863 | 308 | 990 | 6/28/2017 | Rowing Club | V13P-1L | TRUE | A | 6/30/2017 | 6/27/2019 | 727 | 144249 | 596 |
| 15866 | 314 | 1150 | 6/27/2017 | Bayfront Marina | V13P-1L | TRUE | A | 6/29/2017 | 4/25/2020 | 1031 | 132301 | 930 |
| 15873 | 313 | 990 | 6/27/2017 | Bayfront Bay | V13P-1L | TRUE | A | 6/28/2017 | 8/20/2019 | 783 | 57834 | 505 |
| 15876 | 300 | 900 | 6/26/2017 | Bayfront | V13P-1L | TRUE | A | 6/27/2017 | 4/25/2020 | 1033 | 211315 | 935 |

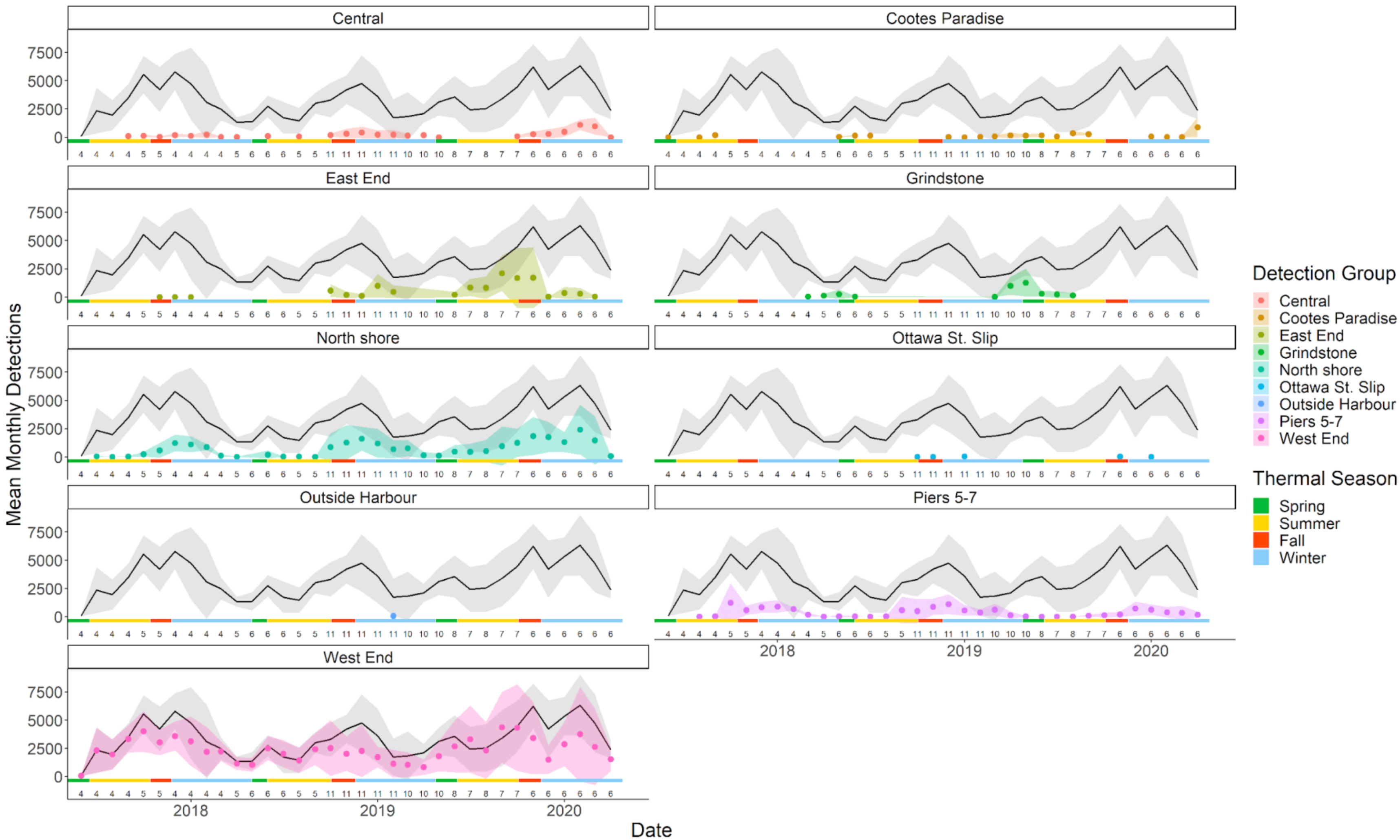


**Figure E1.** Mean (± SD) monthly detections of acoustically tagged Goldfish at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Goldfish at that time.

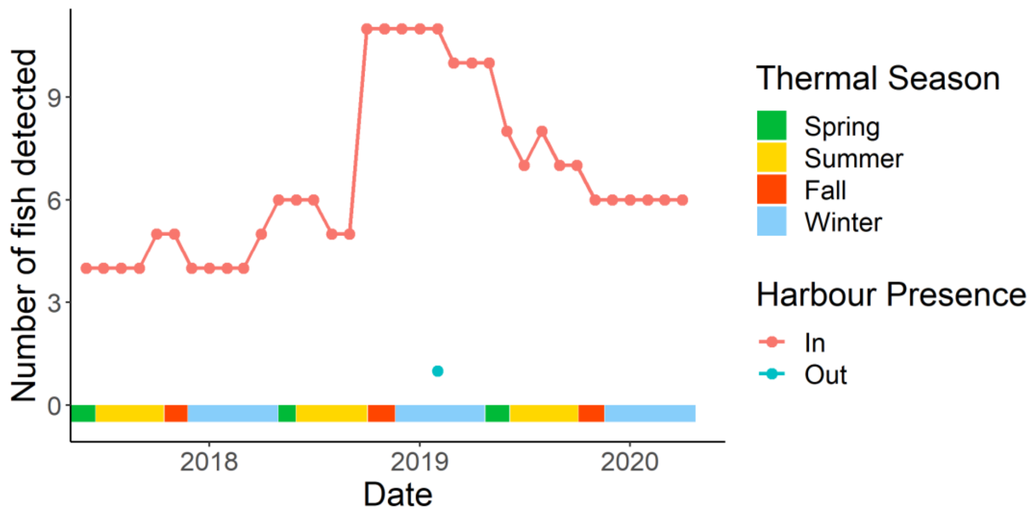


**Figure E2.** Monthly total of acoustically tagged Goldfish detected in or out of Hamilton Harbour over time. The coloured bar indicates the season over time.

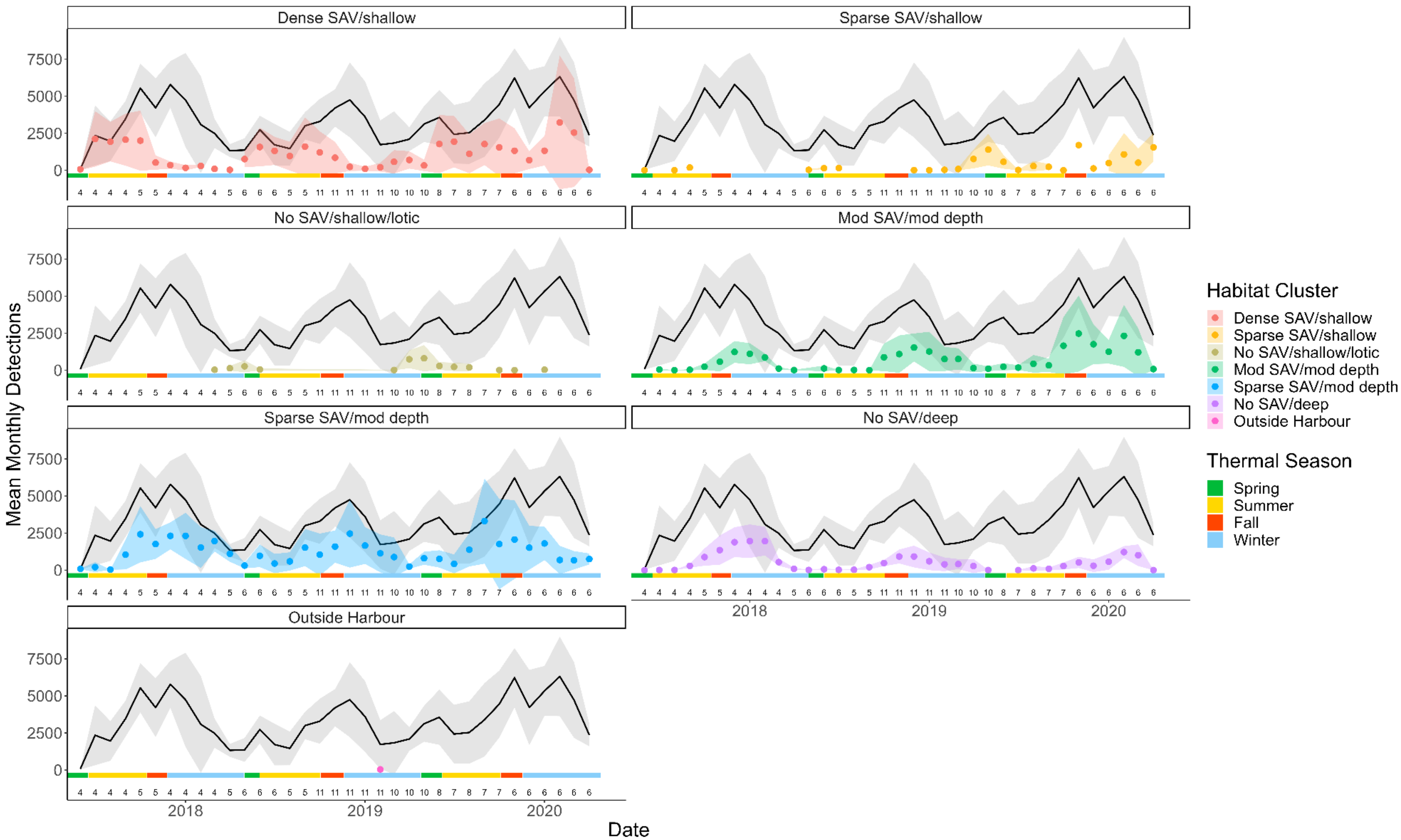


**Figure E3**. Mean (± SD) monthly detections of acoustically tagged Goldfish at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Goldfish.

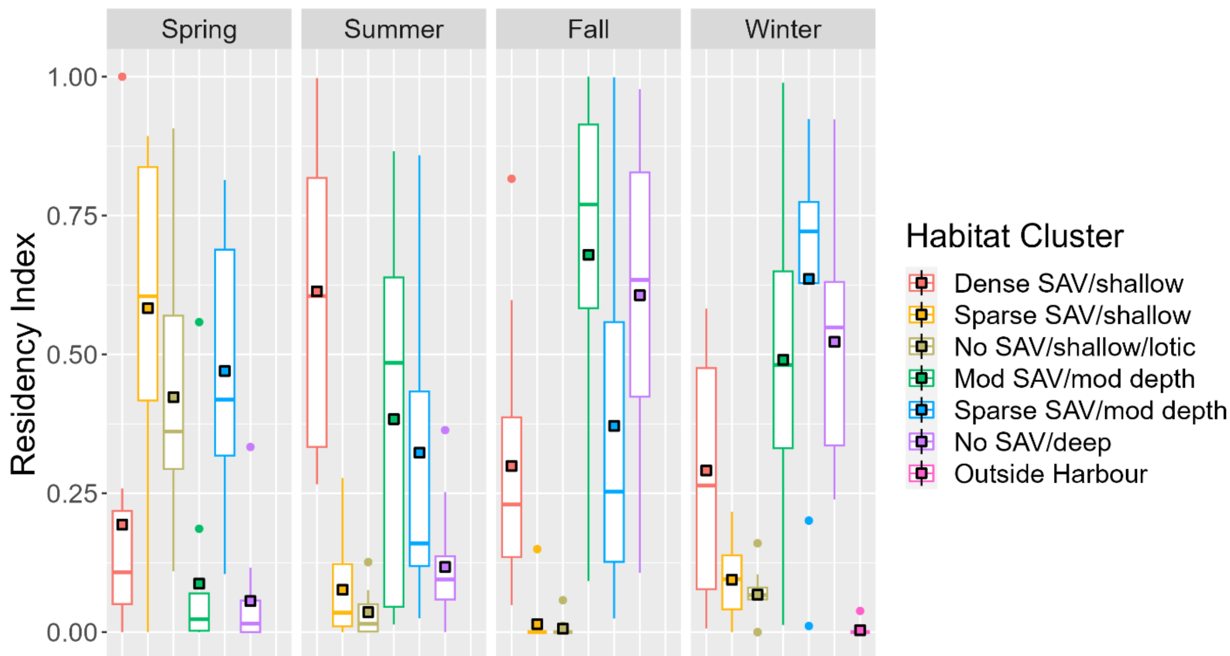


**Figure E4.** Boxplot of individual tagged Goldfish residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

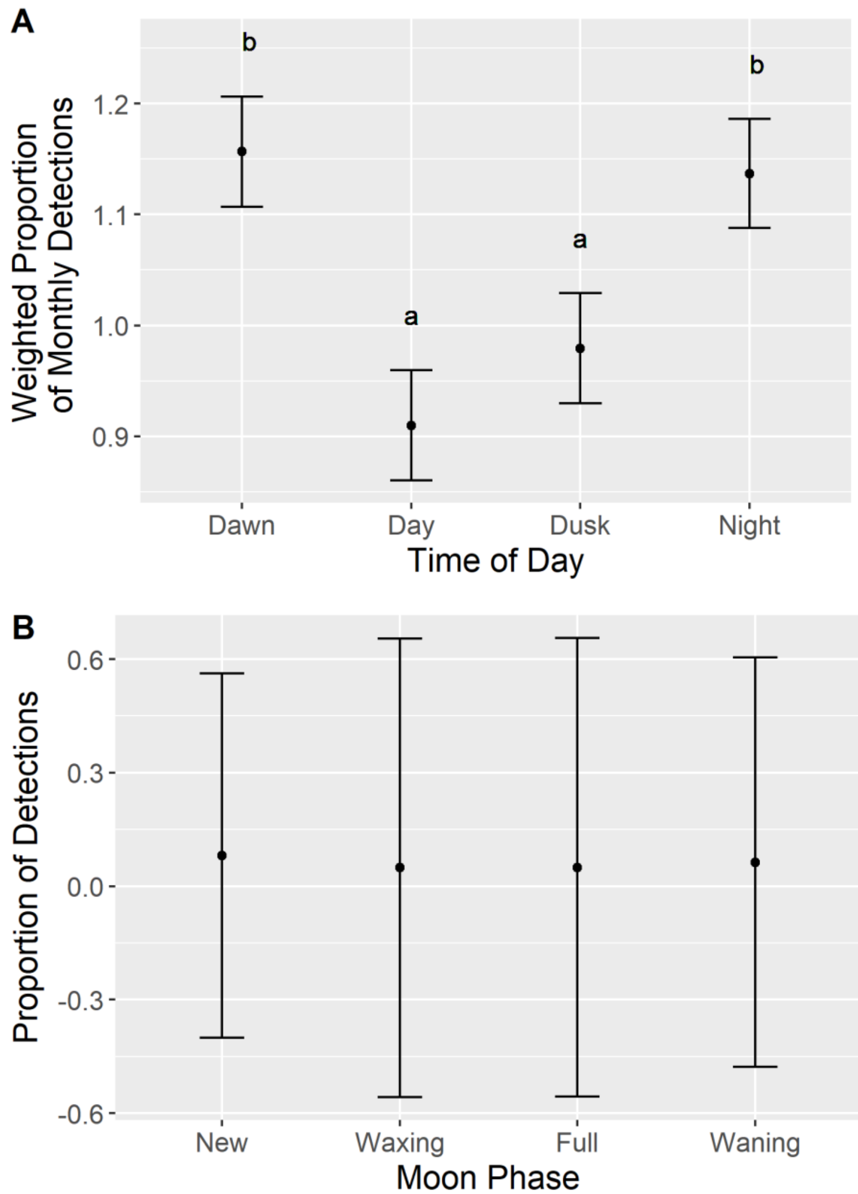


**Figure E5**. A) Mean (± SE) proportion of monthly detections of Goldfish at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Goldfish detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

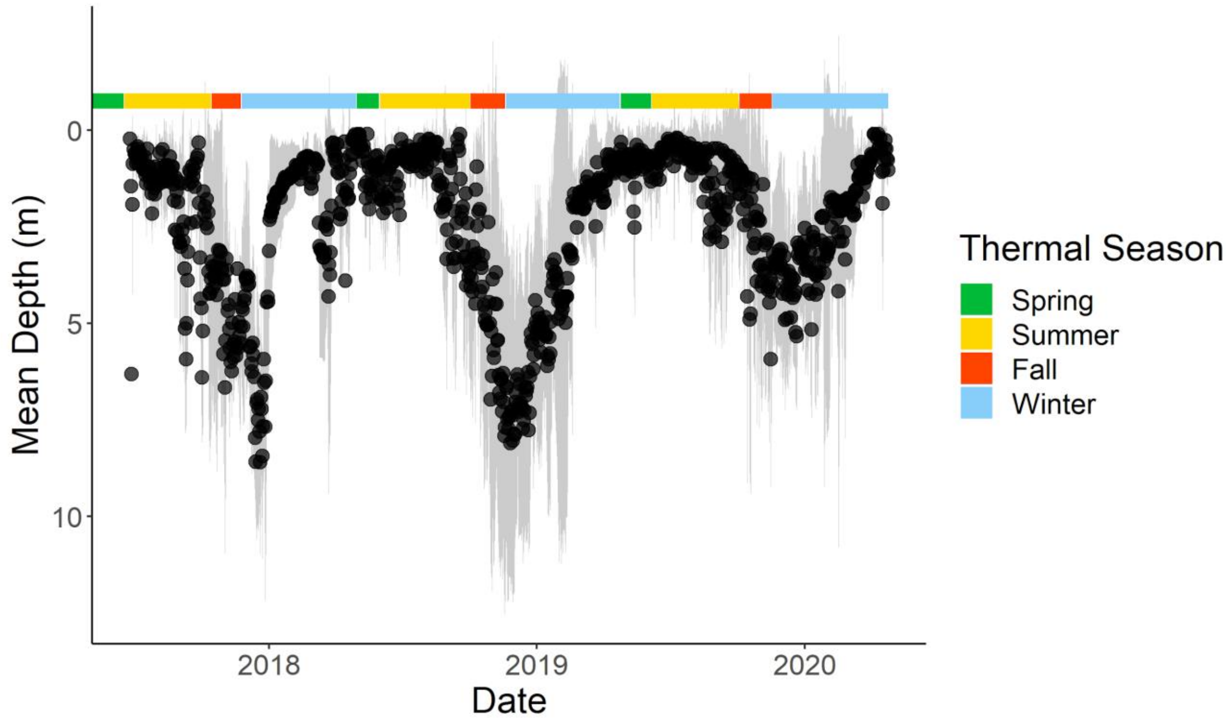


**Figure E6**. Mean (± SD) daily depth use of acoustically tagged Goldfish in Hamilton Harbour over time. The coloured bar indicates the season over time.

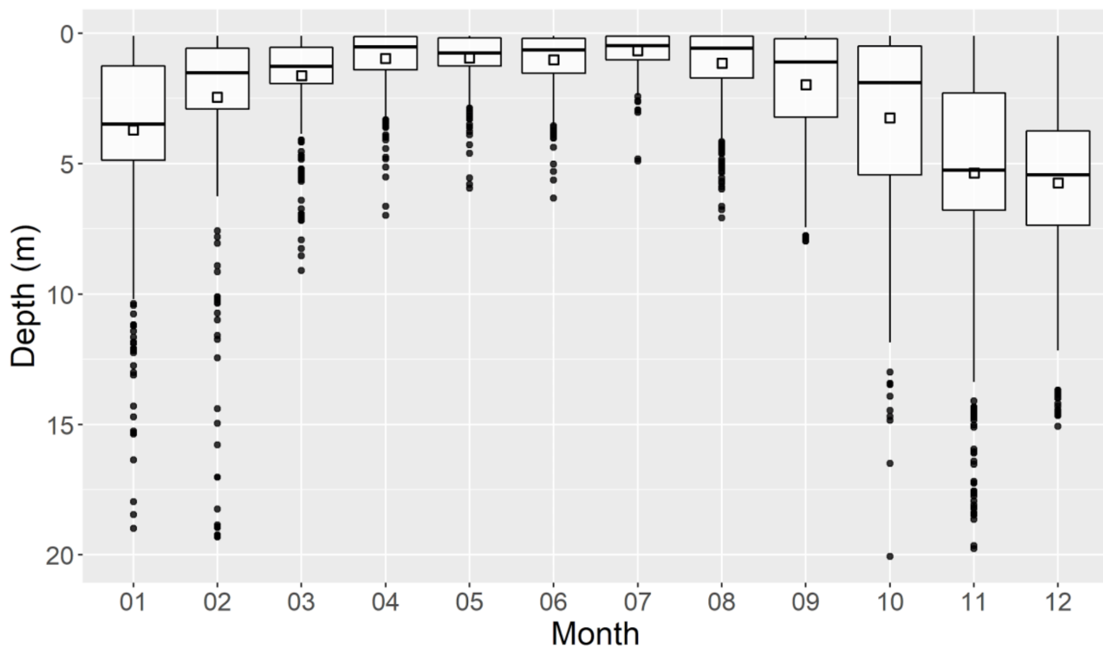


**Figure E7**. Boxplot of monthly depth use based on mean daily depths of acoustically tagged Goldfish in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

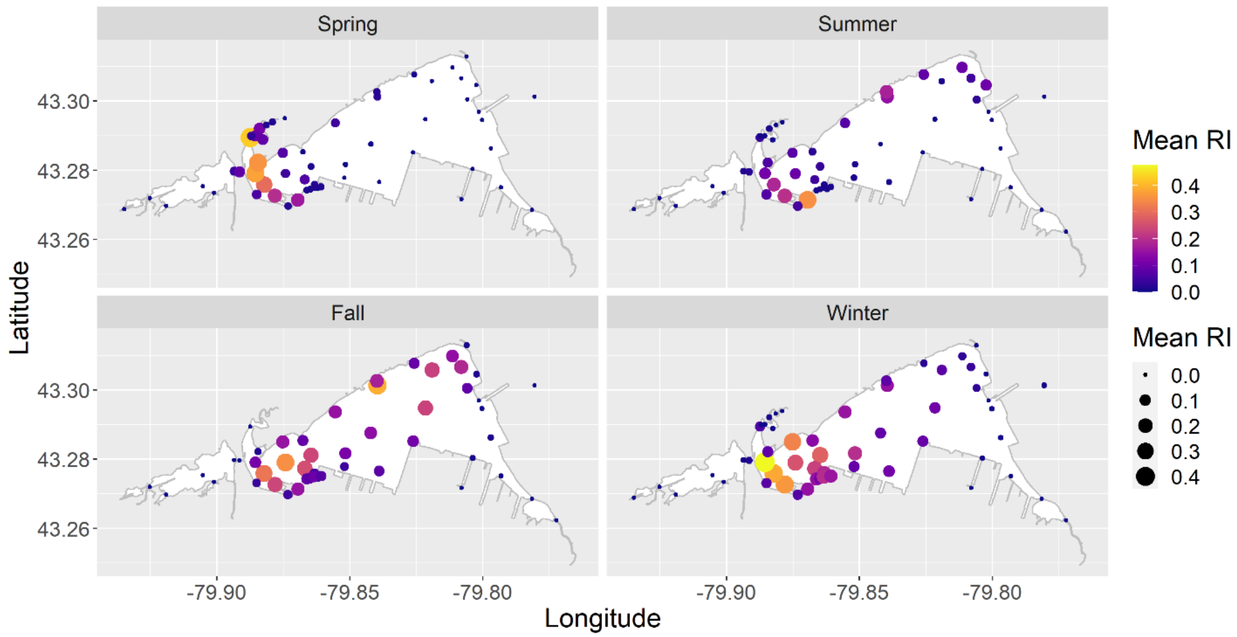


**Figure E8.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Goldfish (N = 12). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

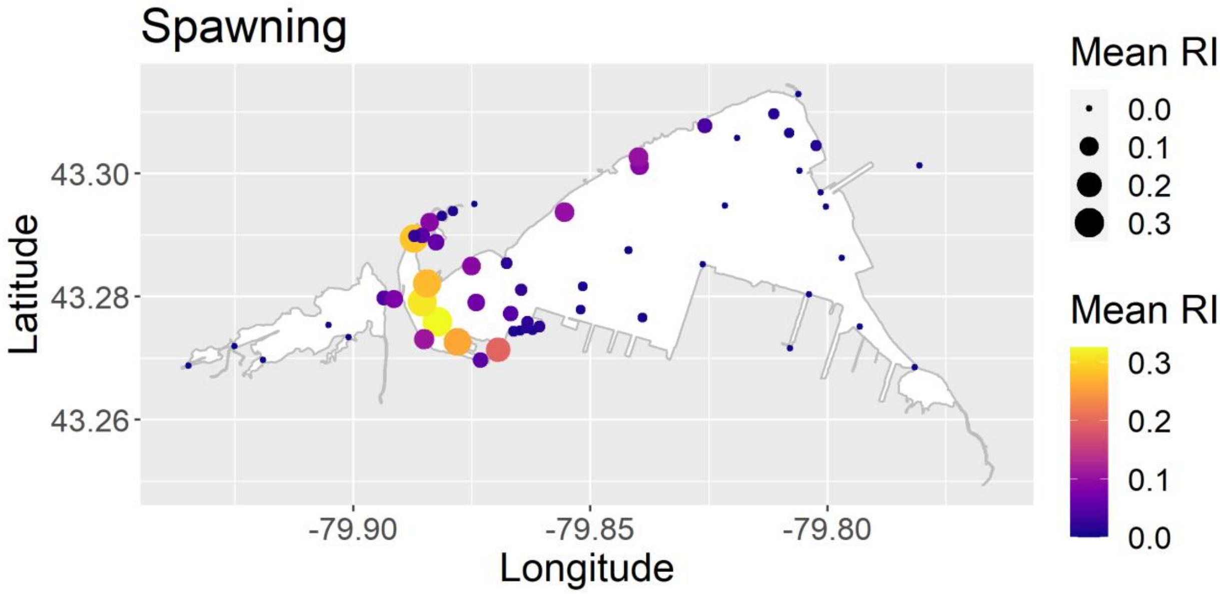


**Figure E9.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Goldfish (N = 12) during their spawning window (May 1 to June 30). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

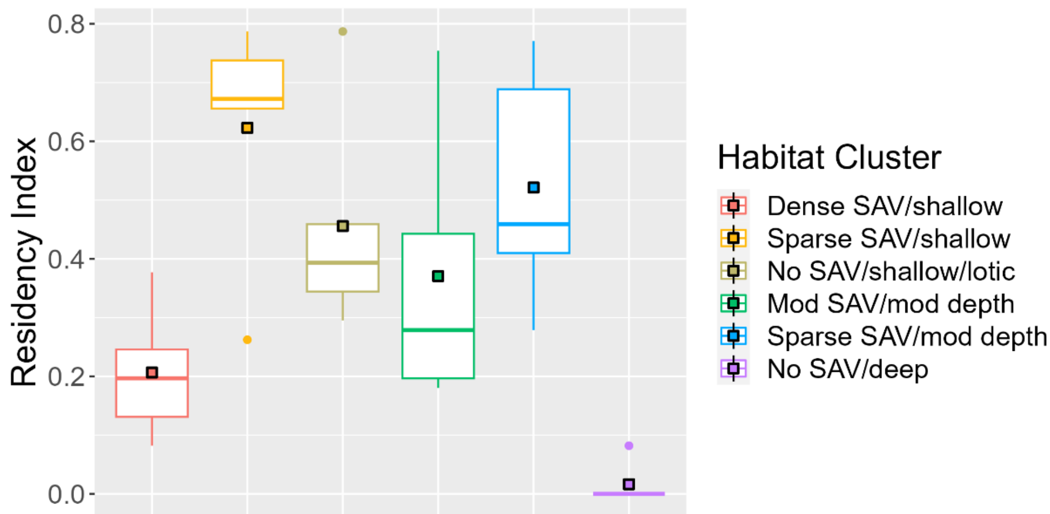


**Figure E10**. Boxplot of individual tagged Goldfish residency during the spawning window (May 1 to June 30) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX F: LARGEMOUTH BASS

## DETECTIONS AND HABITAT USE

Twenty-five Largemouth Bass (*Micropterus nigricans*) were acoustically tagged and monitored in Hamilton Harbour from April 2016 to April 2020 (**Table F1**). Based on mean monthly detections, there appears to be more overall detections of Largemouth Bass in the fall and fewer in the spring, with a general affinity towards the west end year-round with some time spent at Cootes Paradise Marsh or at Piers 5-7 in the summer (**Figure F1**). Further investigation revealed four Largemouth Bass entered Cootes Paradise Marsh proper (detected at Station 31), with only one bass being detected across all five receiver locations of Cootes Paradise Marsh (this did not include fish detected at the fishway - Station 32 and 43). Largemouth Bass were mostly detected in Cootes Paradise Marsh during June and July before returning to the harbour. One fish repeatedly entered Cootes Paradise Marsh during this time of year. Largemouth Bass generally remained within the harbour year-round, with two fish being detected leaving the harbour, with one eventually returning and the other never returning (**Figure F2**). The Largemouth Bass that never returned went into Lake Ontario and was detected as far as Port Credit, while the one that returned remained close (~5 km) to the harbour.

Based on the habitat clusters, Largemouth Bass were primarily detected in areas of sparse SAV at moderate depths in the fall and winter (**Figure F3**). In the late winter and spring, there was an increase of detections in areas of dense SAV in shallow waters, while in the summer detections were primarily in areas of sparse SAV in shallow or moderate depth waters (**Figure F3**). Habitat trends were slightly different when assessed based on seasonal residency by habitat clusters (**Figure F4**). Seasonal residency indicated that Largemouth Bass were primarily located in areas of sparse SAV at moderate depths year-round. However, to a lesser extent Largemouth Bass also used areas of moderate SAV at moderate depths and no SAV at deep depths from fall to winter. Residency within areas of dense SAV at shallow depths increased in winter and spring. Residency, albeit low, within lotic areas occurred in spring and summer only.

There was an increase in detections during dawn, followed by night, compared to dusk and daytime (relative to the duration of time of each daylight category; $\chi^2_3 = 96.060$, $p < 0.001$). There was no change in the relative number of detections based on moon phase ($\chi^2_3 = 3.618$, $p = 0.306$; **Figure F5**).

## DEPTH USE

The depth use of Largemouth Bass was seasonally cyclical (**Figure F6**) with shallowest depths during the spring (seasonal modelled mean ± SE = 0.4 ± 0.2 m) and summer (0.4 ± 0.2 m), followed by fall (0.9 ± 0.2 m), and lastly winter (1.9 ± 0.2 m; $X^2_3 = 4767.1$,

$p < 0.001$). From a monthly perspective, Largemouth Bass had increased depth use from November until March (mean ± SD depth ranged from 1.3 ± 1.0 m to 2.5 ± 1.5 m) and shallower depth use from April until August (mean ± SD depth ranged from 0.4 ± 0.6 m to 0.6 ± 0.8 m; **Figure F7**). The greatest depth use was during the fall in November along the north shore (max = 13.2 m).

## RESIDENCY

Spatially, Largemouth Bass had the highest residency at the west end, year-round (**Figure F8**). However, this west end residency shifted into slightly deeper waters in the fall and winter where Largemouth Bass were residing at depths of ~1.5 – 2.5 m (**Figure F7**). In the spring and summer, west end residency was greater closer to shore, towards Macassa Bay and Bayfront. Overall residency values were lower in spring and summer which may indicate periods of time with lower detectability.

## SPAWNING

May 1 to July 15 was the spawning window used for Largemouth Bass (**Table 2**), during which Largemouth Bass were quite shallow (mean monthly depths were ~0.5 m; **Figure F7**). The shallow waters used in the spring and summer may be attributed to when Largemouth Bass were spawning. Based on the residency index, during the spawning window, Largemouth Bass appear to be in the west end, towards Macassa Bay and Bayfront, and to a lesser extent along the north shore and in Cootes Paradise Marsh (**Figure F9**). Habitat-associated residency of Largemouth Bass during the spawning window was greater in areas of sparse SAV at moderate depths, and to a lesser extent all other habitat clusters were equally represented except lotic areas (**Figure F10**). Habitat residency indicates that Largemouth Bass generally seem to go to semi-vegetated and slightly deeper areas for spawning but will also be found in a variety of habitats.

**Table F1.** Tagging and detection summary of acoustically tagged Largemouth Bass (*Micropterus nigricans*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, AD = alive and later died, or U = unknown, based on the detection/depth profiles. Dash indicates no data recorded.

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 33 | 401 | - | 10/26/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 10/23/2017 | 541 | 72313 | 349 |
| 34 | 402 | - | 10/26/2015 | West | V13P-1L | TRUE | A | 5/3/2016 | 10/30/2017 | 545 | 80577 | 348 |
| 36 | 395 | - | 10/26/2015 | West | V13P-1L | TRUE | A | 5/3/2016 | 6/7/2017 | 400 | 51652 | 232 |
| 37 | 400 | - | 10/26/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 10/4/2017 | 522 | 137822 | 419 |
| 39 | 346 | - | 10/26/2015 | West | V13P-1L | TRUE | AD | 5/2/2016 | 9/8/2016 | 129 | 28797 | 102 |
| 40 | 425 | - | 10/26/2015 | West | V13P-1L | TRUE | AD | 4/30/2016 | 6/22/2016 | 53 | 3137 | 33 |
| 46 | 395 | - | 10/27/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 9/21/2016 | 144 | 11142 | 116 |
| 49 | 405 | - | 10/27/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 10/17/2017 | 535 | 102942 | 446 |
| 50 | 422 | - | 10/27/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 5/26/2017 | 391 | 8450 | 124 |
| 14512 | - | 1250 | 5/28/2018 | MB01 | V13P-1L | TRUE | AD | 5/29/2018 | 3/19/2019 | 294 | 38846 | 273 |
| 14527 | 483 | 1850 | 5/24/2018 | HH38 | V13P-1L | TRUE | AD | 5/24/2018 | 10/8/2018 | 137 | 42143 | 137 |
| 14528 | 515 | 2700 | 5/24/2018 | HH38 | V13P-1L | TRUE | AD | 5/24/2018 | 4/23/2019 | 334 | 32206 | 266 |
| 14807 | 400 | 1070 | 5/23/2018 | HH37 | V13P-1L | TRUE | AD | 5/24/2018 | 9/24/2018 | 123 | 4644 | 103 |
| 15855 | 413 | 1220 | 6/26/2017 | Bayfront | V13P-1L | TRUE | A | 6/27/2017 | 4/25/2020 | 1033 | 185504 | 949 |
| 38 | 426 | - | 10/26/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 11/4/2017 | 553 | 115724 | 432 |
| 42 | 387 | - | 10/27/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 10/31/2017 | 549 | 98470 | 415 |
| 14181 | 449 | 1260 | 10/10/2018 | Unknown | V13P-1L | TRUE | A | 10/11/2018 | 5/23/2019 | 224 | 59477 | 219 |
| 14183 | 391 | 670 | 10/10/2018 | Unknown | V13P-1L | TRUE | A | 10/11/2018 | 4/25/2020 | 562 | 156923 | 487 |
| 14184 | 449 | 1600 | 10/10/2018 | Unknown | V13P-1L | TRUE | A | 10/11/2018 | 4/25/2020 | 562 | 149832 | 525 |
| 14185 | 450 | 1150 | 10/10/2018 | Unknown | V13P-1L | TRUE | A | 10/11/2018 | 6/1/2019 | 233 | 95084 | 235 |
| 14517 | - | 1624 | 5/28/2018 | HH42A | V13P-1L | TRUE | A | 5/29/2018 | 6/21/2019 | 388 | 107934 | 387 |
| 15854 | 421 | 1240 | 6/14/2017 | Lasalle | V13P-1L | TRUE | U | 6/15/2017 | 8/20/2017 | 66 | 2160 | 53 |
| 15870 | 396 | 1040 | 6/27/2017 | Bayfront Bay | V13P-1L | TRUE | A | 6/28/2017 | 5/28/2018 | 334 | 57101 | 248 |
| 15874 | 481 | 2240 | 6/26/2017 | Bayfront | V13P-1L | TRUE | A | 6/27/2017 | 4/25/2020 | 1033 | 124424 | 951 |
| 15875 | 454 | 1780 | 6/26/2017 | Bayfront | V13P-1L | TRUE | A | 6/27/2017 | 4/25/2020 | 1033 | 135897 | 890 |

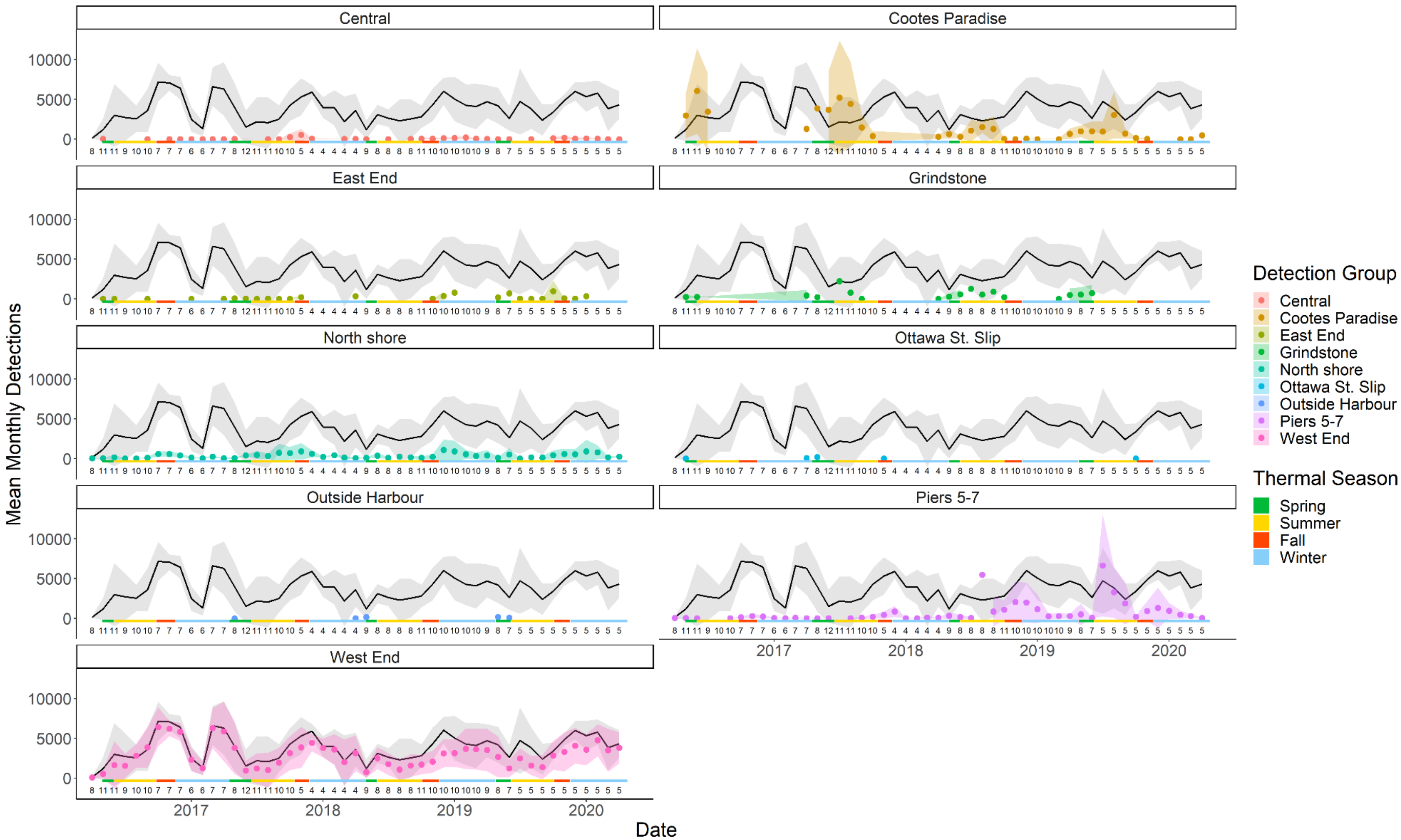


**Figure F1.** Mean (± SD) monthly detections of acoustically tagged Largemouth Bass at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Largemouth Bass at that time.

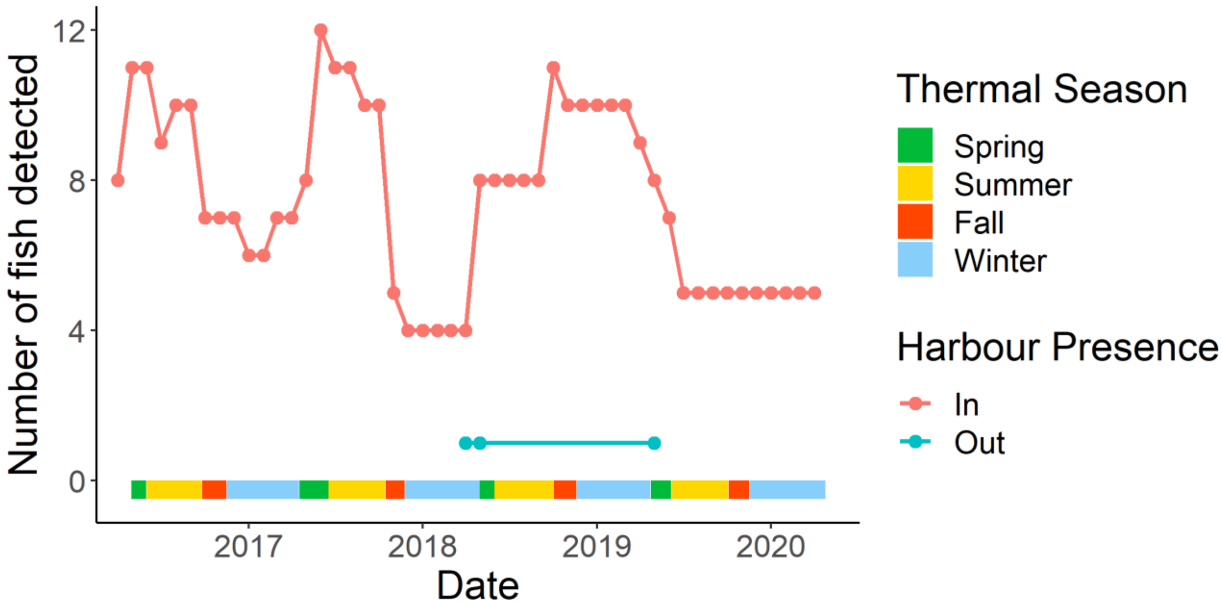


**Figure F2.** Monthly total of acoustically tagged Largemouth Bass detected in or out of Hamilton Harbour over time. The coloured bar indicates the season over time.

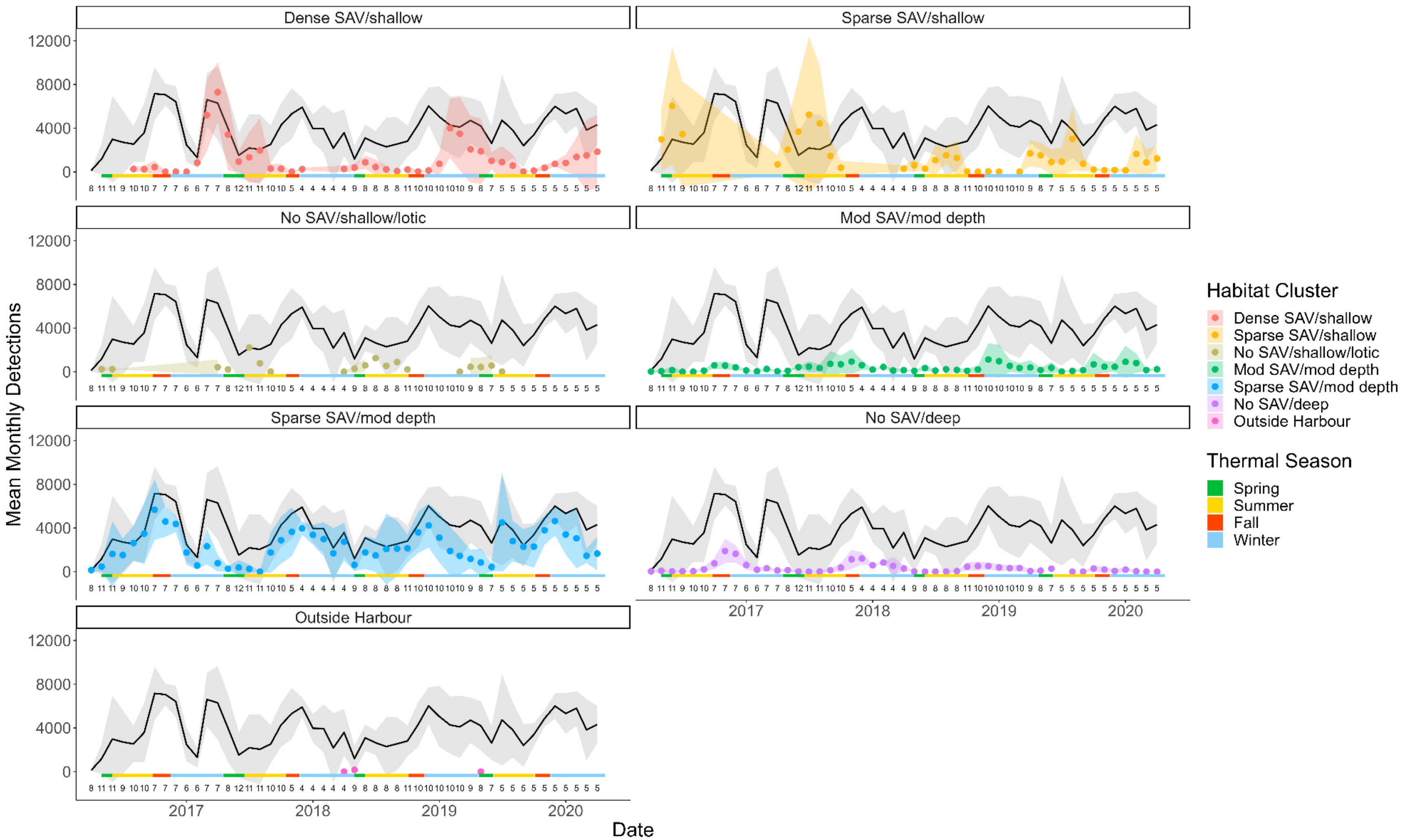


**Figure F3**. Mean (± SD) monthly detections of acoustically tagged Largemouth Bass at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Largemouth Bass.

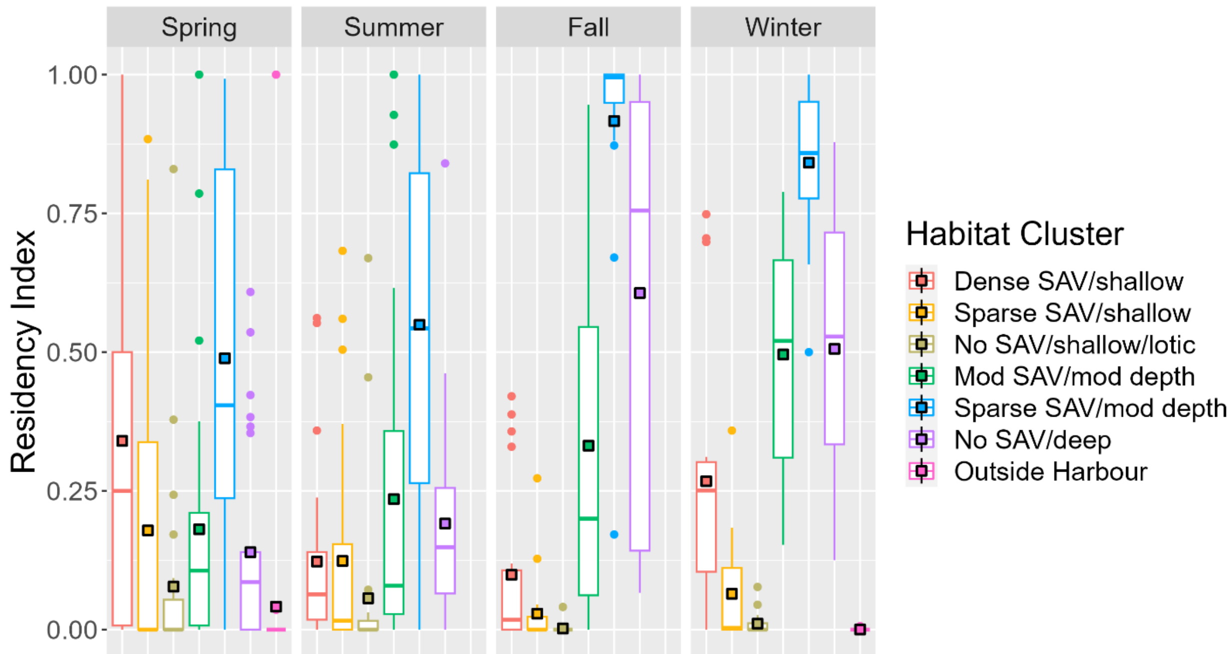


**Figure F4.** Boxplot of individual tagged Largemouth Bass residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

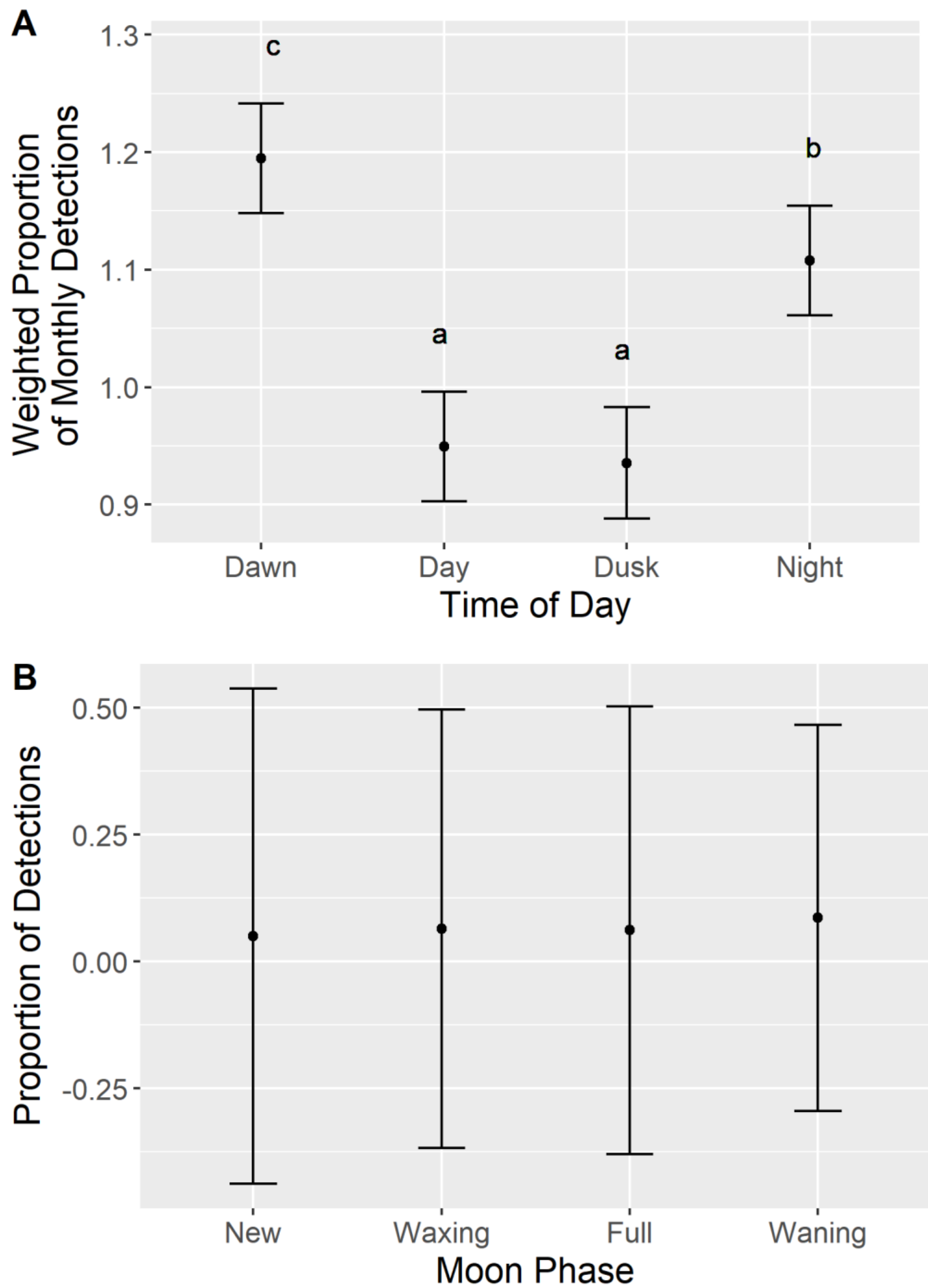


**Figure F5**. A) Mean (± SE) proportion of monthly detections of Largemouth Bass at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Largemouth Bass detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

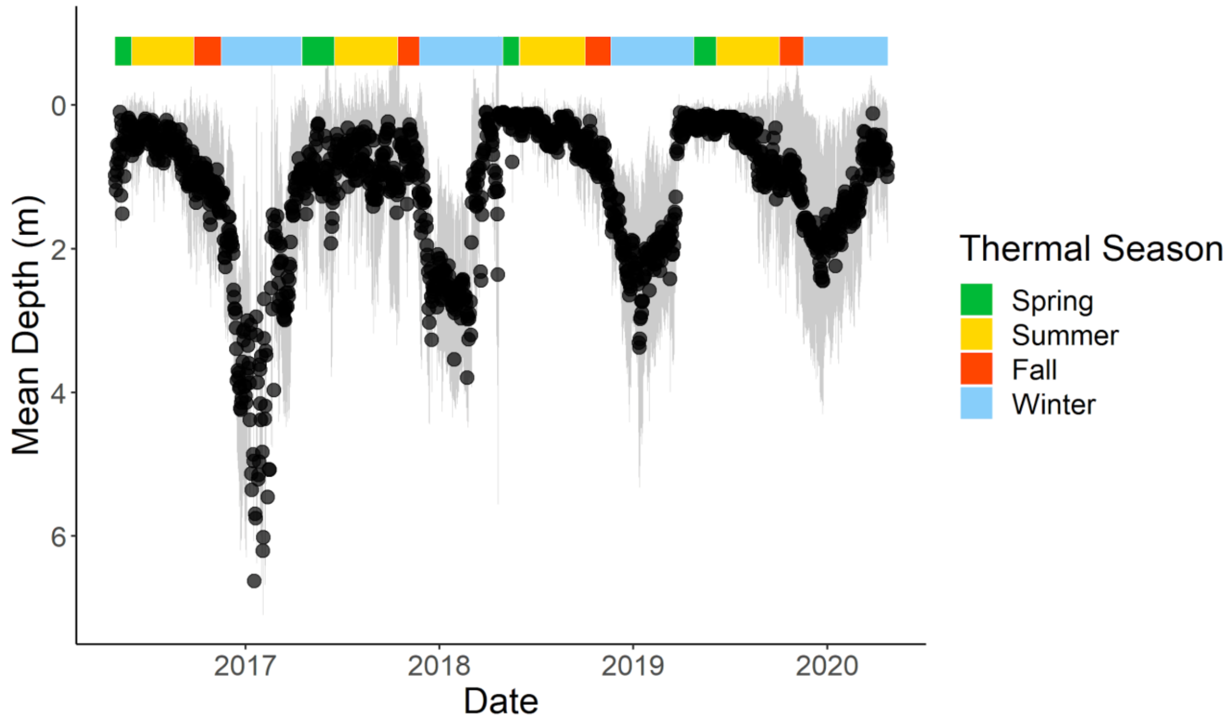


**Figure F6**. Mean (± SD) daily depth use of acoustically tagged Largemouth Bass in Hamilton Harbour over time. The coloured bar indicates the season over time.

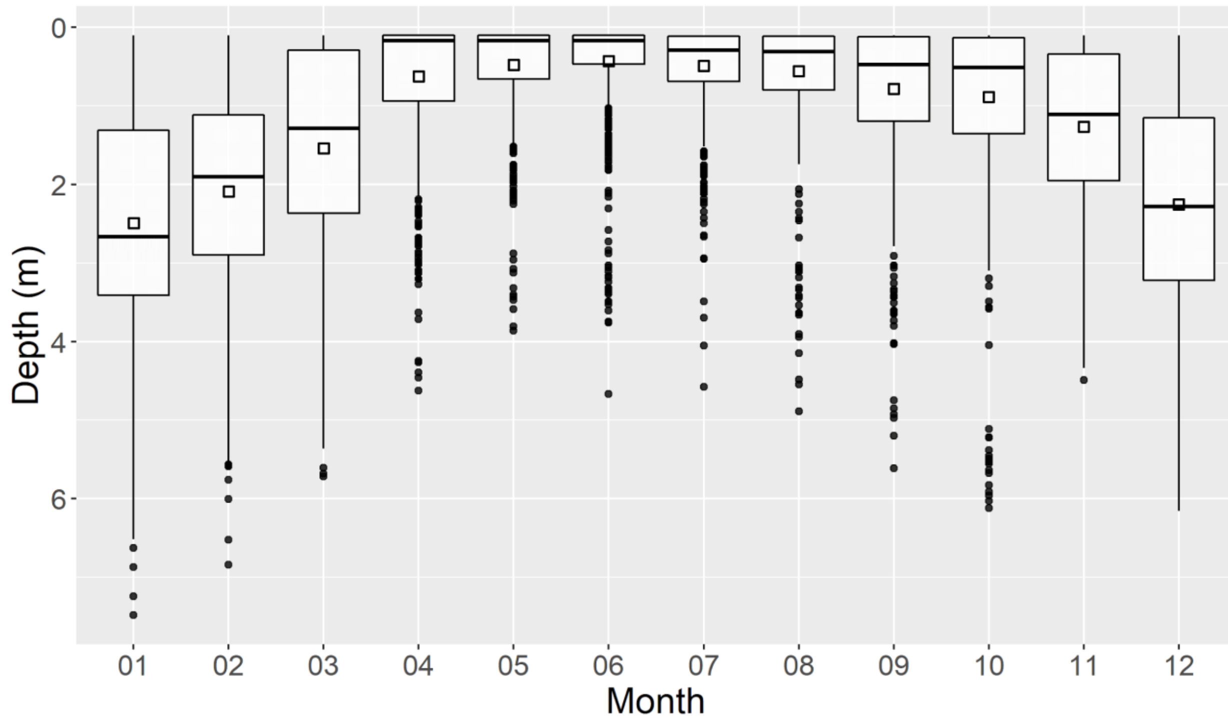


**Figure F7**. Boxplot of monthly depth use based on mean daily depths of acoustically tagged Largemouth Bass in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

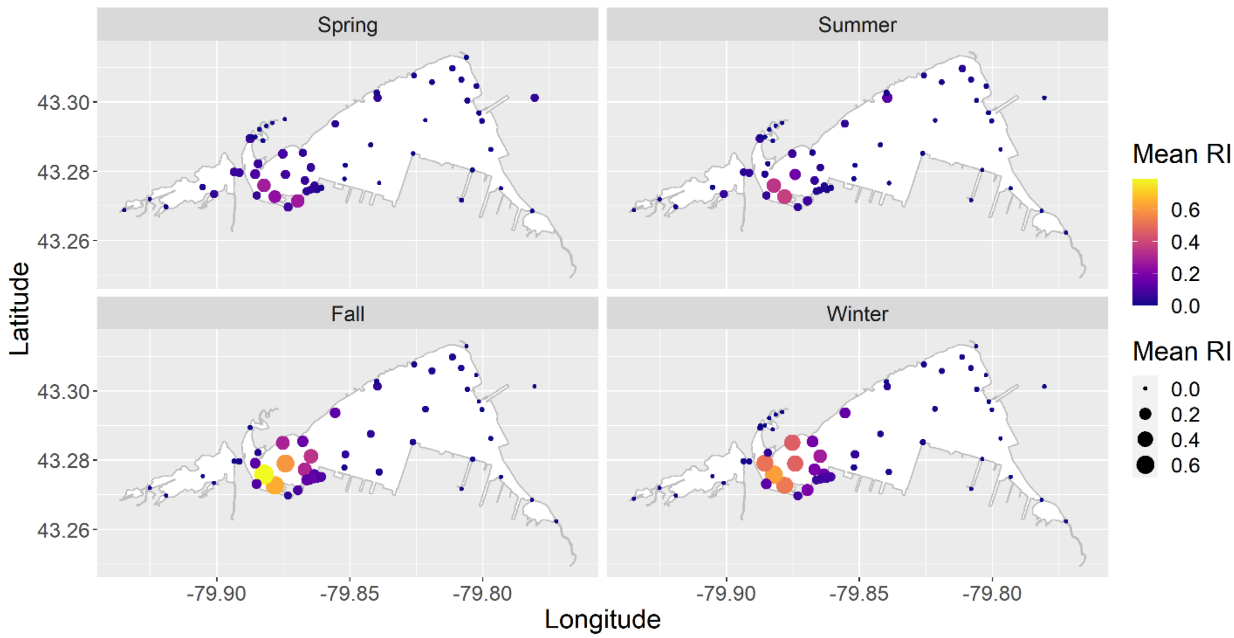


**Figure F8.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Largemouth Bass (N = 25). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

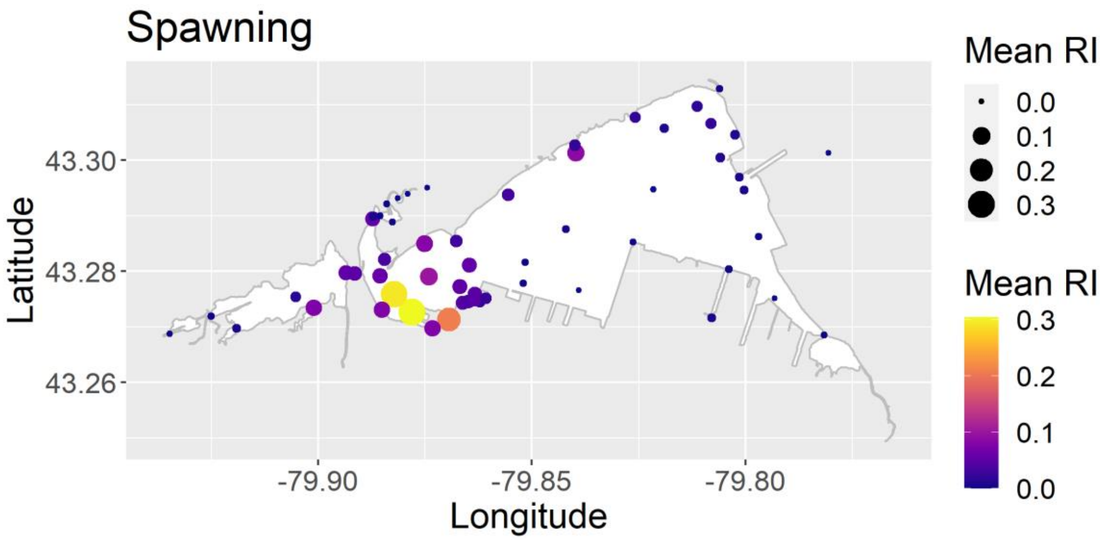


**Figure F9.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Largemouth Bass (N = 25) during their spawning window (May 1 to July 15). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

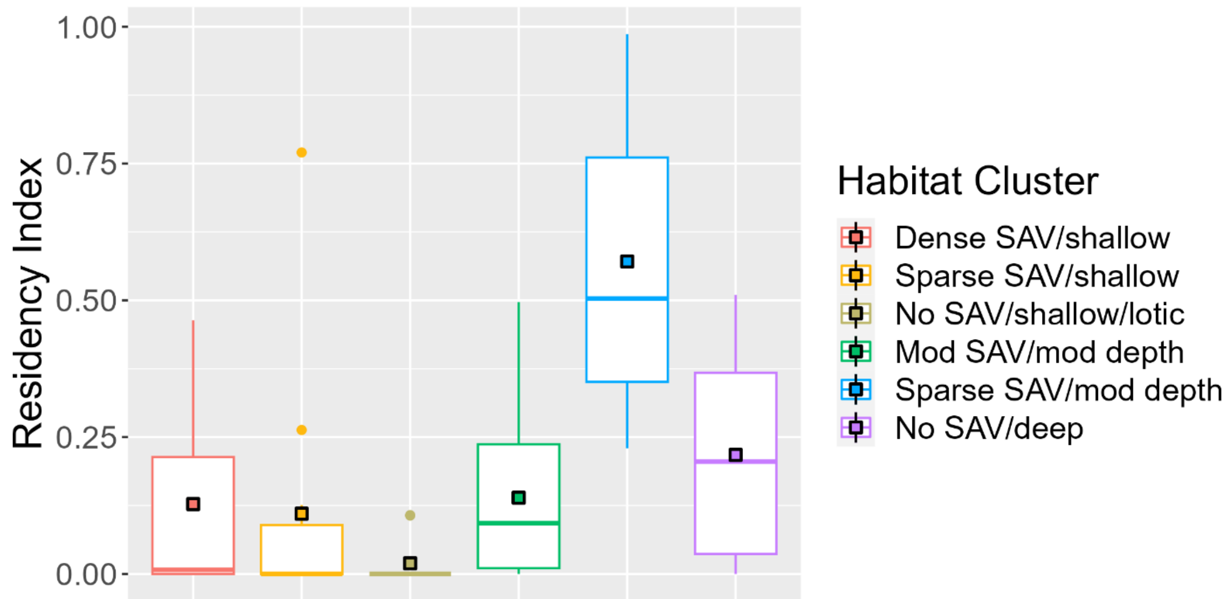


**Figure F10**. Boxplot of individual tagged Largemouth Bass residency during the spawning window (May 1 to July 15) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX G: LONGNOSE GAR

## DETECTIONS AND HABITAT USE

Thirteen Longnose Gar (*Lepisosteus osseus*) were acoustically tagged and monitored in Hamilton Harbour from June 2016 to April 2020 (**Table G1**). Based on mean monthly detections, there appears to be more overall detections in the summer and fewer in the winter, with a general affinity towards the Ottawa St. Slip in the summer and west end in the winter (**Figure G1**). No Longnose Gar were detected in Cootes Paradise. It appears that a portion of the tagged Longnose Gar generally leave Hamilton Harbour in the summer and return to the harbour in the winter (**Figure G2**). Of the ten Longnose Gar that left the harbour, six left and returned, and four left and never returned. The duration and extent of movements into Lake Ontario varied by individuals.

Based on the habitat clusters, Longnose Gar were primarily detected in areas of sparse or moderate SAV at moderate depths and no SAV and deep depths in the winter (**Figure G3**). From spring through fall, there was an increase of detections in areas of sparse SAV in shallow waters, (**Figure G3**). Habitat trends were slightly different when assessed based on seasonal residency by habitat clusters (**Figure G4**). Seasonal residency indicated that Longnose Gar were primarily residing in areas of sparse SAV in shallow waters year-round. To a lesser extent, from spring through fall, some Longnose Gar were also outside of the harbour, and in winter, they were in areas of no SAV and deep depths, and sparse and moderate SAV at moderate depths (**Figure G4**). Longnose Gar did not use lotic areas in the harbour nor dense SAV at shallow depths.

The number of detections were similar at different times of day (relative to the duration of time of each daylight category; $\chi^2_3 = 7.684$, $p = 0.053$), and there was no change in the relative number of detections based on moon phase ($\chi^2_3 = 4.259$, $p = 0.235$; **Figure G5**).

## DEPTH USE

The depth use of Longnose Gar appears to be seasonally cyclical (**Figure G6**) with shallowest depths during the spring (seasonal modelled mean ± SE = 0.2 ± 0.5 m) and summer (0.4 ± 0.4 m), followed by fall (2.1 ± 0.5 m), and lastly winter (4.6 ± 0.5 m; $X^2_3 = 4122$, $p < 0.001$). From a monthly perspective, Longnose Gar had increased depth use from November until March (mean ± SD depth ranged from 3.8 ± 3.5 m to 6.0 ± 4.4 m) and shallower depth use from May until September (mean ± SD depth ranged from 0.4 ± 0.5 m to 0.8 ± 1.0 m; **Figure G7**). The greatest depth use was in April along the north shore (max = 22.1 m).

## RESIDENCY

Spatially, Longnose Gar were generally detected in the Ottawa St. Slip or outside of the harbour. (**Figure G8**). The Ottawa St. Slip had a high residency year-round and all tagged Longnose Gar were captured and released at this site. However, in the fall, some Longnose Gar were returning and roaming around the harbour. In winter, residency of Longnose Gar decreased outside of the harbour and increased in the deeper waters of the west end (**Figure G8**), at the time when Longnose Gar moved to deeper depths (~6 m; **Figure G7**). When Longnose Gar were outside of Hamilton Harbour, the KUD home ranges were generally along the south shore of Lake Ontario towards the Niagara River in spring and summer (**Figure G9**). However, in the fall general home ranges were along the north shore of Lake Ontario towards Toronto, as well as along the south shore towards the Niagara River (**Figure G9**). In the winter, there were some detections at the mouth of the Niagara River but generally, Longnose Gar had returned to Hamilton Harbour or were otherwise undetected.

## SPAWNING

May 1 to June 30 was the spawning window used for Longnose Gar (**Table 2**), during which Longnose Gar were at their shallowest depths (mean monthly depths were ~0.4 m) (**Figure G7**). The shallow waters used in the spring and summer may be attributed to when Longnose Gar were spawning. Based on the residency index, during the spawning window, Longnose Gar appear to be in the Ottawa St. Slip, which is also where all Longnose Gar were tagged (**Table G1**), or outside of the harbour (**Figure G10**). Habitat-associated residency of Longnose Gar during the spawning window was greater in areas of sparse SAV at shallow depths or were outside of the harbour (**Figure G11**) indicating that Longnose Gar generally seem to go to semi-vegetated and shallow areas for spawning but it might occur in areas outside of the harbour as well.

**Table G1.** Tagging and detection summary of acoustically tagged Longnose Gar (*Lepisosteus osseus*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, or AD = alive and later died, based on the detection/depth profiles.

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15202 | 823 | 1230 | 6/30/2016 | Ottawa Slip | V13P-1L | TRUE | AD | 6/30/2016 | 4/25/2018 | 664 | 117068 | 506 |
| 15206 | 704 | 790 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 6/17/2017 | 353 | 38937 | 253 |
| 15207 | 728 | 1000 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 8/1/2018 | 763 | 116778 | 616 |
| 15208 | 727 | 910 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/30/2016 | 6/16/2017 | 351 | 38712 | 270 |
| 15211 | 781 | 1110 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 10/22/2019 | 1210 | 219139 | 1101 |
| 15212 | 858 | 1650 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 5/16/2018 | 686 | 151067 | 629 |
| 15213 | 752 | 970 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 8/21/2018 | 783 | 133681 | 602 |
| 15217 | 680 | 680 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 8/17/2018 | 779 | 92189 | 543 |
| 15203 | 732 | 790 | 6/30/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/30/2016 | 9/3/2018 | 795 | 33927 | 309 |
| 15205 | 920 | 1750 | 6/30/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/30/2016 | 5/12/2017 | 316 | 46822 | 291 |
| 15209 | 978 | 2370 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 4/12/2020 | 1383 | 64836 | 463 |
| 15210 | 902 | 1330 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 10/4/2019 | 1192 | 1767 | 57 |
| 15214 | 834 | 1290 | 6/29/2016 | Ottawa Slip | V13P-1L | TRUE | A | 6/29/2016 | 11/2/2016 | 126 | 20511 | 124 |

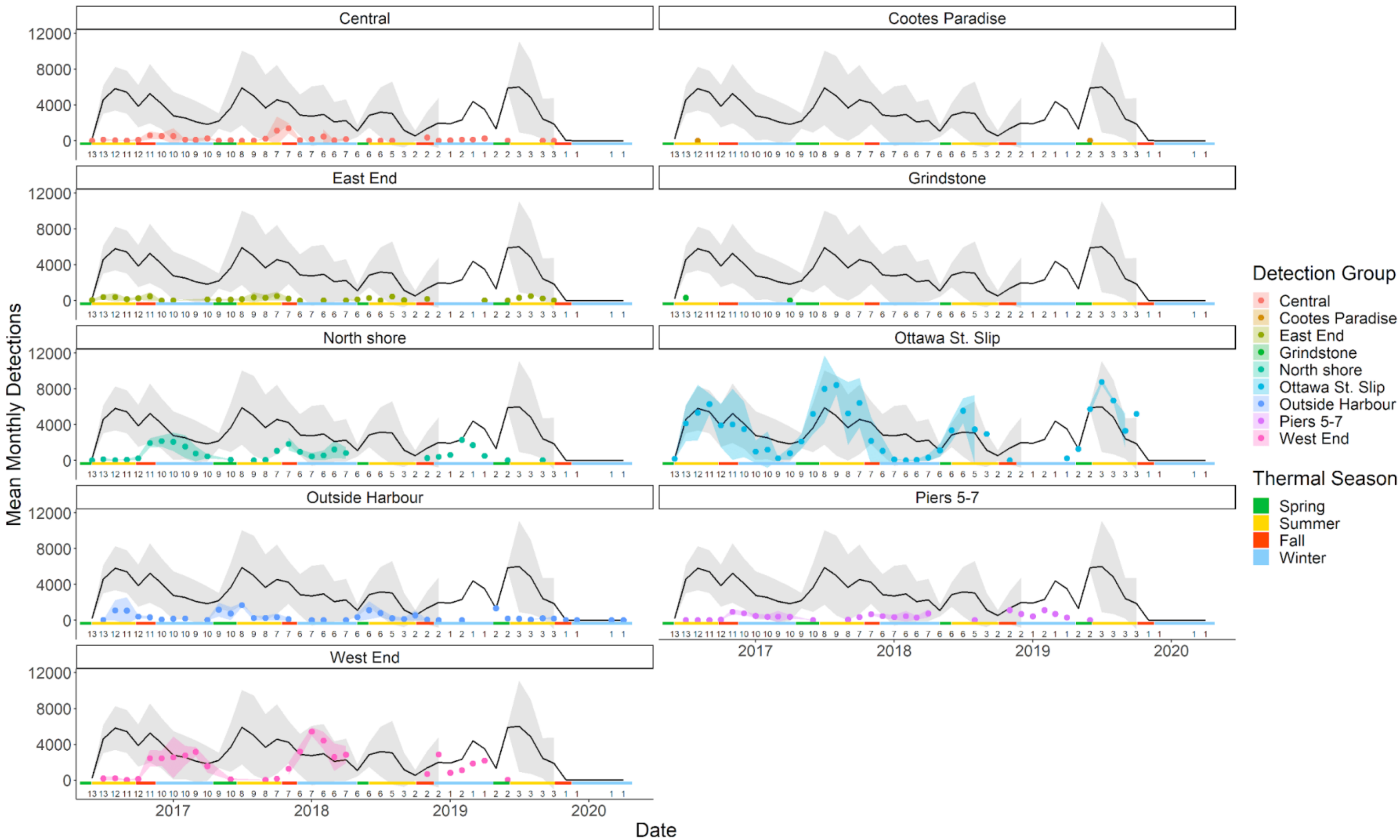


**Figure G1.** Mean (± SD) monthly detections of acoustically tagged Longnose Gar at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Longnose Gar at that time.

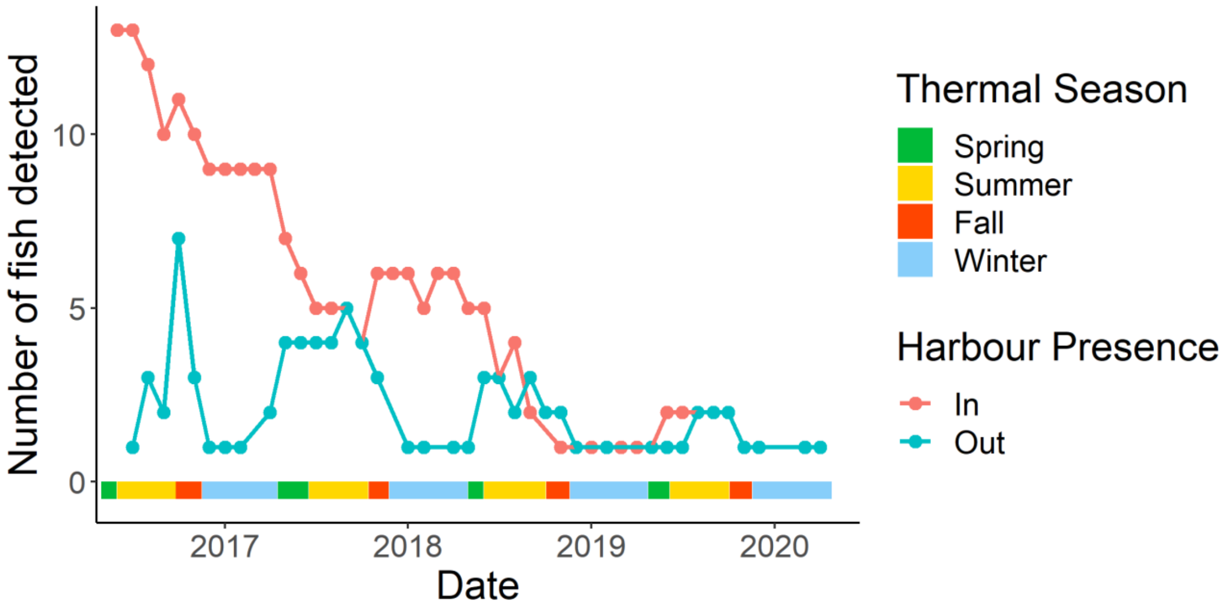


**Figure G2.** Monthly number of acoustically tagged Longnose Gar detected in or out of Hamilton Harbour over time. The coloured bar indicates the season over time.

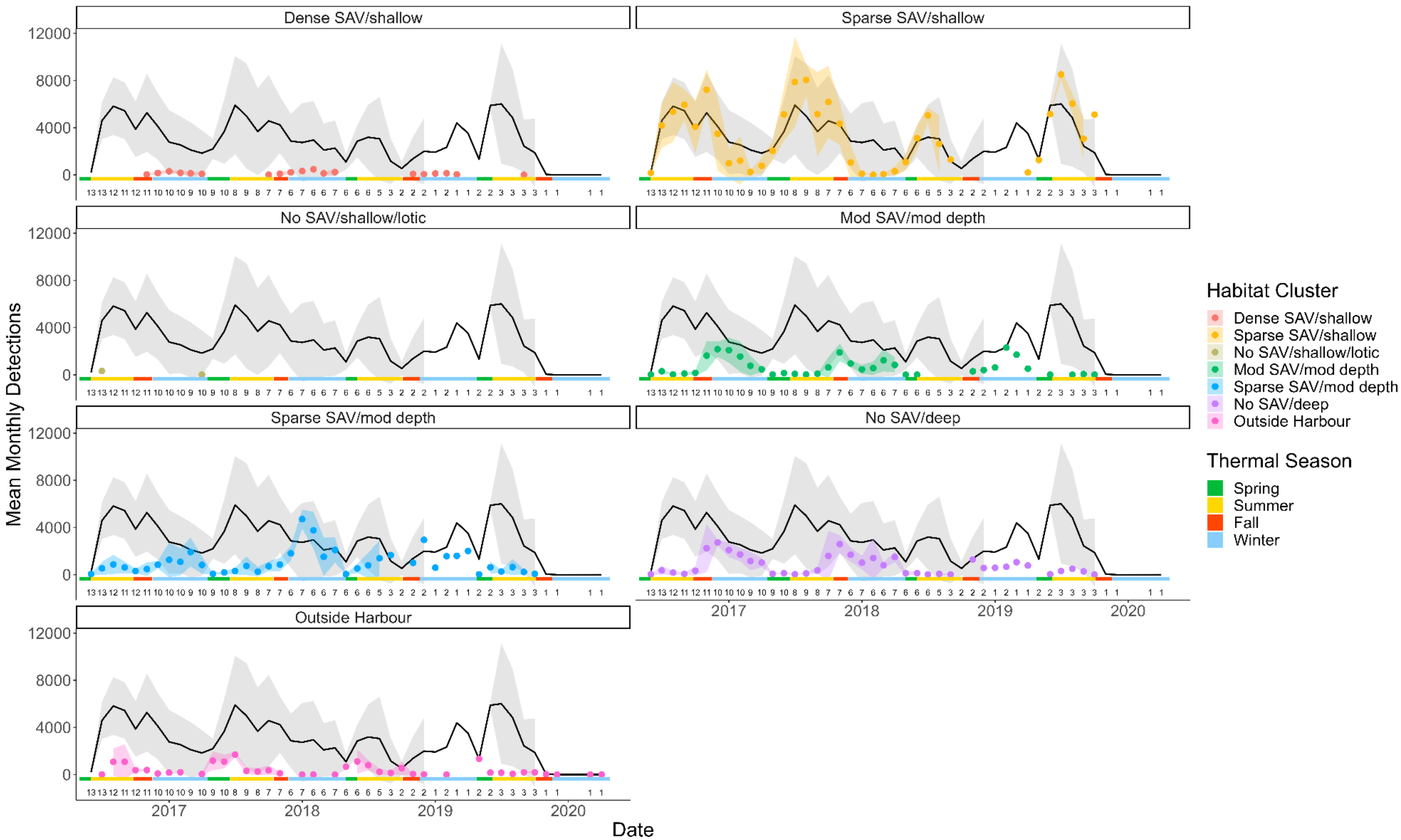


**Figure G3**. Mean (± SD) monthly detections of acoustically tagged Longnose Gar at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Longnose Gar.

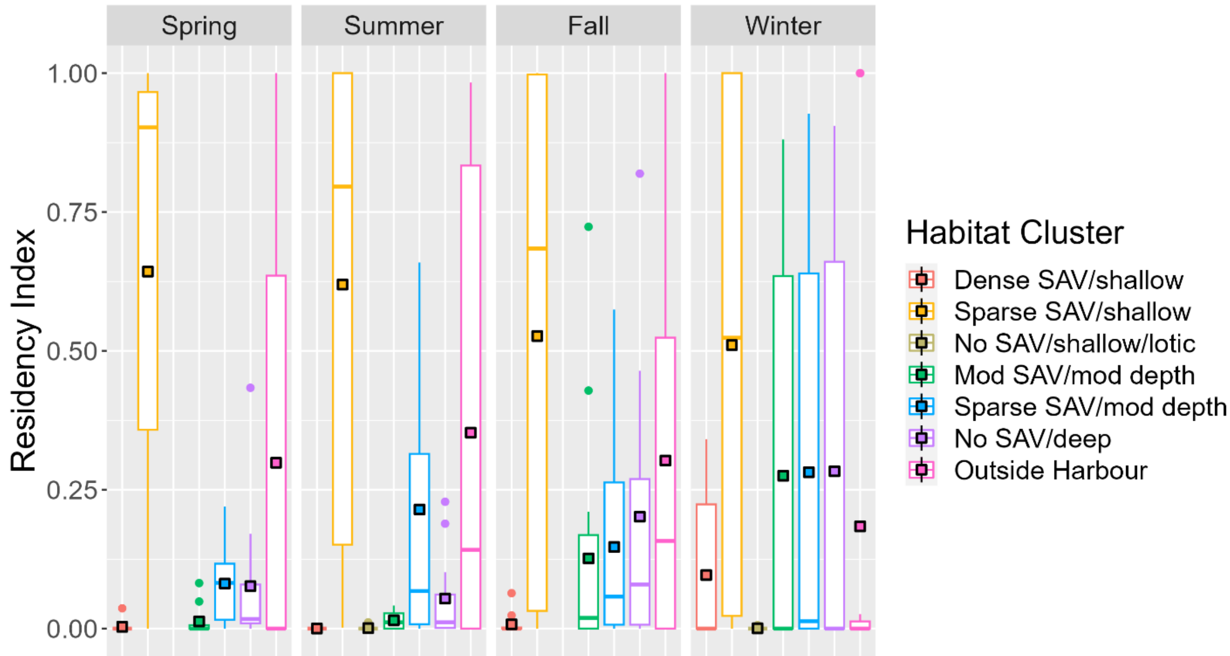


**Figure G4.** Boxplot of individual tagged Longnose Gar residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

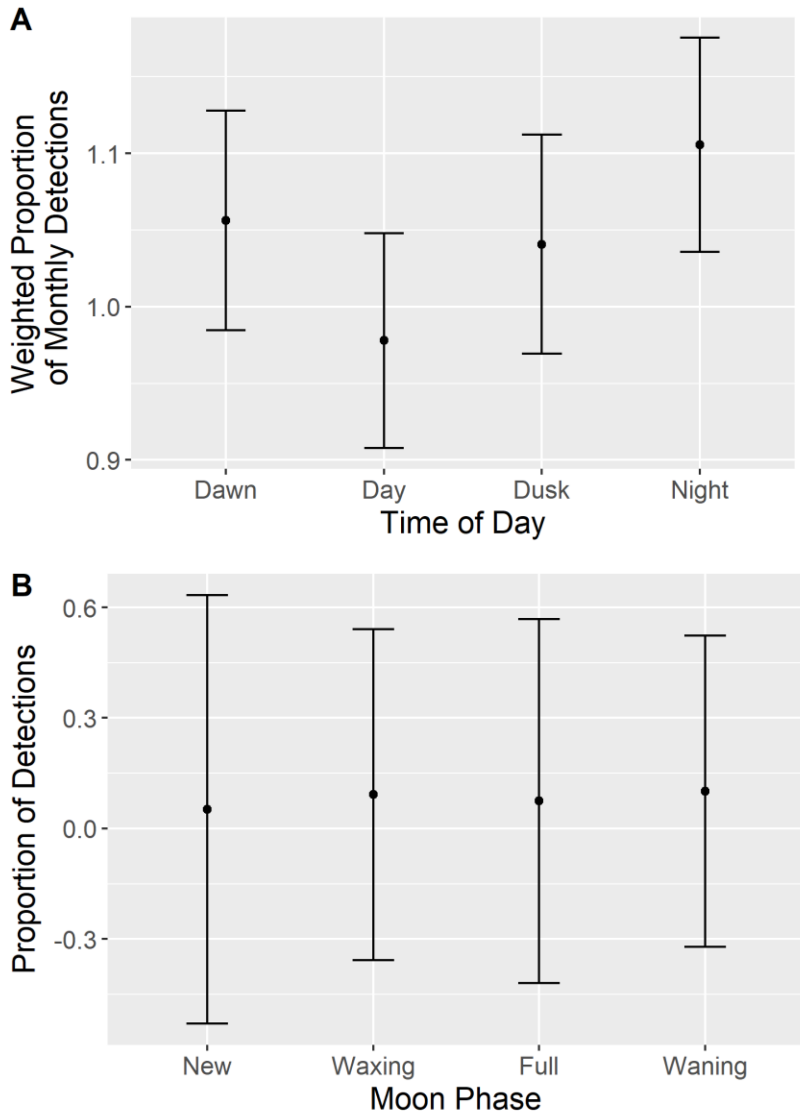


**Figure G5**. A) Mean (± SE) proportion of monthly detections of Longnose Gar at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Longnose Gar detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

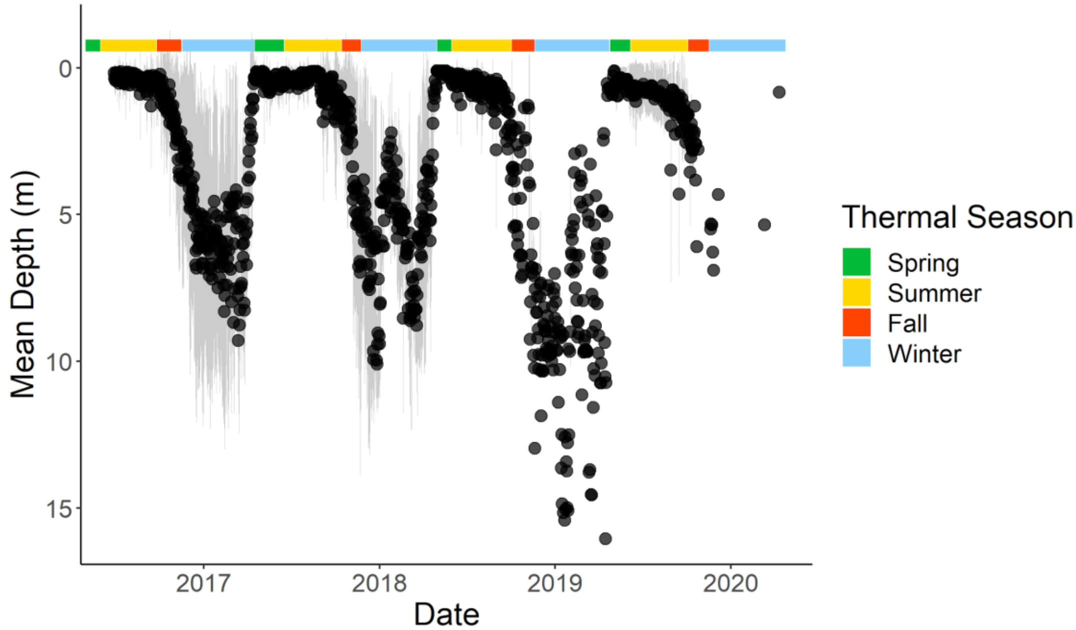


**Figure G6**. Mean (± SD) daily depth use of acoustically tagged Longnose Gar in Hamilton Harbour over time. The coloured bar indicates the season over time.

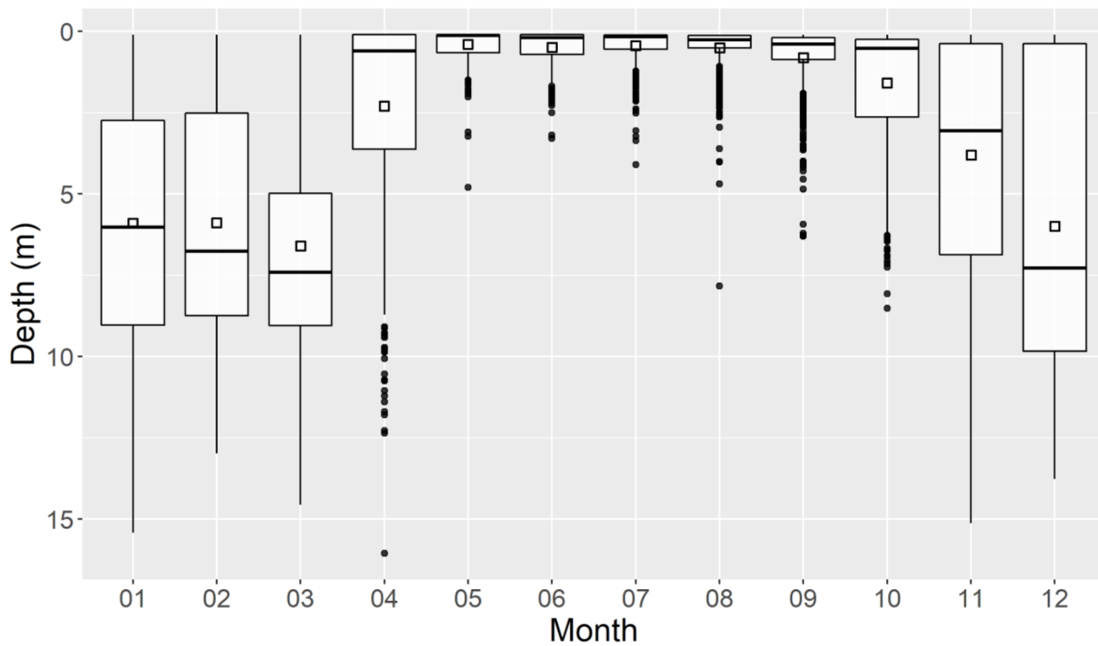


**Figure G7.** Boxplot of monthly depth use based on mean daily depths of acoustically tagged Longnose Gar in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

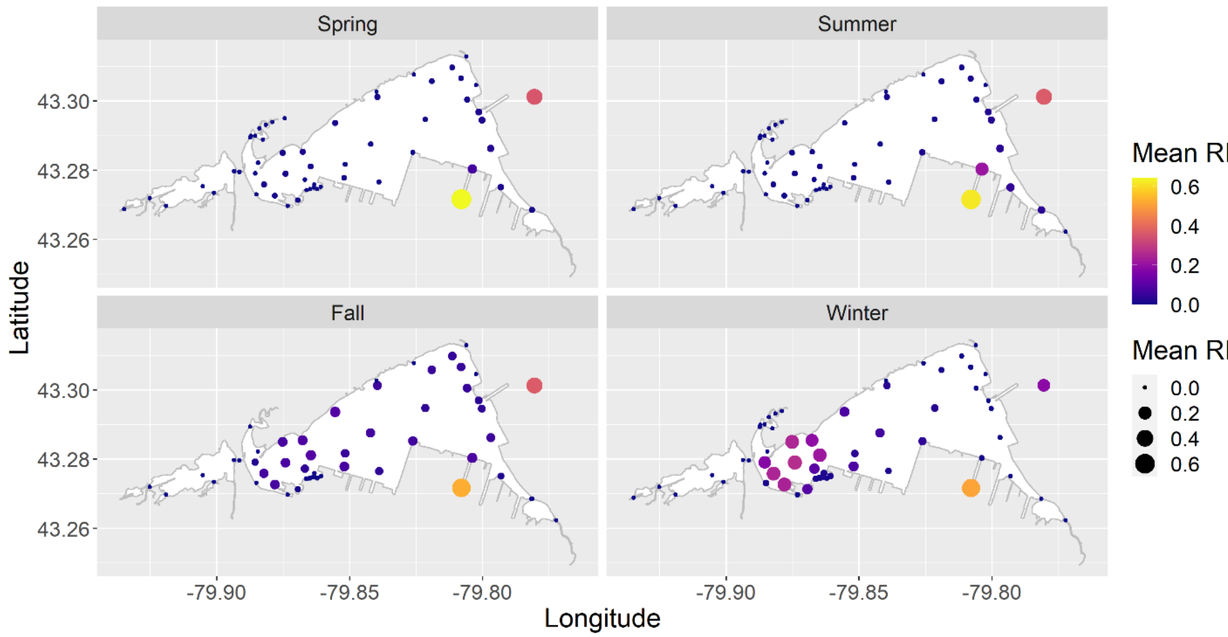


**Figure G8.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Longnose Gar (N = 13). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

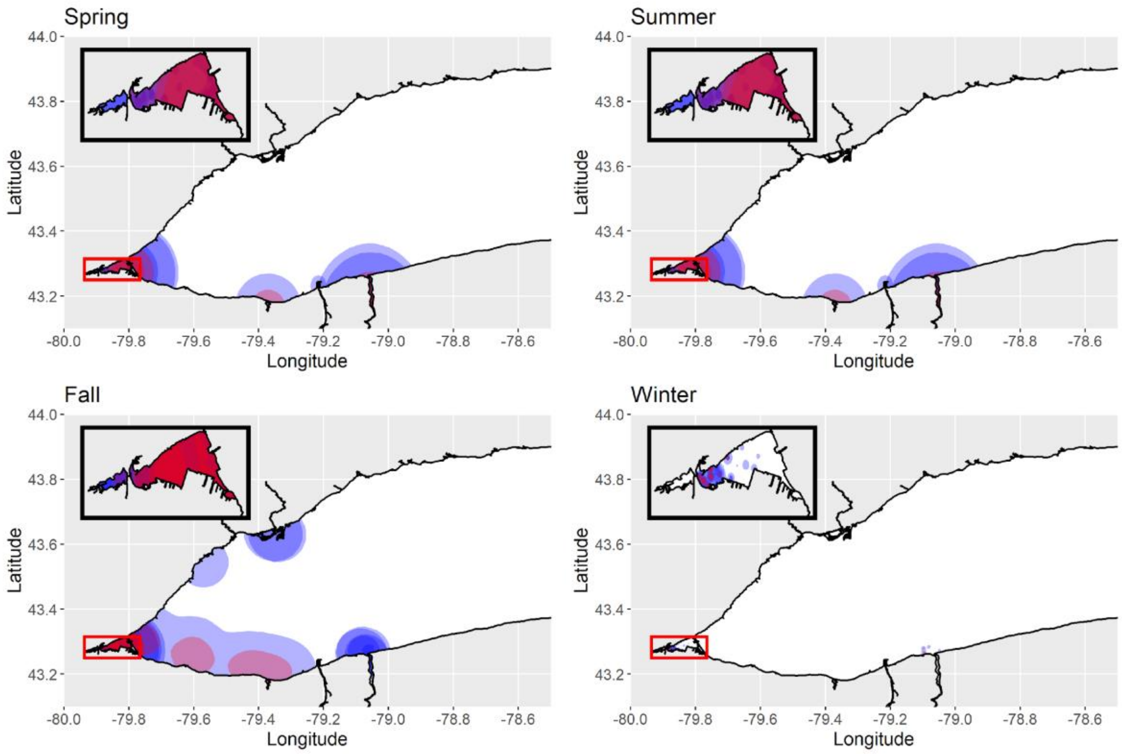


**Figure G9**. Seasonal 50% (red) and 95% (blue) home ranges (via kernel utilization distribution) of individual Longnose Gar tagged in Hamilton Harbour, 2016 – 2020. Darker colours indicate overlapping home ranges of individuals. Most Longnose Gar left the harbour at some point during the study but the duration and distance varied.

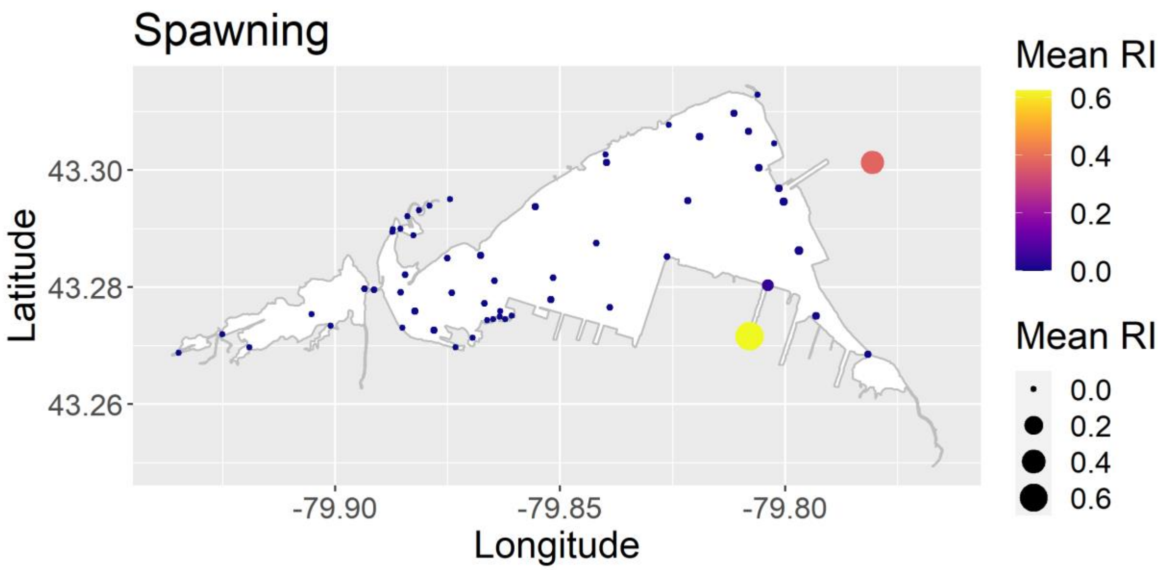


**Figure G10.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Longnose Gar (N = 13) during their spawning window (May 1 to June 30). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

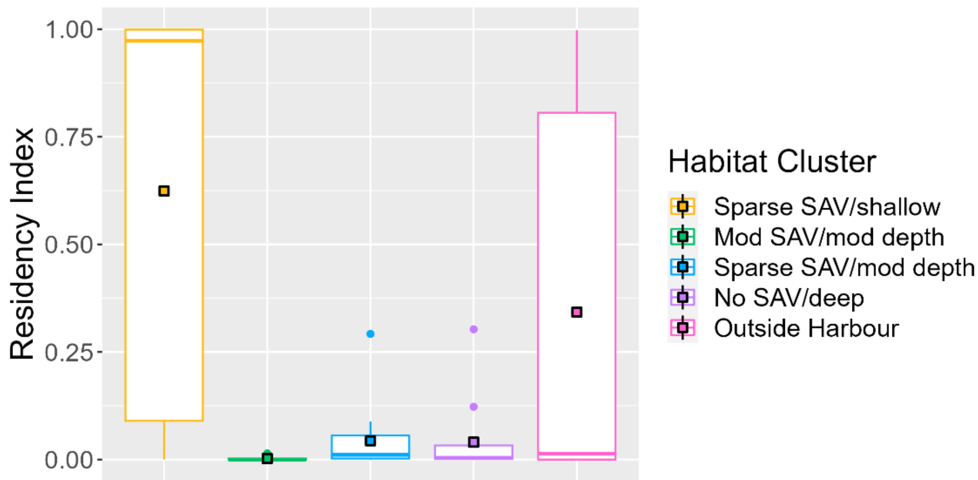


**Figure G11**. Boxplot of individual tagged Longnose Gar residency during the spawning window (May 1 to June 30) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX H: NORTHERN PIKE

## DETECTIONS AND HABITAT USE

Twenty-four Northern Pike (*Esox lucius*) were acoustically tagged and monitored in Hamilton Harbour from April 2016 to April 2020 (**Table H1**). Based on mean monthly detections, there were more overall detections of Northern Pike in the fall and fewer in the spring, however, this trend disappeared with more receiver coverage in 2019 (**Figure H1**). Northern Pike had a general affinity towards the west end year-round, yet as the array expanded, Northern Pike were also detected at Grindstone Creek in the spring, and at Cootes Paradise Marsh and Piers 5-7 in the summer (**Figure H1**). Further investigation revealed six Northern Pike entered Cootes Paradise Marsh proper (detected at Station 31), with two pike reaching Spencer Creek (this did not include fish detected at the fishway - Station 32 and 43). Northern Pike were mostly detected in Cootes Paradise Marsh from March until June before returning to the harbour, however, a few entered and remained for longer durations before leaving. Two fish repeatedly entered and left Cootes Paradise. All Northern Pike remained within the harbour year-round.

Based on the habitat clusters, Northern Pike were primarily detected in areas of sparse SAV at moderate depths year-round (**Figure H2**). In the fall, late winter and spring, there was an increase of detections in areas of dense SAV in shallow waters, and to a lesser extent an increase of detections in areas of sparse SAV in shallow waters (**Figure H2**). Habitat trends were slightly different when assessed based on seasonal residency by habitat clusters (**Figure H3**). Seasonal residency indicated that Northern Pike were primarily located in areas of sparse SAV at moderate depths year-round. However, to a lesser extent Northern Pike also used areas of sparse and dense SAV in shallow waters in the spring, and areas of moderate SAV at moderate depths and no SAV at deep depths in the fall and winter.

There was an increase in detections during night, followed by dawn and dusk, compared to daytime (relative to the duration of time of each daylight category; $\chi^2_3 = 140.100$, $p < 0.001$), but no change in the relative number of detections based on moon phase ($\chi^2_3 = 1.660$, $p = 0.646$; **Figure H4**).

## DEPTH USE

The depth use of Northern Pike was seasonally cyclical (**Figure H5**) with shallowest depths during the spring (seasonal modelled mean ± SE = 0.6 ± 0.3 m), followed by fall (1.6 ± 0.3 m), then summer (1.8 ± 0.3 m), and lastly winter (2.5 ± 0.3 m; $X^2_3 = 886.32$, $p < 0.001$). From a monthly perspective, Northern Pike had increased depth use from July until September (mean ± SD depth ranged from 1.9 ± 2.1 m to 2.1 ± 2.1 m) and November until March (mean ± SD depth ranged from 2.1 ± 1.8 m to 3.4 ± 2.5 m) and shallower depth use from April until June (mean ± SD depth ranged from 0.6 ± 0.6 m to 0.8 ± 1.0 m) and during October (1.4 ± 1.4 m; **Figure H6**). The greatest depth use was during the winter in the central basin (max = 22.9 m).

## RESIDENCY

Spatially, Northern Pike had the greatest residency at the west end, year-round (**Figure H7**). However, this west end residency shifted into slightly deeper waters in the fall and winter where Northern Pike were residing at depths of ~1.5 – 3.5 m (**Figure H6**). In the spring and summer, west end residency was greater closer to shore, towards Bayfront. Also, in the spring, there was a slight increase of Northern Pike residency in Cootes Paradise Marsh and at the mouth of Grindstone Creek. Overall residency values were lower in spring and summer which may indicate periods of time with lower detectability.

## SPAWNING

March 15 to April 30 was the spawning window used for Northern Pike (**Table 2**), during which Northern Pike were quite shallow (mean monthly depths were ~0.7 m) (**Figure H6**). The shallow waters used in the spring may be attributed to when Northern Pike were spawning. Based on the residency index, during the spawning window, Northern Pike appear to be in the west end, towards Bayfront, and to a lesser extent along the north shore, in Grindstone Creek and in Cootes Paradise Marsh (**Figure H8**). Habitat-associated residency of Northern Pike during the spawning window was greater in areas of sparse SAV at moderate and shallow depths, and to a lesser extent all other habitat clusters were equally represented (**Figure H9**). Habitat residency indicates that Northern Pike generally seem to go to semi-vegetated areas for spawning but will also be found in a variety of habitats, including traversing in lotic areas to find suitable spawning habitat.

**Table H1.** Tagging and detection summary of acoustically tagged Northern Pike (*Esox lucius*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive or AD = alive and later died, based on the detection/depth profiles. Note: RBG = Royal Botanical Gardens. Dash means no data recorded.

| Tag ID | Fork Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 29 | 590 | - | 10/27/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 5/29/2017 | 394 | 51459 | 247 |
| 31 | 575 | - | 10/26/2015 | West | V13P-1L | TRUE | AD | 4/30/2016 | 10/6/2016 | 159 | 7548 | 44 |
| 41 | 632 | - | 10/27/2015 | West | V13P-1L | TRUE | AD | 5/13/2016 | 7/1/2016 | 49 | 3859 | 37 |
| 14180 | 590 | 1470 | 10/11/2018 | Bayfront | V13P-1L | TRUE | AD | 10/12/2018 | 9/1/2019 | 324 | 41637 | 277 |
| 14795 | 649 | 2180 | 3/23/2018 | RBG Fishway | V13P-1L | TRUE | AD | 3/23/2018 | 3/30/2019 | 372 | 50036 | 344 |
| 14796 | 548 | 1430 | 3/23/2018 | RBG Fishway | V13P-1L | TRUE | AD | 3/23/2018 | 9/10/2018 | 171 | 13037 | 138 |
| 15246 | 580 | 1391 | 7/27/2016 | West Islands | V13P-1L | TRUE | AD | 8/15/2016 | 10/8/2017 | 419 | 52337 | 256 |
| 15448 | 550 | - | 6/21/2016 | Bayfront | V13P-1L | TRUE | AD | 6/27/2016 | 9/29/2016 | 94 | 9033 | 77 |
| 15452 | 923 | - | 6/18/2016 | Bayfront | V13P-1L | TRUE | A | 6/21/2016 | 7/15/2017 | 389 | 57377 | 338 |
| 15773 | 705 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 4/17/2017 | 352 | 33440 | 268 |
| 15831 | 778 | 3500 | 10/20/2017 | Bayfront | V13P-1L | TRUE | AD | 10/21/2017 | 8/1/2019 | 649 | 93855 | 605 |
| 15834 | 700 | 2400 | 10/20/2017 | Bayfront | V13P-1L | TRUE | AD | 10/20/2017 | 9/10/2018 | 325 | 58514 | 258 |
| 14179 | - | - | 10/11/2018 | Bayfront | V13P-1L | TRUE | A | 10/12/2018 | 4/25/2020 | 561 | 106696 | 452 |
| 14800 | 701 | 2110 | 10/11/2018 | Police Docks | V13P-1L | TRUE | A | 10/12/2018 | 4/25/2020 | 561 | 164388 | 537 |
| 15449 | 650 | - | 6/21/2016 | Islands West | V13P-1L | TRUE | A | 6/22/2016 | 9/13/2016 | 83 | 3982 | 74 |
| 15832 | 715 | 3000 | 10/20/2017 | Bayfront | V13P-1L | TRUE | A | 10/20/2017 | 4/25/2020 | 918 | 162850 | 868 |
| 15833 | 703 | 2600 | 10/20/2017 | Bayfront Beach | V13P-1L | TRUE | A | 10/20/2017 | 4/4/2018 | 166 | 22870 | 161 |
| 15837 | 710 | 2600 | 10/20/2017 | Bayfront Beach | V13P-1L | TRUE | A | 10/20/2017 | 3/23/2020 | 885 | 147944 | 817 |
| 15842 | 592 | 1620 | 10/5/2017 | Desjardins West | V13P-1L | TRUE | A | 10/5/2017 | 4/21/2020 | 929 | 81071 | 710 |
| 15843 | 597 | 1400 | 10/5/2017 | Desjardins West | V13P-1L | TRUE | A | 10/5/2017 | 4/13/2018 | 190 | 26480 | 181 |
| 15845 | 821 | - | 10/5/2017 | Bayfront | V13P-1L | TRUE | A | 10/5/2017 | 4/25/2020 | 933 | 170802 | 893 |
| 15861 | 562 | 1250 | 6/28/2017 | Rowing Club | V13P-1L | TRUE | A | 6/29/2017 | 4/25/2020 | 1031 | 254718 | 909 |
| 15864 | 690 | 2250 | 10/3/2017 | Macassa Bay | V13P-1L | TRUE | A | 10/3/2017 | 4/25/2020 | 935 | 153506 | 883 |
| 15877 | 878 | 4850 | 6/26/2017 | Bayfront | V13P-1L | TRUE | A | 6/27/2017 | 8/15/2018 | 414 | 97426 | 404 |

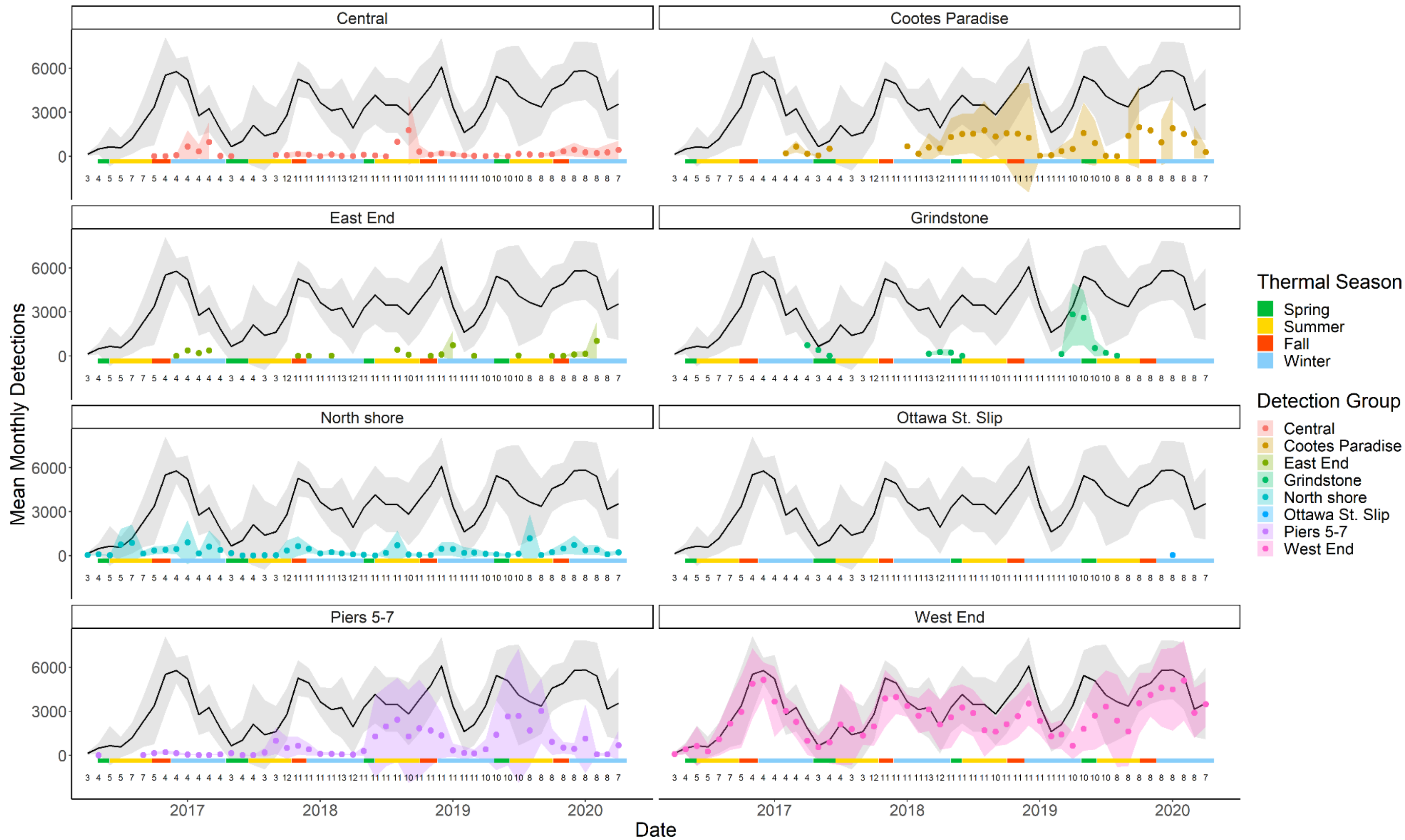


**Figure H1.** Mean (± SD) monthly detections of acoustically tagged Northern Pike at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Northern Pike at that time.

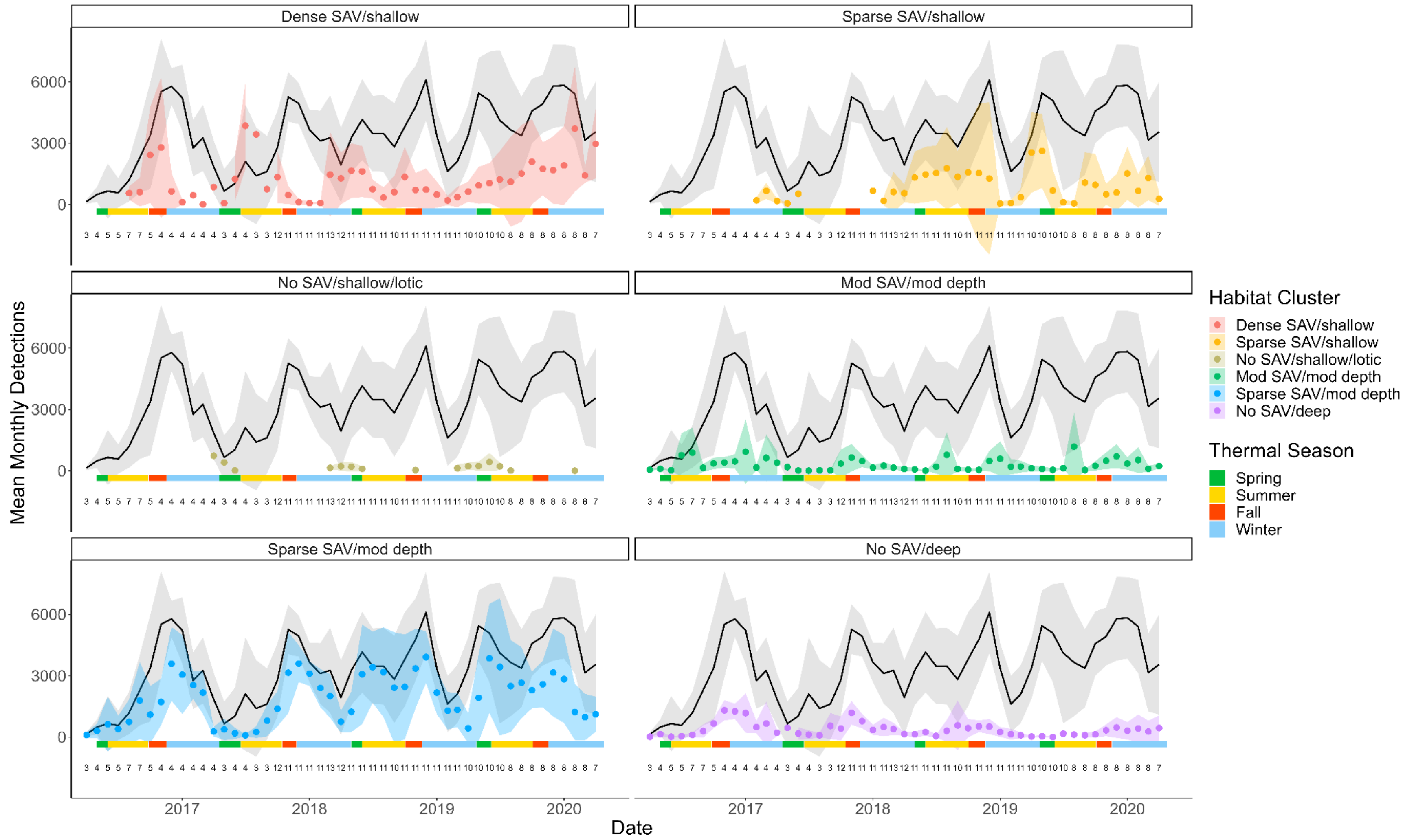


**Figure H2**. Mean (± SD) monthly detections of acoustically tagged Northern Pike at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Northern Pike.

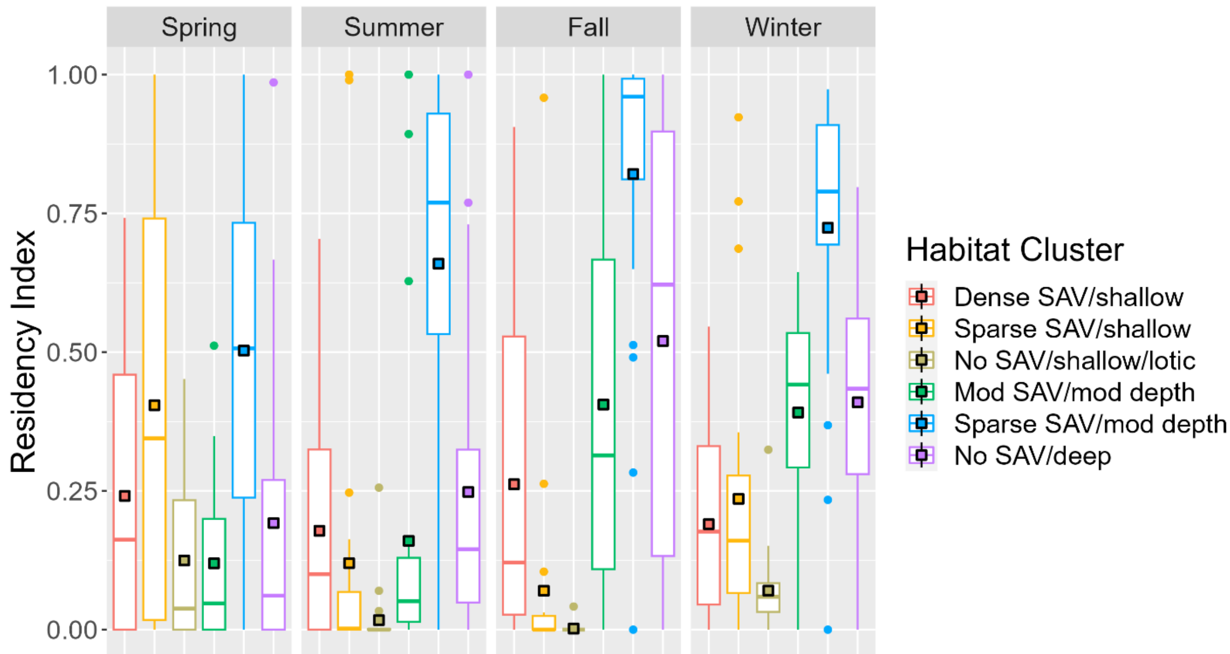


**Figure H3.** Boxplot of individual tagged Northern Pike residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

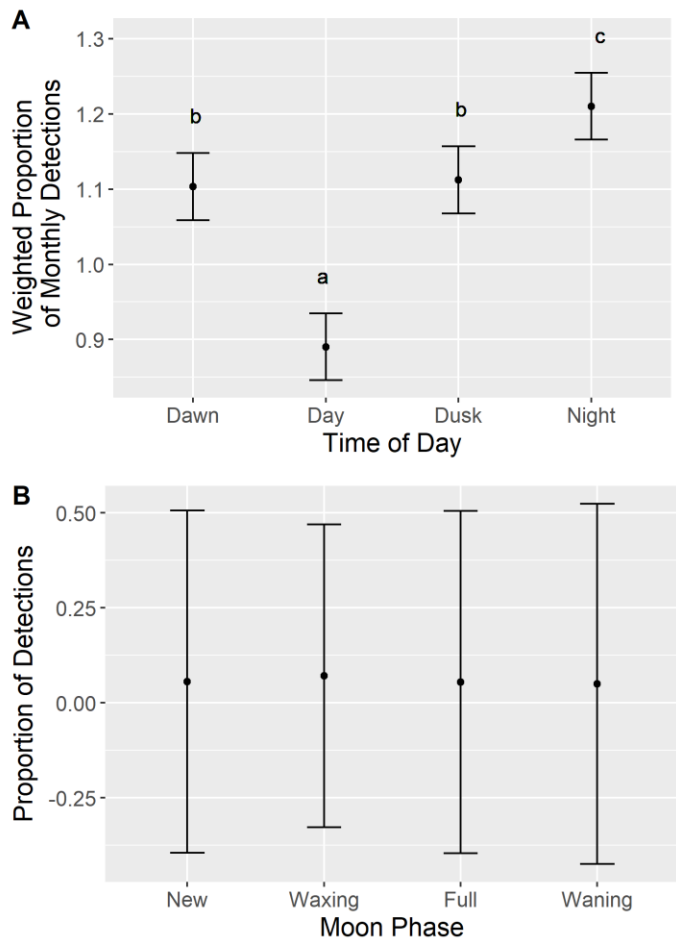


**Figure H4**. A) Mean (± SE) proportion of monthly detections of Northern Pike at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Northern Pike detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

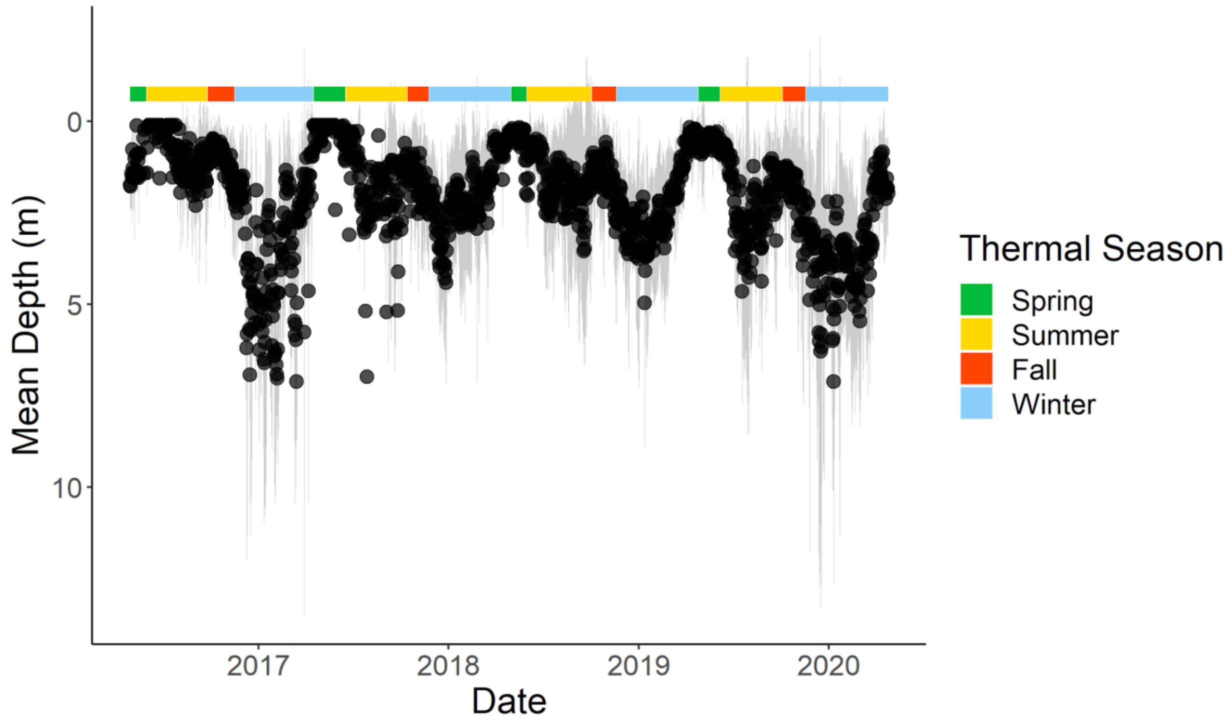


**Figure H5**. Mean (± SD) daily depth use of acoustically tagged Northern Pike in Hamilton Harbour over time. The coloured bar indicates the season over time.

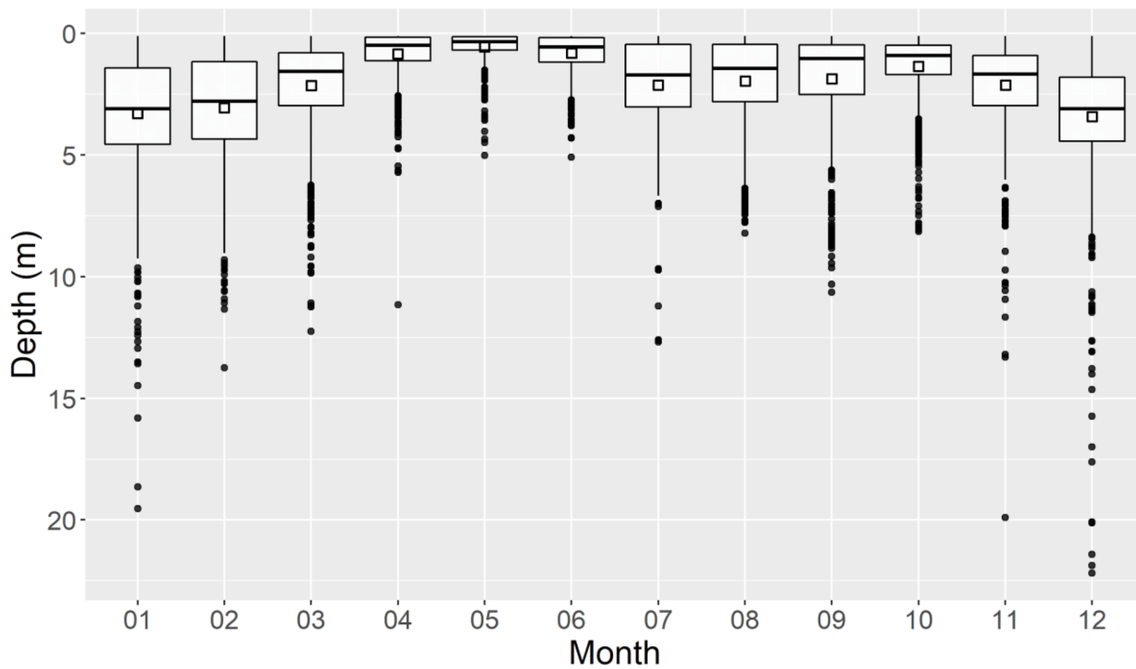


**Figure H6.** Boxplot of monthly depth use based on mean daily depths of acoustically tagged Northern Pike in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

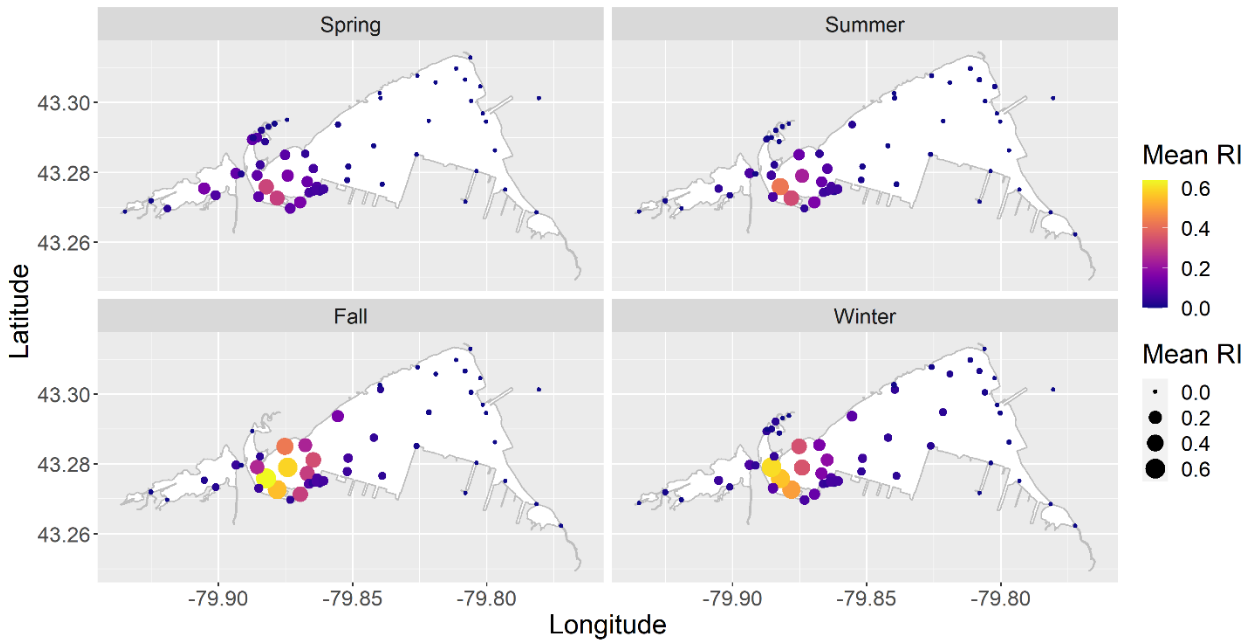


**Figure H7.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Northern Pike (N = 24). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

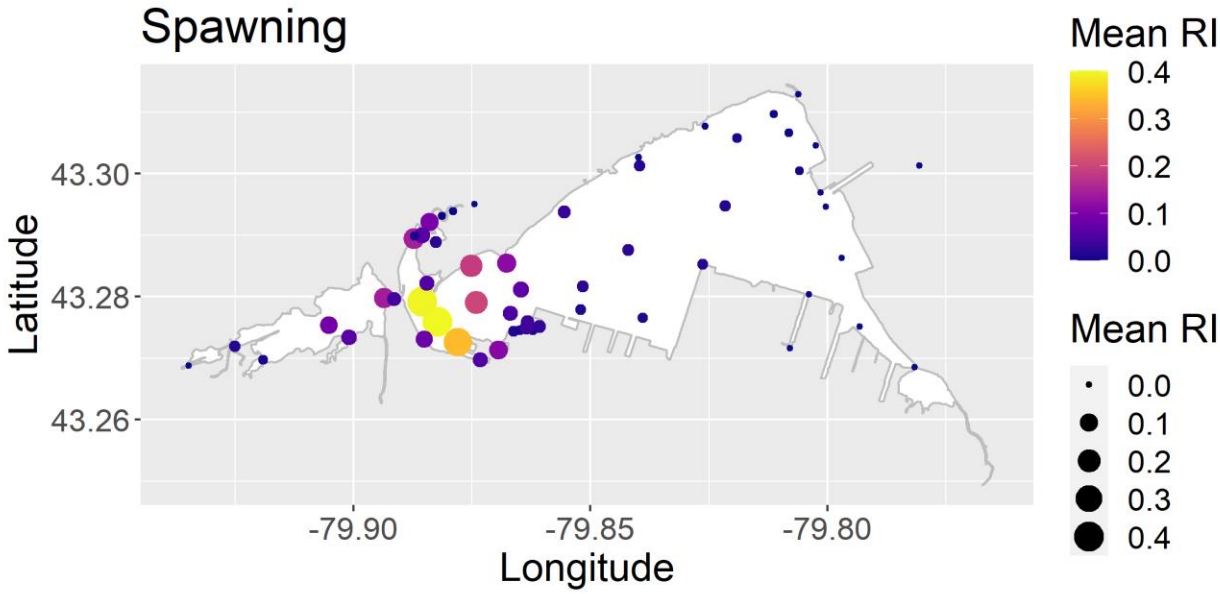


**Figure H8.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Northern Pike (N = 24) during their spawning window (March 15 to April 30). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

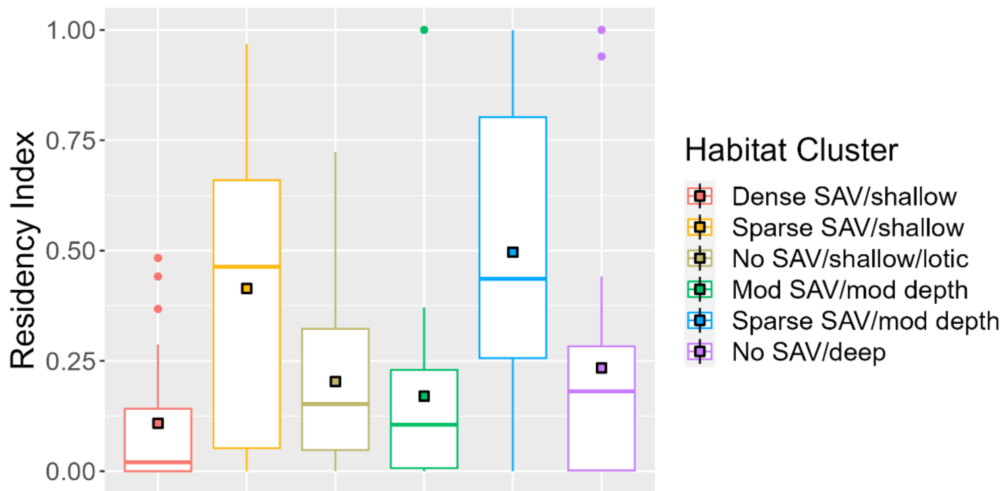


**Figure H9**. Boxplot of individual tagged Northern Pike residency during the spawning window (March 15 to April 30) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX I: SMALLMOUTH BASS

## DETECTIONS AND HABITAT USE

Six Smallmouth Bass (*Micropterus dolomieu*) were acoustically tagged and monitored in Hamilton Harbour from June 2017 to April 2020 (**Table I1**). Based on mean monthly detections, Smallmouth Bass had a general affinity towards Piers 5-7 year-round with some detections in the west end in the summer (**Figure I1**). No Smallmouth Bass entered Cootes Paradise Marsh or left the harbour during the study period.

Based on mean monthly detections at habitat clusters, Smallmouth Bass were primarily detected in areas of sparse SAV at moderate depths year-round (**Figure I2**). However, in the summer, Smallmouth Bass were also detected in areas of dense SAV in shallow waters, and in the winter were occasionally seen in areas of no SAV at deeper depths (**Figure I2**). Habitat trends were slightly different when assessed based on seasonal residency by habitat clusters (**Figure I3**). Seasonal residency indicated that Smallmouth Bass were primarily located in areas of sparse SAV at moderate depths year-round. However, to a lesser extent Smallmouth Bass also used areas of dense SAV in shallow waters and no SAV in deep waters in the spring and summer, and areas of moderate SAV at moderate depths and no SAV at deep depths in the fall and winter.

There was an increase in detections during night, dawn, and dusk, compared to daytime (relative to the duration of time of each daylight category; $\chi^2_3 = 32.021$, $p < 0.001$), but no change in the relative number of detections based on moon phase ($\chi^2_3 = 0.434$, $p = 0.933$; **Figure I4**).

## DEPTH USE

The depth use of Smallmouth Bass was seasonally cyclical (**Figure I5**) with shallowest depths during the summer (seasonal modelled mean ± SE = -0.4 ± 0.7 m) and spring (-0.3 ± 0.7 m), followed by fall (1.8 ± 0.7 m), and lastly winter (6.5 ± 0.7 m; $X^2_3 = 3040.9$, $p < 0.001$). Note seasonal modelled depth use was in the negatives for spring and summer and although that was not possible, it indicates very shallow depth use for Smallmouth Bass in these seasons. From a monthly perspective, Smallmouth Bass had increased depth use from December until March (mean ± SD depth ranged from 6.0 ± 3.0 m to 8.1 ± 2.6 m) and decreased depth use from May until October (mean ± SD depth ranged from 0.2 ± 0.3 m to 0.3 ± 0.4 m; **Figure I6**). The greatest depth use was during the winter in the west end (max = 14.7 m).

## RESIDENCY

Spatially, Smallmouth Bass had the greatest residency at Piers 5-7 area, year-round (**Figure I7**). However, residency shifted into slightly deeper waters and towards the north shore in the fall and winter where Smallmouth Bass were residing at depths of ~4 – 8 m (**Figure I6**). Overall residency values were lower in the summer, which may indicate periods of time with lower detectability.

**SPAWNING**

May 1 to July 15 was the spawning window used for Smallmouth Bass (**Table 2**), during which Smallmouth Bass were quite shallow (mean monthly depths were ~0.2 m; **Figure I6**). The shallow waters used in the spring and summer may be attributed to when Smallmouth Bass were spawning. Based on the residency index, during the spawning window, Smallmouth Bass appear to be in the Piers 5-7 area, similar to where they generally resided year-round (**Figure I8**). Habitat-associated residency of Smallmouth Bass during the spawning window was in areas of sparse SAV at moderate depths (**Figure I9**).

**Table I1.** Tagging and detection summary of acoustically tagged Smallmouth Bass (*Micropterus dolomieu*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive or AD = alive and later died, based on the detection/depth profiles. Dash means no date recorded.

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14178 | - | - | 10/11/2018 | Bayfront | V13P-1L | TRUE | AD | 10/12/2018 | 1/2/2020 | 447 | 241429 | 422 |
| 15862 | 411 | 1210 | 6/28/2017 | Rowing Club | V13P-1L | TRUE | AD | 6/29/2017 | 7/17/2018 | 383 | 126104 | 360 |
| 15869 | 437 | 1250 | 6/28/2017 | Rowing Club | V13P-1L | TRUE | AD | 6/28/2017 | 10/29/2017 | 123 | 17379 | 107 |
| 14172 | 439 | 1510 | 6/12/2019 | HH52 | V13P-1L | TRUE | A | 6/13/2019 | 4/25/2020 | 317 | 134896 | 314 |
| 14173 | 453 | 1590 | 6/11/2019 | HH52 | V13P-1L | TRUE | A | 6/12/2019 | 4/25/2020 | 318 | 139903 | 315 |
| 15858 | 421 | 1140 | 6/28/2017 | Rowing Club | V13P-1L | TRUE | A | 6/28/2017 | 6/28/2018 | 365 | 84404 | 350 |

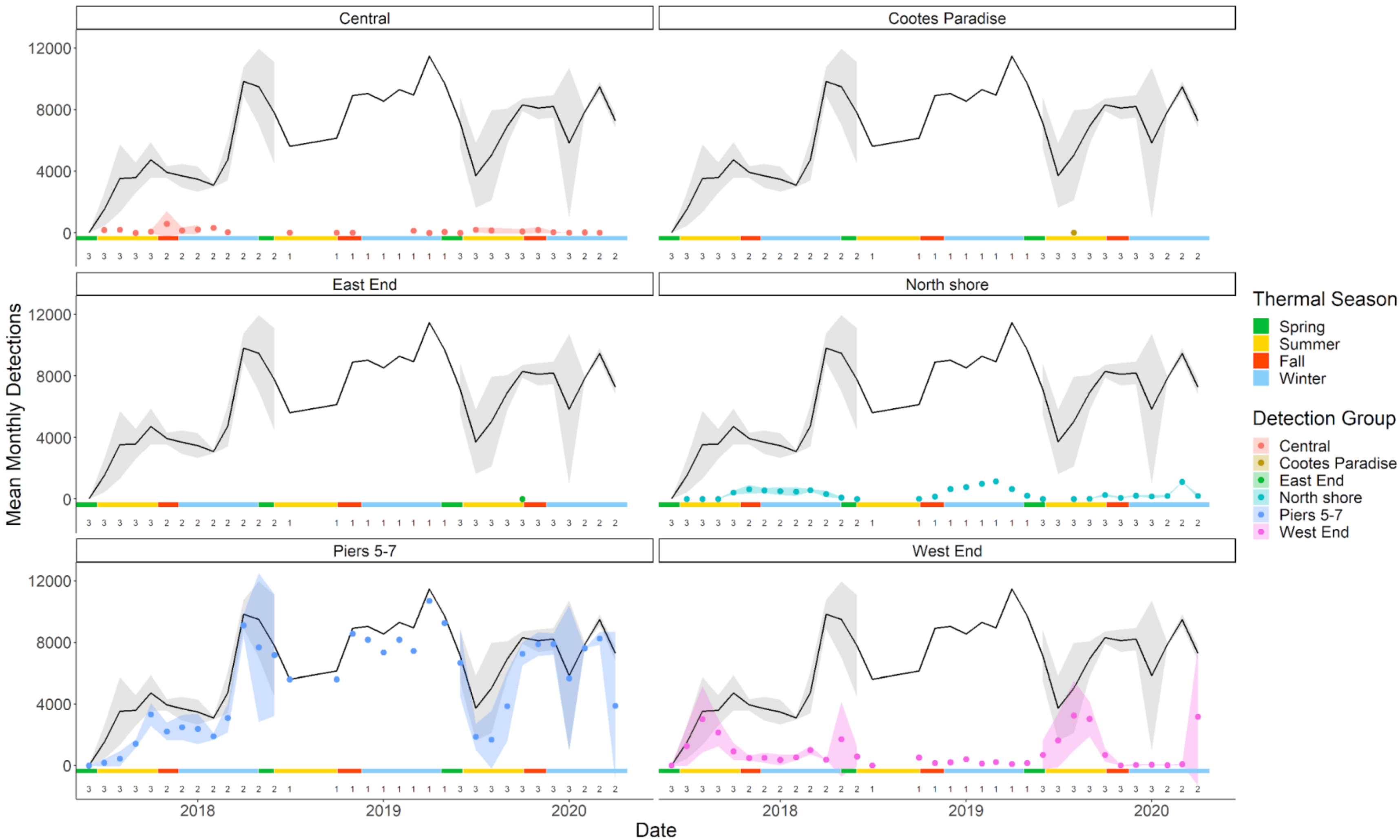


**Figure I1.** Mean (± SD) monthly detections of acoustically tagged Smallmouth Bass at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Smallmouth Bass at that time.

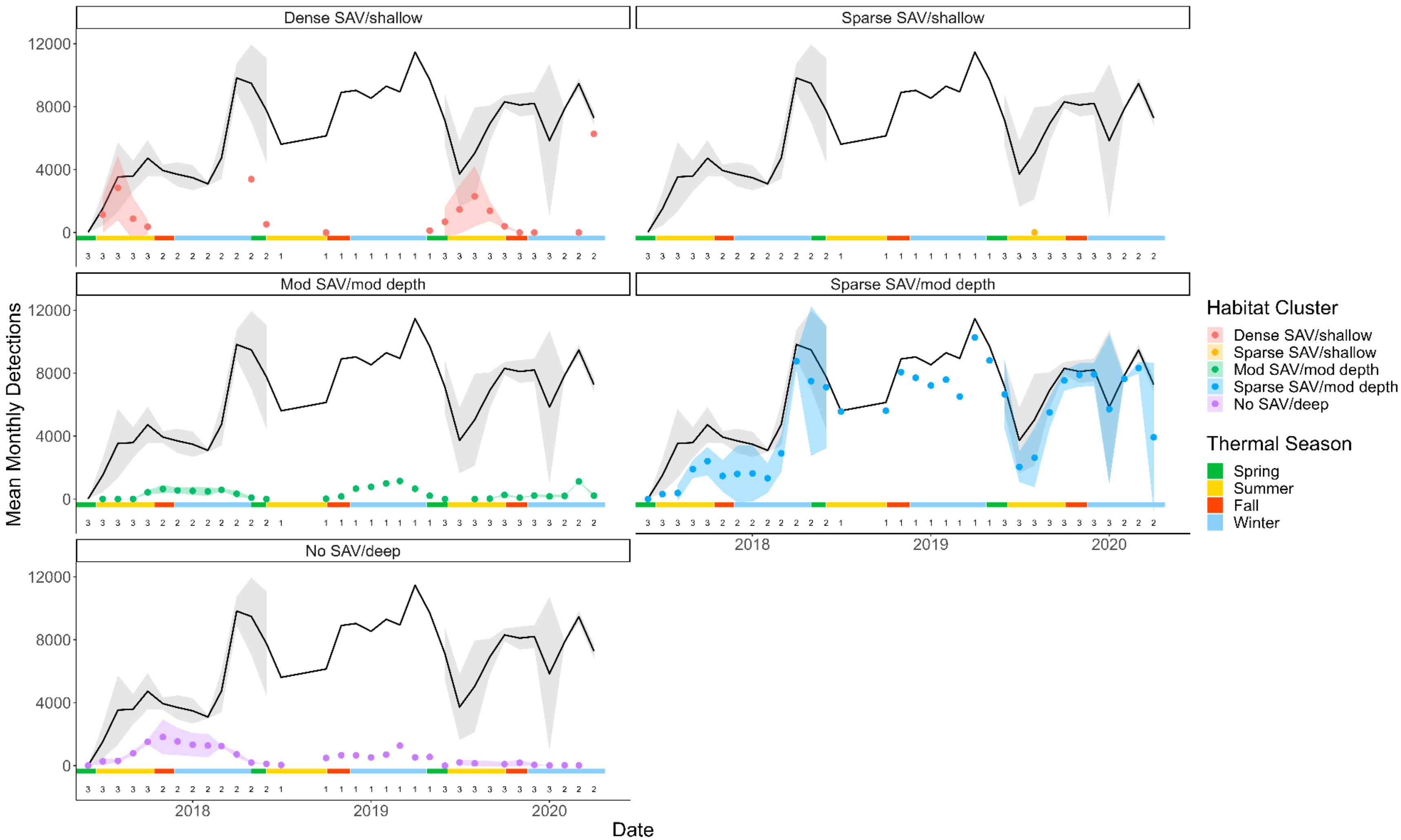


**Figure I2**. Mean (± SD) monthly detections of acoustically tagged Smallmouth Bass at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Smallmouth Bass.

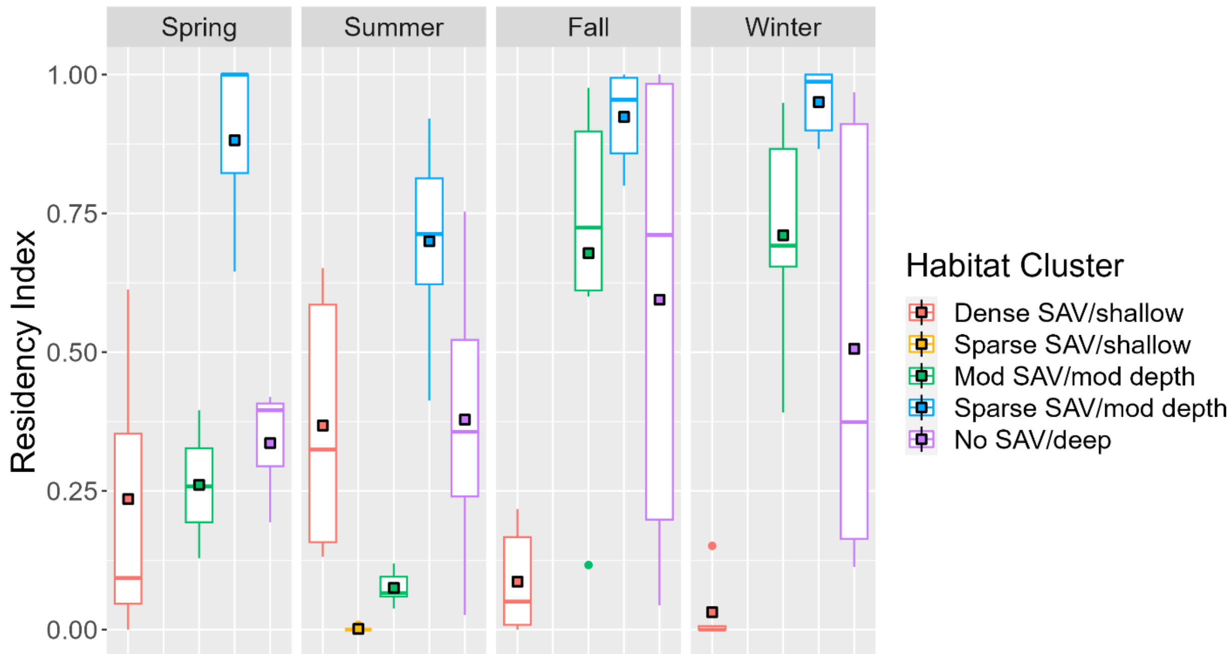


**Figure I3.** Boxplot of individual tagged Smallmouth Bass residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

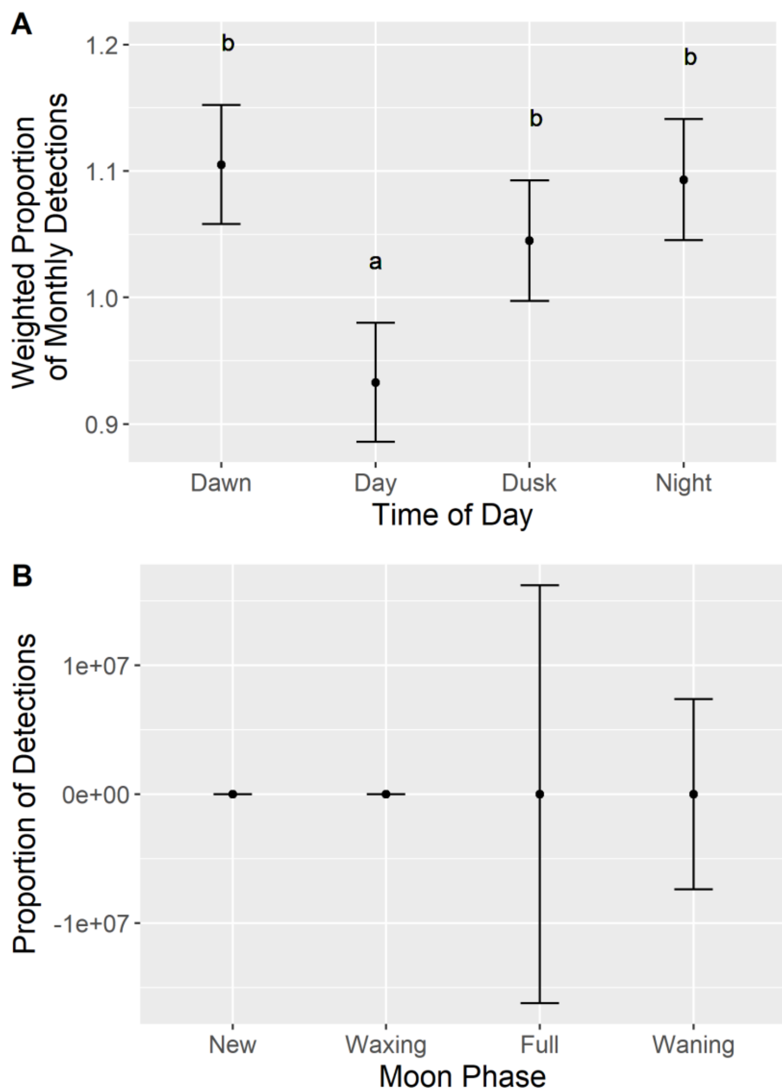


**Figure I4**. A) Mean (± SE) proportion of monthly detections of Smallmouth Bass at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Smallmouth Bass detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

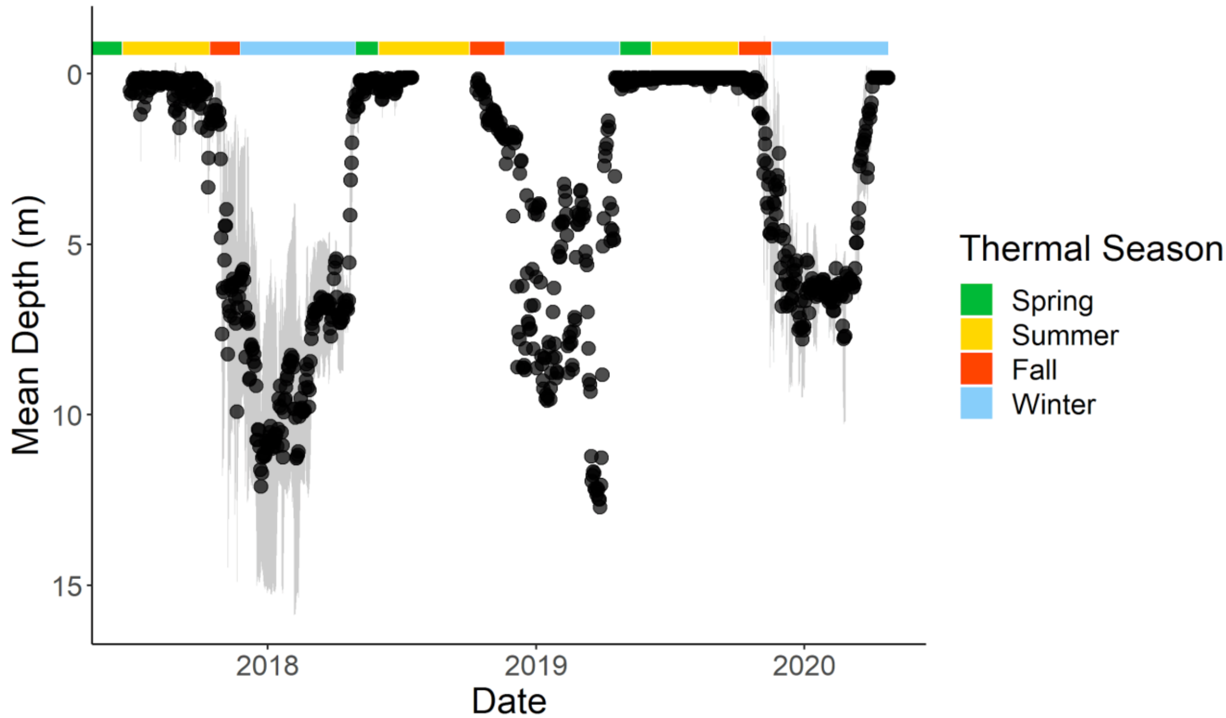


**Figure I5**. Mean (± SD) daily depth use of acoustically tagged Smallmouth Bass in Hamilton Harbour over time. The coloured bar indicates the season over time.

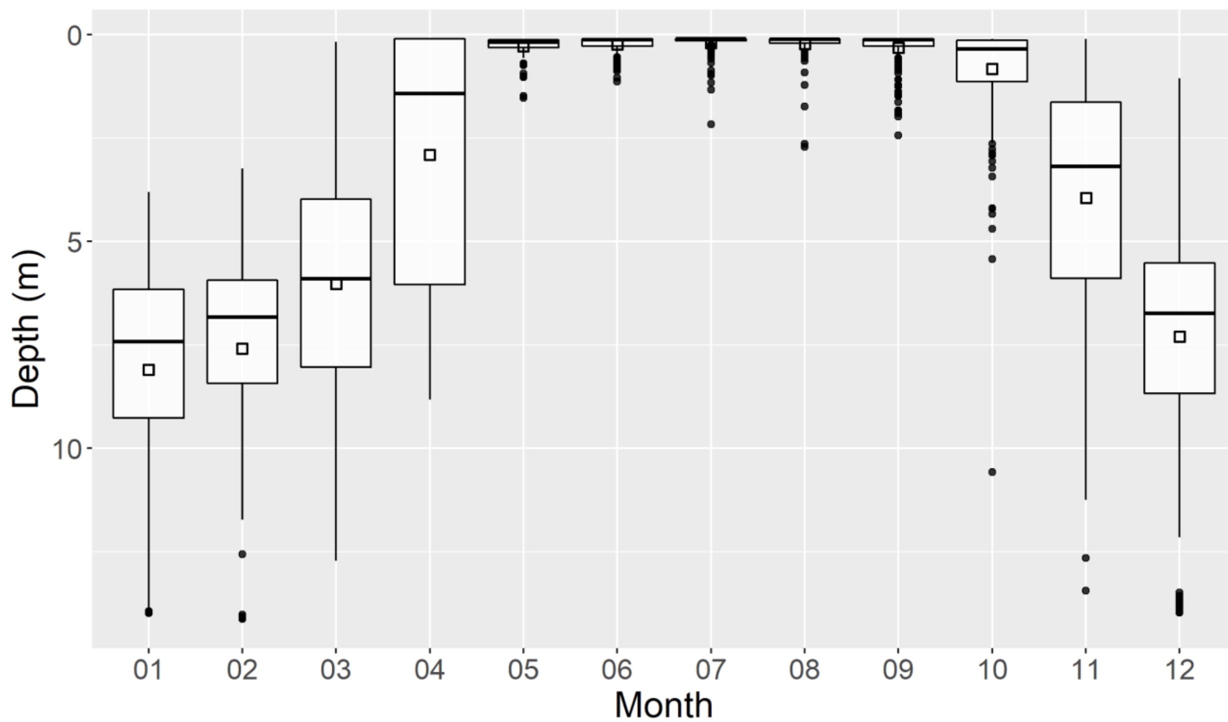


**Figure I6.** Boxplot of monthly depth use based on mean daily depths of acoustically tagged Smallmouth Bass in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

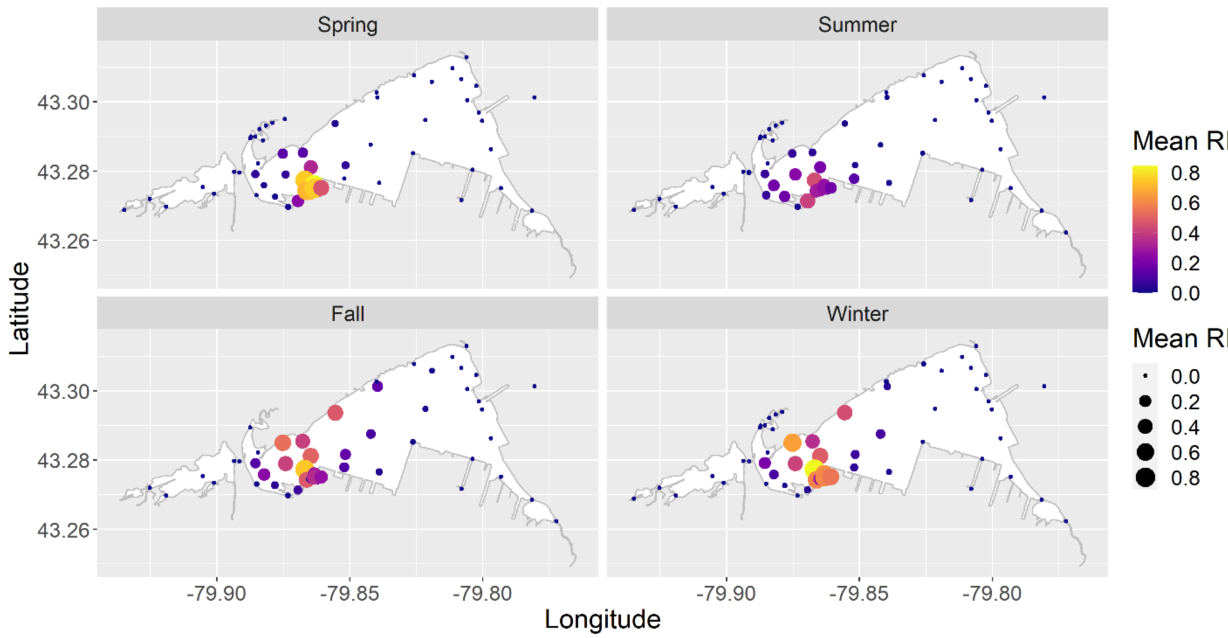


**Figure I7.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Smallmouth Bass (N = 6). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

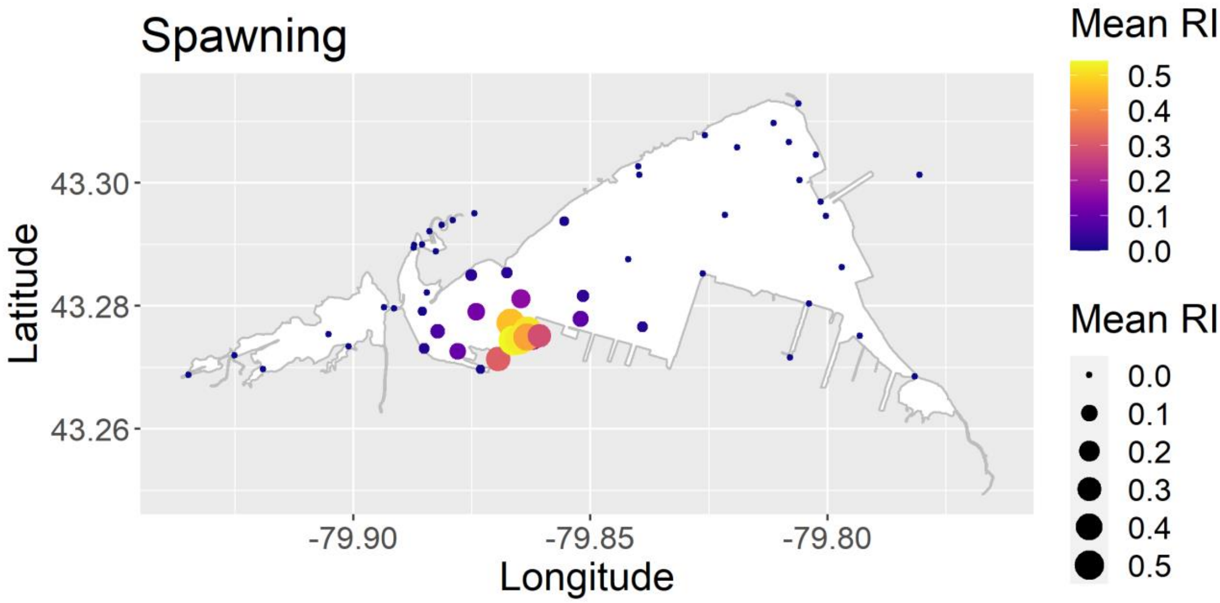


**Figure I8.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Smallmouth Bass (N = 6) during their spawning window (May 1 to July 15). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

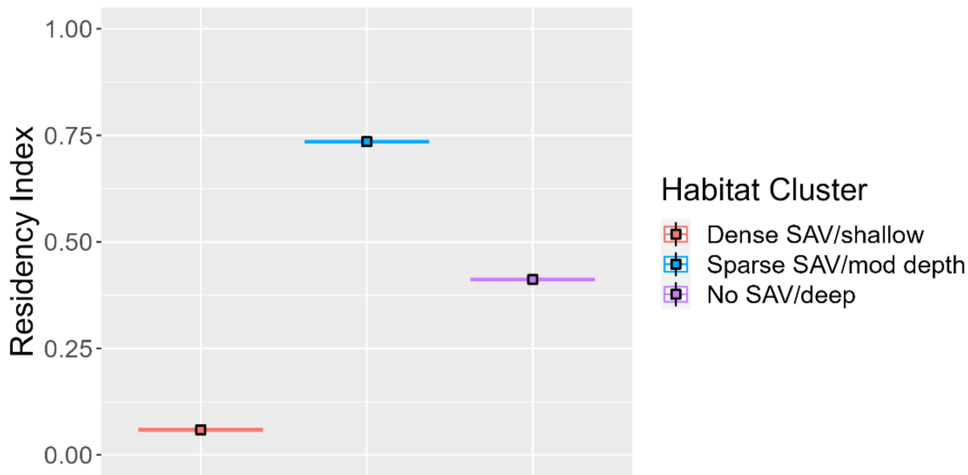


**Figure I9**. Boxplot of individual tagged Smallmouth Bass residency during the spawning window (May 1 to July 15) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX J: WALLEYE

## DETECTIONS AND HABITAT USE

Thirty-seven Walleye (*Sander vitreus*) were acoustically tagged and monitored in Hamilton Harbour from April 2016 to April 2020 (**Table J1**). Based on mean monthly detections, there appears to more overall detections in the winter and fewer in the summer, with a general affinity towards the east end in the summer, and central basin and north shore in the winter (**Figure J1**). Although six Walleye were detected at Cootes Paradise Marsh receivers it was only at the receivers at the entrance to Cootes Paradise Marsh near the fishway and no Walleye were detected in Cootes Paradise. A large portion of Walleye leave Hamilton Harbour in the summer for a period of time and return to the harbour by the winter (**Figure J2**). Two Walleye left Hamilton Harbour and never returned, while 18 did return. Although it appears that 17 Walleye stayed within the harbour, at least seven Walleye were last detected at the canal (Station 22) and were undetected, presumably leaving Hamilton Harbour for a period of time (e.g., months) before returning. Reduced Lake Ontario receiver coverage in 2016 and 2017 limited the ability for Walleye to be detected outside of the harbour, hence the period of time when undetected. Thus, 27 of 37 (73%) tagged Walleye left the harbour during the study, though the duration and extent of movements into Lake Ontario varied by individuals.

Based on the habitat clusters, mean monthly detections indicated that Walleye were primarily detected in areas of no SAV and deep depths and either sparse or moderate SAV at moderate depths year-round (**Figure J3**). However, in the summer, there was an increase of detections in areas of sparse SAV in shallow waters as well as outside of the harbour (**Figure J3**). Habitat trends were slightly different when assessed based on seasonal residency by habitat clusters (**Figure J4**). Seasonal residency indicated that Walleye were primarily located in areas of no SAV and deep depths, followed by moderate and sparse SAV at moderate depths, year-round. However, Walleye residency in areas outside of the harbour increased in the summer and fall, and residency in areas of dense SAV in shallow waters increased slightly in the winter (**Figure J4**). Walleye did not use lotic areas in the harbour.

There was an increase in the proportion of Walleye detections during dawn and night, followed by dusk, and then daytime (relative to the duration of time of each daylight category; $\chi^2_3 = 44.659$, $p < 0.001$), and there were proportionally more detections during the waning and new moon phase compared to the full moon ($\chi^2_3 = 14.986$, $p = 0.002$; **Figure J5**).

## DEPTH USE

The depth use of Walleye appears to be seasonally cyclical (**Figure J6**) with shallowest depths during the summer (seasonal modelled mean ± SE = 3.2 ± 0.5 m), followed by spring (3.8 ± 0.5 m), then fall (6.2 ± 0.5 m), and lastly winter (9.4 ± 0.5 m; $X^2_3 = 10412$, $p < 0.001$). From a monthly perspective, Walleye had increased depth use from

November until March (mean ± SD depth ranged from 7.5 ± 4.3 m to 12.1 ± 2.4 m) and shallower depth use from April until September (mean ± SD depth ranged from 2.7 ± 1.5 m to 4.4 ± 3.6 m; **Figure J7**). The greatest depth use was during the winter in Lake Ontario at 29.1 m.

**RESIDENCY**

Spatially, Walleye had increased residency throughout the harbour in deeper/central waters, along the west and east end and north shore year-round (**Figure J8**). This affinity for the harbour-wide deeper sites still occurred in summer but greater residency was seen outside of the harbour. In the fall, residency was still high outside of the harbour but also with more movement throughout the harbour (**Figure J8**), at the time when Walleye moved to deeper depths (~7 m; **Figure J7**). By winter, residency was greatest along the north shore and central waters, but individuals were still seen throughout the harbour further offshore, at which time Walleye were using deeper depths (~11 m; **Figure J7**). When Walleye were outside of Hamilton Harbour, the KUD home ranges were generally along the south shore of Lake Ontario towards the Niagara River for all seasons (**Figure J9**). However, in the winter, the general home ranges of Walleye were mostly all back in Hamilton Harbour (**Figure J9**).

**SPAWNING**

March 15 to May 15 was the spawning window used for Walleye (**Table 2**), however, this is not when Walleye were at their shallowest depths (mean monthly depths were ~5 m; **Figure J7**). The shallower waters used in the summer may be attributed to feeding strategies of Walleye as opposed to spawning-related in the spring. Based on the residency index, during the spawning window, Walleye appear to be harbour-wide, primarily along the north shore, but also the west and east ends (**Figure J10**). Habitat-associated residency of Walleye during the spawning window was similar to seasonal habitat use, with greater residency in areas of no SAV in deep waters, as well as moderate and sparse SAV at moderate depths (**Figure J11**) indicating that Walleye generally seem to go to deeper depths with minimal vegetation for spawning or staging prior to spawning.

**Table J1.** Tagging and detection summary of acoustically tagged Walleye (*Sander vitreus*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, or AD = Alive and later died, based on the detection/depth profiles. Dash means no data recorded.

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79 | 520 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 10/7/2017 | 525 | 145393 | 391 |
| 83 | 515 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 7/3/2017 | 429 | 127530 | 367 |
| 15755 | 490 | - | 8/12/2015 | Unknown | V13P-1L | TRUE | A | 4/30/2016 | 5/26/2017 | 391 | 91134 | 375 |
| 15759 | 471 | - | 8/13/2015 | Unknown | V13P-1L | TRUE | A | 4/30/2016 | 7/3/2017 | 429 | 114846 | 409 |
| 15760 | 512 | - | 8/13/2015 | Unknown | V13P-1L | TRUE | A | 4/30/2016 | 3/10/2017 | 314 | 43444 | 201 |
| 15763 | 506 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 8/2/2017 | 459 | 105419 | 383 |
| 15764 | 570 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 1/23/2017 | 268 | 33784 | 156 |
| 15765 | 521 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 6/18/2017 | 414 | 87390 | 303 |
| 15769 | 513 | - | 8/13/2015 | Unknown | V13P-1L | TRUE | A | 4/30/2016 | 6/28/2016 | 59 | 11123 | 55 |
| 15771 | 562 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 7/31/2017 | 457 | 91103 | 456 |
| 15772 | 555 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 5/24/2017 | 389 | 83092 | 361 |
| 15774 | 525 | - | 10/20/2015 | West | V13P-1L | TRUE | A | 4/30/2016 | 7/6/2017 | 432 | 115386 | 421 |
| 16057 | 652 | 3150 | 4/19/2017 | Unknown | V13P-1L | TRUE | A | 4/20/2017 | 4/25/2020 | 1101 | 290526 | 951 |
| 16060 | 602 | 2240 | 4/19/2017 | Unknown | V13P-1L | TRUE | A | 4/20/2017 | 8/29/2019 | 861 | 196172 | 596 |
| 16061 | 562 | 1760 | 4/18/2017 | North Shore | V13P-1L | TRUE | A | 4/19/2017 | 4/25/2020 | 1102 | 180746 | 720 |
| 16063 | 605 | 2300 | 4/13/2017 | East | V13P-1L | TRUE | AD | 4/14/2017 | 4/15/2018 | 366 | 105365 | 333 |
| 14516 | 550 | 1860 | 5/24/2018 | HH26 | V13P-1L | TRUE | A | 5/25/2018 | 4/25/2020 | 701 | 208086 | 676 |
| 14519 | 590 | 2100 | 5/23/2018 | HH34 | V13P-1L | TRUE | A | 5/24/2018 | 4/25/2020 | 702 | 311734 | 703 |
| 15756 | 700 | - | 8/13/2015 | Unknown | V13P-1L | TRUE | A | 4/30/2016 | 10/12/2016 | 165 | 12913 | 150 |
| 15761 | 485 | - | 8/13/2015 | Unknown | V13P-1L | TRUE | A | 5/2/2016 | 6/8/2019 | 1132 | 59877 | 746 |
| 15766 | 430 | - | 8/13/2015 | Unknown | V13P-1L | TRUE | A | 4/30/2016 | 8/29/2016 | 121 | 11462 | 86 |
| 16051 | 584 | 2250 | 4/18/2017 | North Shore | V13P-1L | TRUE | A | 4/19/2017 | 4/25/2020 | 1102 | 326764 | 1012 |
| 16052 | 579 | 1940 | 4/18/2017 | Unknown | V13P-1L | TRUE | A | 4/19/2017 | 4/25/2020 | 1102 | 332060 | 974 |
| 16053 | 610 | 2240 | 4/13/2017 | East | V13P-1L | TRUE | A | 4/14/2017 | 4/25/2020 | 1107 | 431459 | 1090 |
| 16055 | 574 | 2200 | 4/19/2017 | Unknown | V13P-1L | TRUE | A | 4/20/2017 | 4/25/2020 | 1101 | 284896 | 911 |

| Tag ID | Total Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 16056 | 610 | 2500 | 4/19/2017 | Unknown | V13P-1L | TRUE | A | 4/20/2017 | 4/25/2020 | 1101 | 217738 | 884 |
| 16058 | 556 | 1840 | 4/19/2017 | Unknown | V13P-1L | TRUE | A | 4/20/2017 | 4/24/2020 | 1100 | 322775 | 1025 |
| 16059 | 564 | 2070 | 4/19/2017 | Unknown | V13P-1L | TRUE | A | 4/20/2017 | 4/25/2020 | 1101 | 186359 | 803 |
| 16062 | 579 | 1980 | 4/18/2017 | Unknown | V13P-1L | TRUE | A | 4/19/2017 | 9/24/2018 | 523 | 92153 | 320 |
| 18965 | 590 | 2230 | 6/30/2016 | Ottawa Slip | V13-1L | FALSE | A | 6/30/2016 | 4/24/2020 | 1394 | 107598 | 763 |
| 18966 | 557 | 1770 | 6/30/2016 | Ottawa Slip | V13-1L | FALSE | A | 6/30/2016 | 5/28/2017 | 332 | 95318 | 317 |
| 18967 | 550 | 1660 | 6/30/2016 | Ottawa Slip | V13-1L | FALSE | A | 6/30/2016 | 4/23/2020 | 1393 | 341779 | 1371 |
| 18969 | - | - | 6/22/2016 | Bayfront Beach | V13-1L | FALSE | A | 6/22/2016 | 4/25/2020 | 1403 | 340385 | 1044 |
| 18970 | - | - | 6/22/2016 | Bayfront Beach | V13-1L | FALSE | A | 6/22/2016 | 6/16/2017 | 359 | 36520 | 148 |
| 18971 | - | 1463 | 6/18/2016 | Bayfront Beach | V13-1L | FALSE | A | 6/23/2016 | 8/20/2016 | 58 | 11417 | 51 |
| 18972 | - | - | 6/17/2016 | HH16 | V13-1L | FALSE | A | 6/17/2016 | 3/26/2018 | 647 | 60193 | 278 |
| 18973 | 545 | 1720 | 6/29/2016 | Ottawa Slip | V13-1L | FALSE | A | 6/29/2016 | 8/10/2018 | 772 | 145884 | 707 |

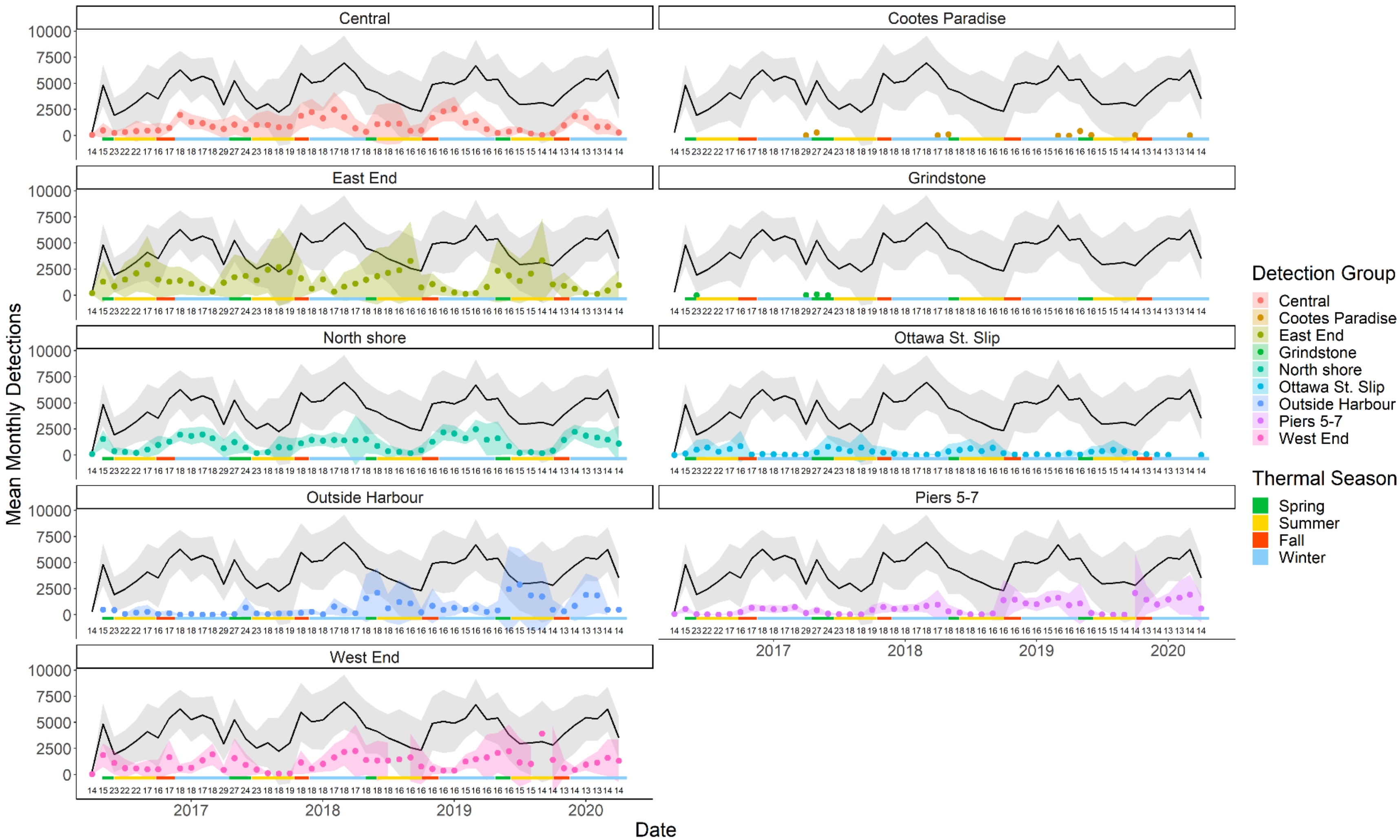


**Figure J1.** Mean (± SD) monthly detections of acoustically tagged Walleye at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Walleye at that time.

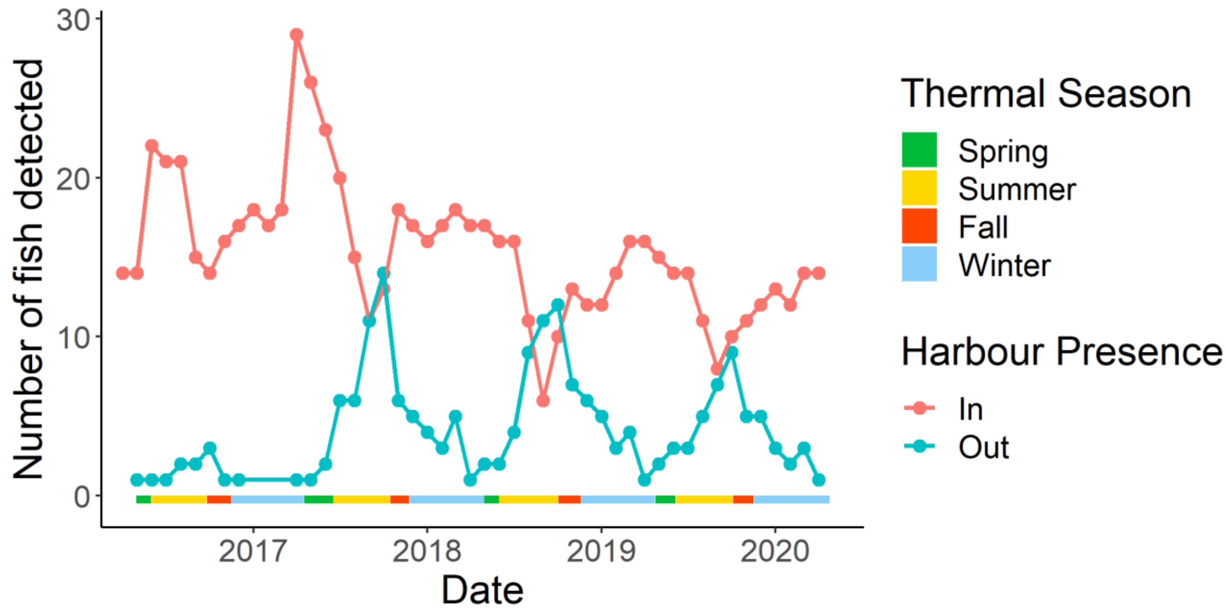


**Figure J2.** Monthly total of acoustically tagged Walleye detected in or out of Hamilton Harbour over time. The coloured bar indicates the season over time.

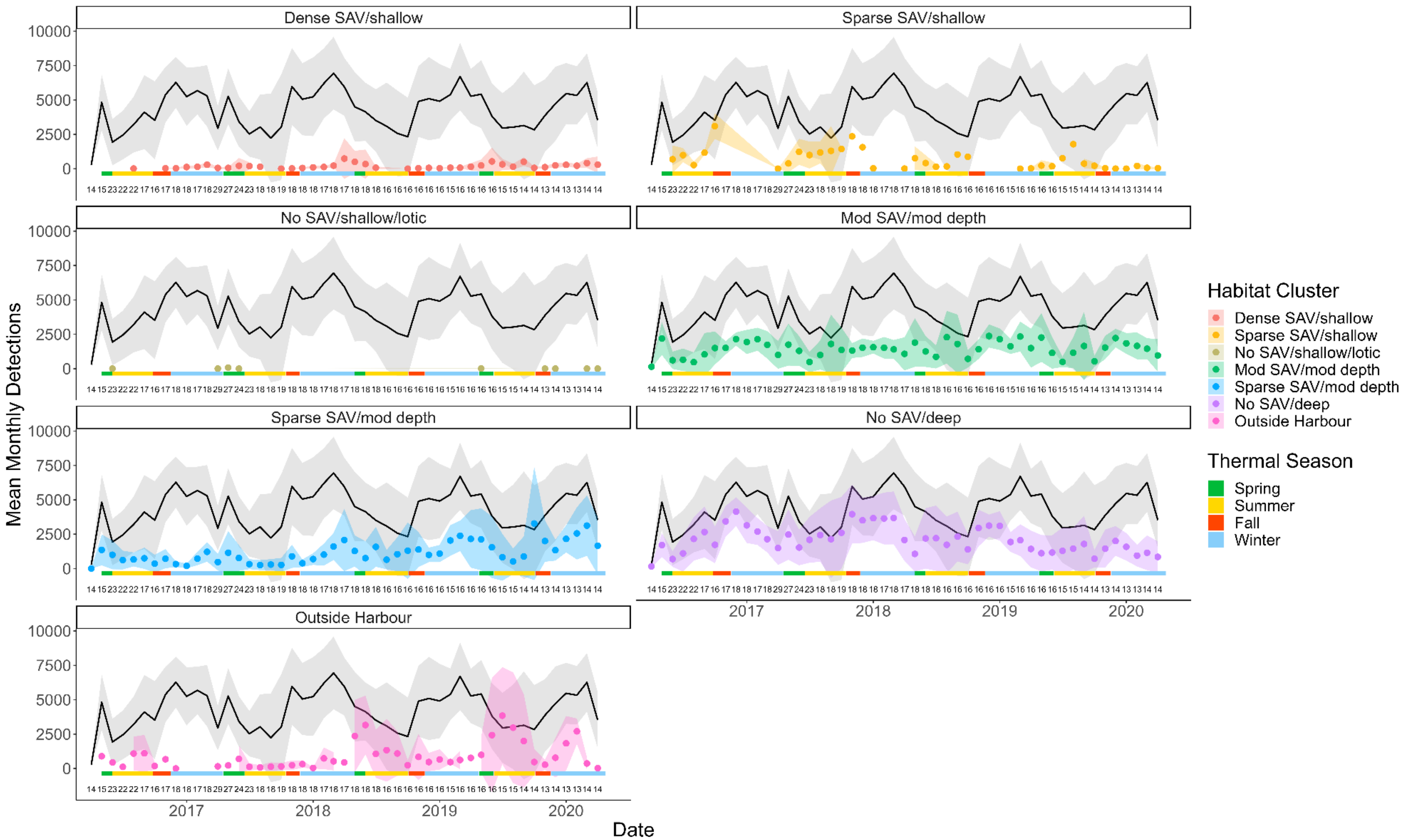


**Figure J3**. Mean (± SD) monthly detections of acoustically tagged Walleye at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Walleye during that month.

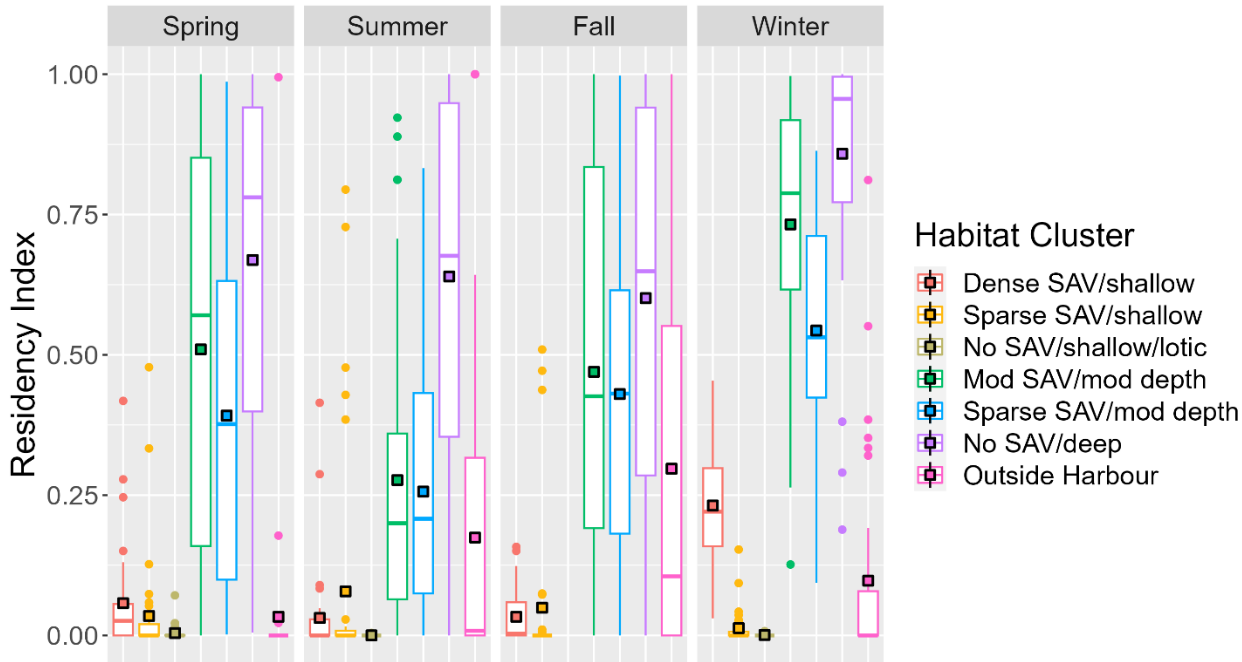


**Figure J4.** Boxplot of individual tagged Walleye residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

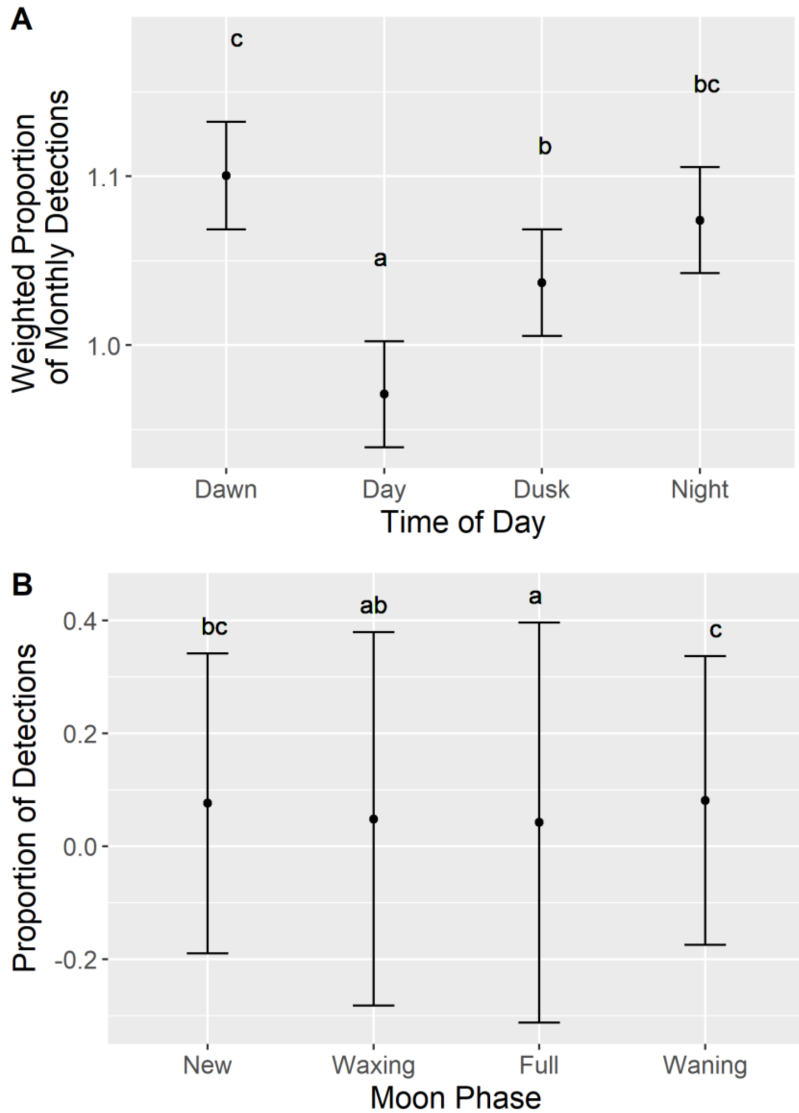


**Figure J5**. A) Mean (± SE) proportion of monthly detections of Walleye at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Walleye detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

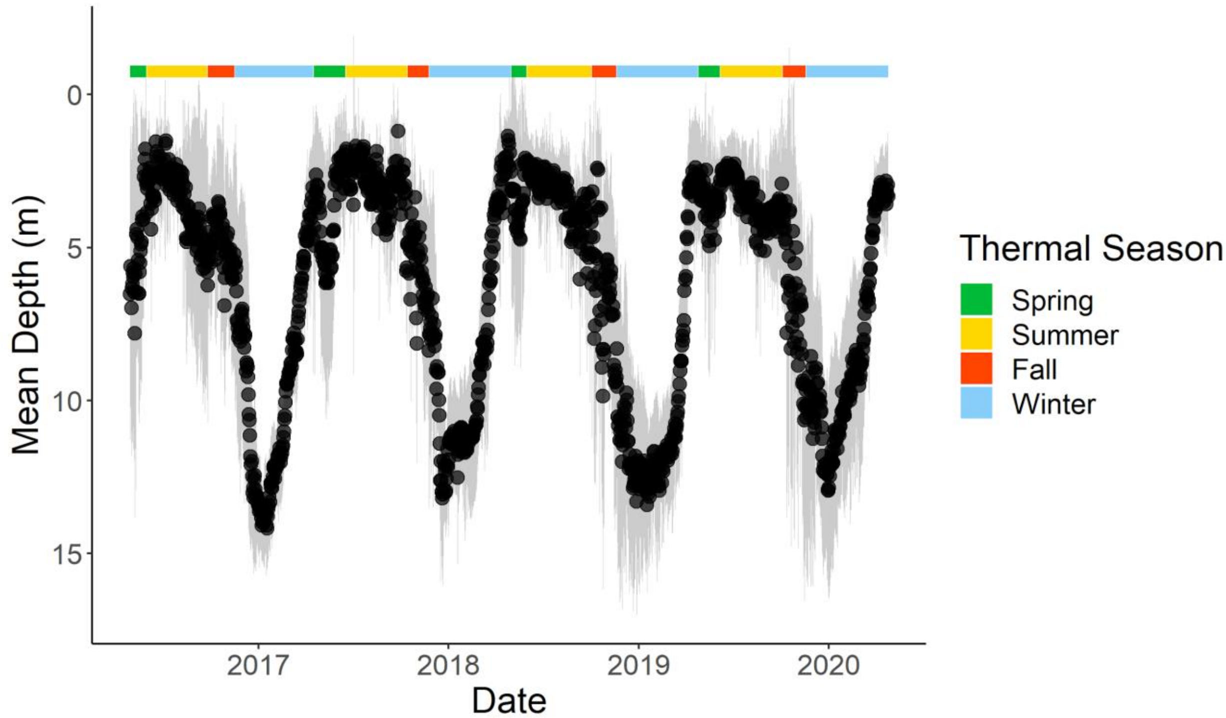


**Figure J6**. Mean (± SD) daily depth use of acoustically tagged Walleye in Hamilton Harbour over time. The coloured bar indicates the season over time.

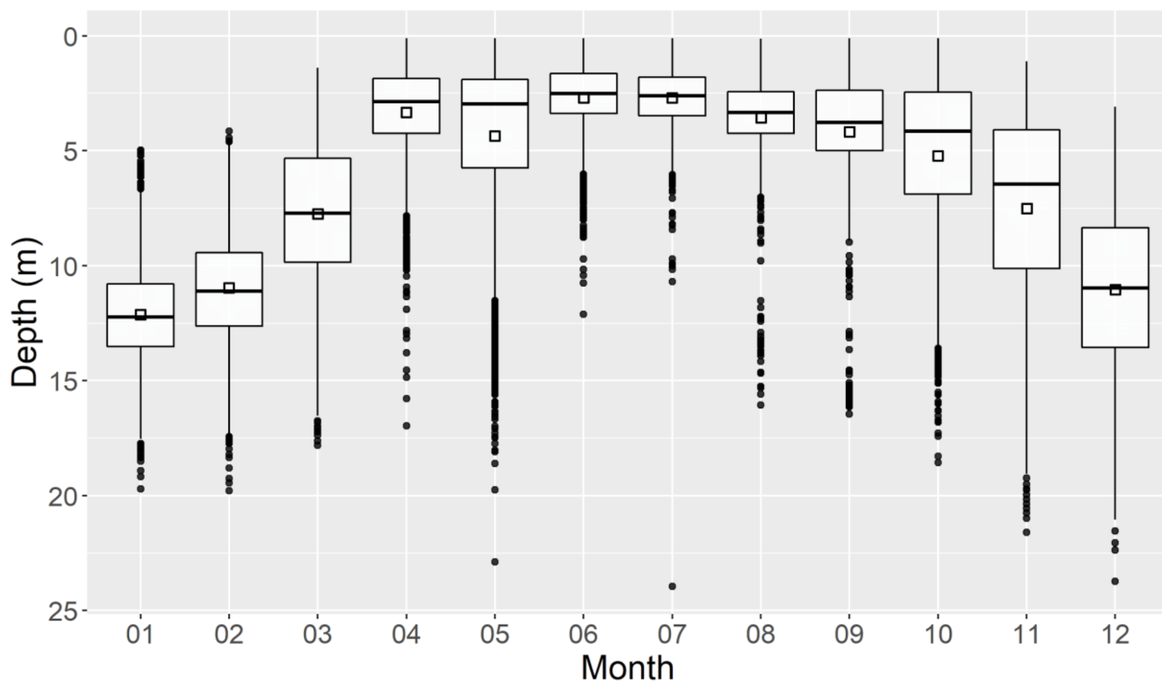


**Figure J7.** Boxplot of monthly depth use based on mean daily depths of acoustically tagged Walleye in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

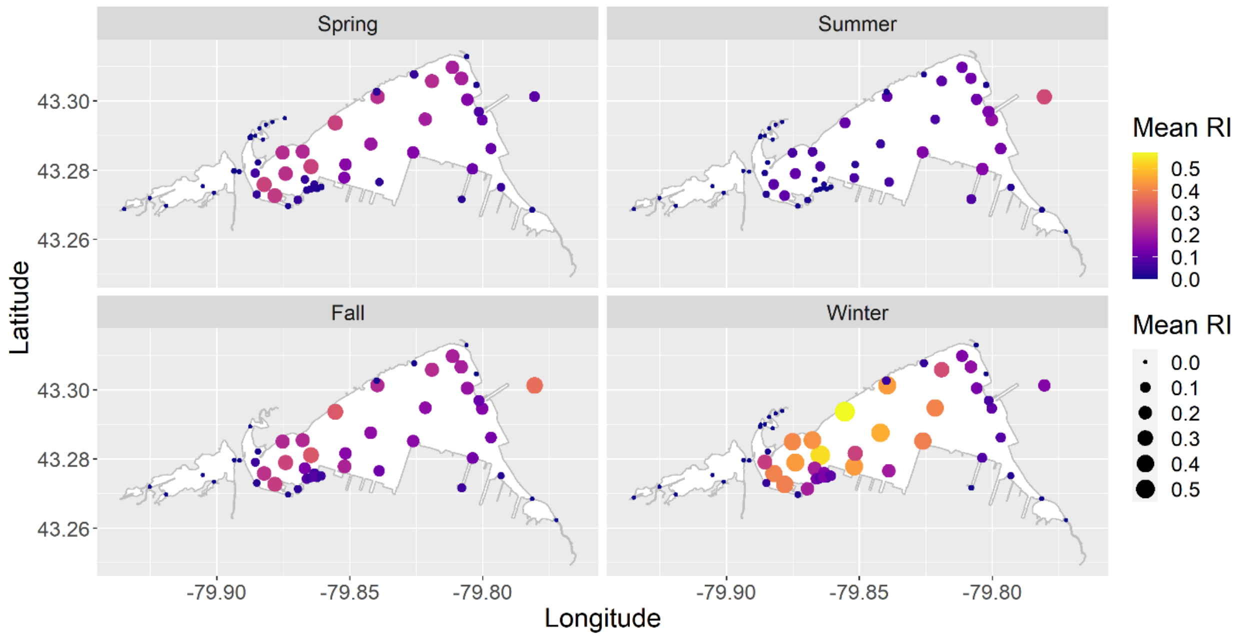


**Figure J8.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Walleye (N = 37). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

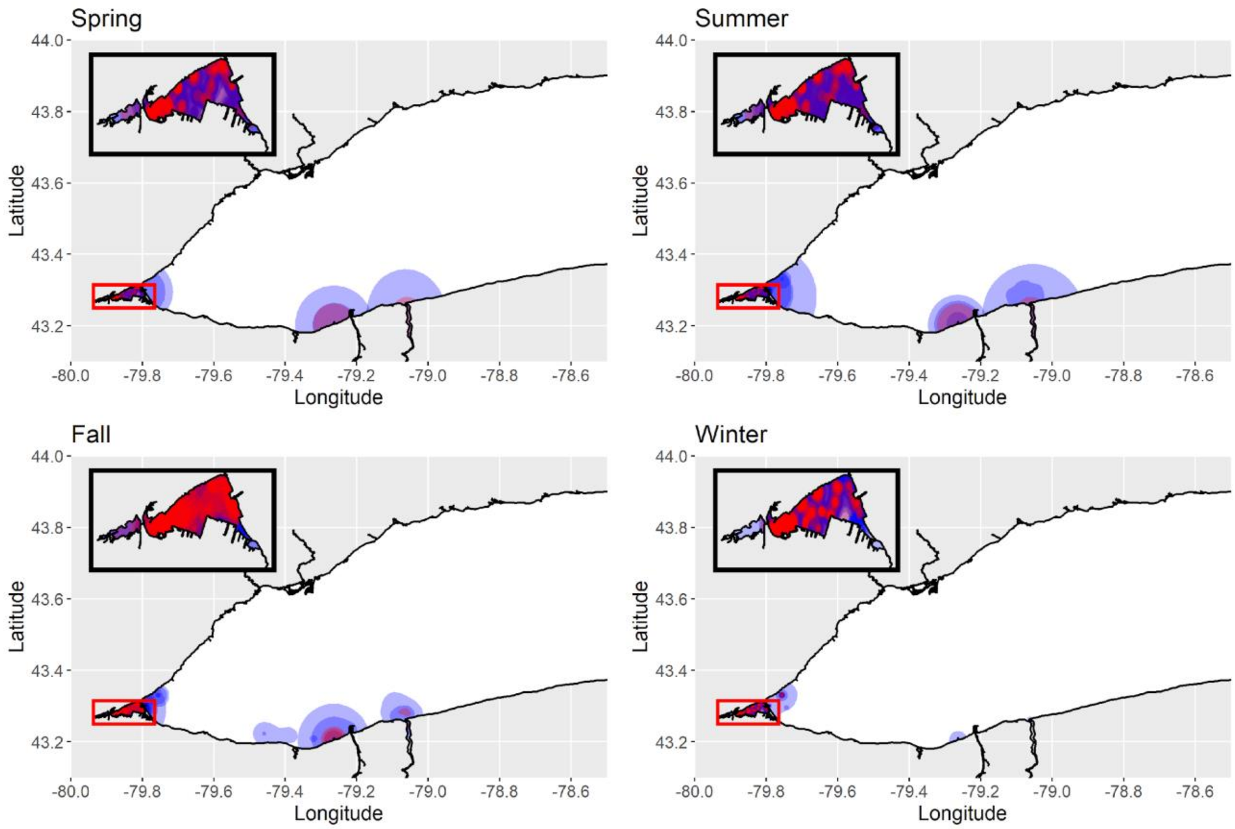


**Figure J9**. Seasonal 50% (red) and 95% (blue) home ranges (via kernel utilization distribution) of individual Walleye tagged in Hamilton Harbour, 2016 – 2020. Darker colours indicate overlapping home ranges of individuals. All Walleye left the harbour at some point during the study but the duration and distance varied.

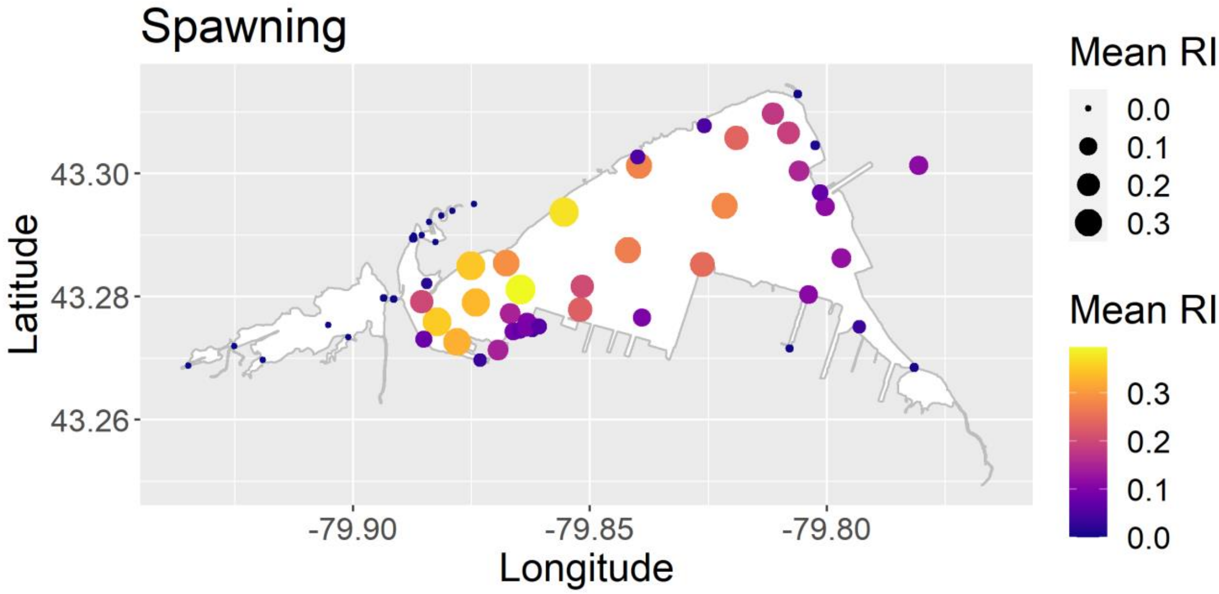


**Figure J10.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Walleye (N = 37) during their spawning window (March 15 to May 15). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

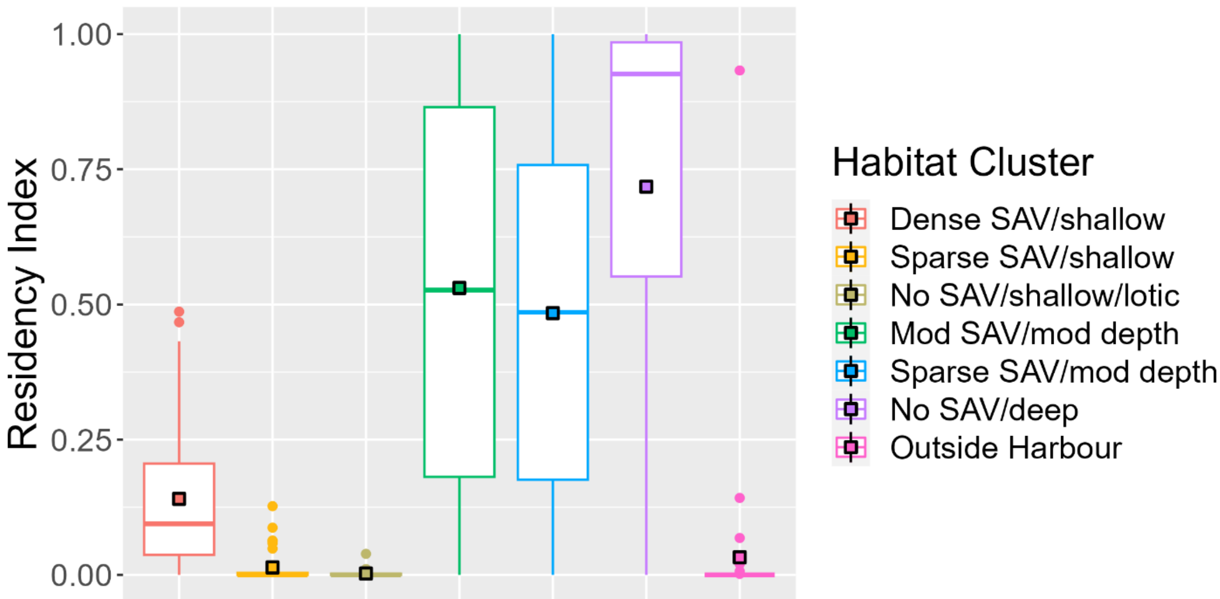


**Figure J11**. Boxplot of individual tagged Walleye residency during the spawning window (March 15 to May 15) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX K: WHITE SUCKER

## DETECTIONS AND HABITAT USE

Eight White Sucker (*Catostomus commersonii*) were acoustically tagged and monitored in Hamilton Harbour from June 2016 to April 2020 (**Table K1**). Based on mean monthly detections, there appears to be more overall detections in the winter and early spring, and fewer detections in the summer. White Sucker detections were generally in the west end in the fall and winter, Cootes Paradise Marsh and north shore in the spring, and outside the harbour in the summer (**Figure K1**). Although six White Sucker were detected at Cootes Paradise Marsh receivers it was only at the receivers at the marsh entrance near the fishway; only one White Sucker was detected inside Cootes Paradise. This individual was detected at Spencer Creek (Station 30) in early spring (March-April) two years in a row. Five White Sucker left Hamilton Harbour in the summer for a period of time and returned to the harbour by the winter (**Figure K2**). Two White Sucker left Hamilton Harbour and never returned. Only one White Sucker stayed within the harbour during the study period.

Based on the habitat clusters, mean monthly detections indicated that White Sucker were primarily detected in areas of no SAV and deep depths or outside the harbour in the summer, sparse SAV at moderate depths in the fall and winter, and moderate SAV at moderate depths in the spring (**Figure K3**). Habitat trends were slightly different when assessed based on seasonal residency by habitat clusters (**Figure K4**). Seasonal residency indicated that White Sucker were primarily located outside the harbour and in areas of no SAV and deep depths in the summer. Similarly in the fall, White Sucker were primarily in areas of no SAV and deep depths, but with a decrease in residency outside of the harbour. By winter, White Sucker had increased residency in areas of sparse SAV at moderate depths, but also were in areas of moderate SAV at moderate depths and no SAV at deep depths. In the spring, White Sucker had increased residency in areas of moderate SAV at moderate depths, followed by no SAV at deep depths and dense SAV in shallow waters (**Figure K4**). White Sucker only used lotic areas in the harbour during winter and spring.

There was an increase in the proportion of White Sucker detections during dusk compared to daytime (relative to the duration of time of each daylight category; $\chi^2_3$ = 10.414, p = 0.015), though no change in the relative number of detections based on moon phase ($\chi^2_3$ = 1.918, p = 0.590; **Figure K5**).

## DEPTH USE

The depth use of White Sucker appears to be seasonally cyclical (**Figure K6**) with shallowest depths during spring (seasonal modelled mean ± SE = 2.0 ± 1.0 m) and winter (2.3 ± 1.0 m), followed by fall (4.7 ± 1.0 m), and lastly summer (8.7 ± 1.0 m; $X^2_3$ = 1215.9, p < 0.001). From a monthly perspective, White Sucker had shallower depth use from November until May (mean ± SD depth ranged from 1.6 ± 1.5 m to 3.5 ± 2.7 m) and increased depth use from July until September (mean ± SD depth ranged from 8.7

± 6.4 m to 12.4 ± 4.7 m; **Figure K7**). The greatest depth use was in June (max = 31.7 m) in Lake Ontario.

## RESIDENCY

Spatially, White Sucker had increased residency at the west end and along the north shore in the spring but there was general movement throughout the harbour (**Figure K8**). However, by the summer, residency was almost entirely outside of the harbour (**Figure K8**), where White Sucker moved to deeper depths (~10 m; **Figure K7**). In the fall, residency was still high outside of the harbour but there was increased residency in the west end (**Figure K8)**. By winter, residency was greatest in the west end as well as outside of the harbour for some fish (**Figure K8**). White Sucker were mostly outside of Hamilton Harbour in the summer and fall, and the KUD home ranges indicated they remained relatively close to the harbour (within ~5 km) while in Lake Ontario, but one individual was detected as far as Jordan Harbour (~40 km) along the south shore in summer (**Figure K9**). And one White Sucker was detected at the mouths of Bronte Creek, Oakville Creek, and Credit River at different years, up to ~ 50 km away from Hamilton before returning.

## SPAWNING

April 1 to May 31 was the spawning window used for White Sucker (**Table 2**), when White Sucker were at their shallowest depths (mean monthly depths were ~2 m; **Figure K7**). The shallower waters used in the spring may be attributed spawning activities for White Sucker. Based on the residency index, during the spawning window, White Sucker tend to be in the west end, near Bayfront, but also along the north shore, and the mouth of Grindstone Creek and Cootes Paradise Marsh (**Figure K10**). Habitat-associated residency of White Sucker during the spawning window was greatest in areas of sparse SAV at moderate depths, however, all habitat clusters except sparse SAV in shallow areas and lotic areas were equally represented (**Figure K11**). Lower residency in lotic areas indicated that White Sucker were using lotic areas to reach spawning habitat, yet it was unclear if they were targeting a specific habitat cluster associated with vegetation and depth for spawning.

**Table K1.** Tagging and detection summary of acoustically tagged White Sucker (*Catostomus commersonii*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, or AD = Alive and later died, based on the detection/depth profiles.

| Tag ID | Fork Length (mm) | Mass (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 15440 | 485 | 1450 | 6/18/2016 | Bayfront Beach | V13P-1L | TRUE | AD | 6/18/2016 | 2/4/2019 | 961 | 32562 | 392 |
| 15451 | 392 | 949 | 6/18/2016 | Bayfront Beach | V13P-1L | TRUE | AD | 6/18/2016 | 7/14/2017 | 391 | 55158 | 263 |
| 14794 | 415 | 810 | 4/27/2018 | RBG Fishway | V13P-1L | TRUE | A | 4/27/2018 | 4/25/2020 | 729 | 39136 | 249 |
| 14798 | 495 | 1260 | 5/11/2018 | RBG Fishway | V13P-1L | TRUE | A | 5/11/2018 | 4/25/2020 | 715 | 33813 | 210 |
| 14802 | 460 | 1260 | 4/27/2018 | RBG Fishway | V13P-1L | TRUE | A | 4/27/2018 | 4/25/2020 | 729 | 73904 | 550 |
| 14803 | 428 | 970 | 4/27/2018 | RBG Fishway | V13P-1L | TRUE | A | 4/27/2018 | 7/7/2018 | 71 | 9938 | 49 |
| 14805 | 465 | 1160 | 5/11/2018 | RBG Fishway | V13P-1L | TRUE | A | 5/11/2018 | 4/25/2020 | 715 | 55185 | 451 |
| 15836 | 465 | 1500 | 10/20/2017 | Bayfront Beach | V13P-1L | TRUE | A | 10/20/2017 | 4/21/2018 | 183 | 20398 | 163 |

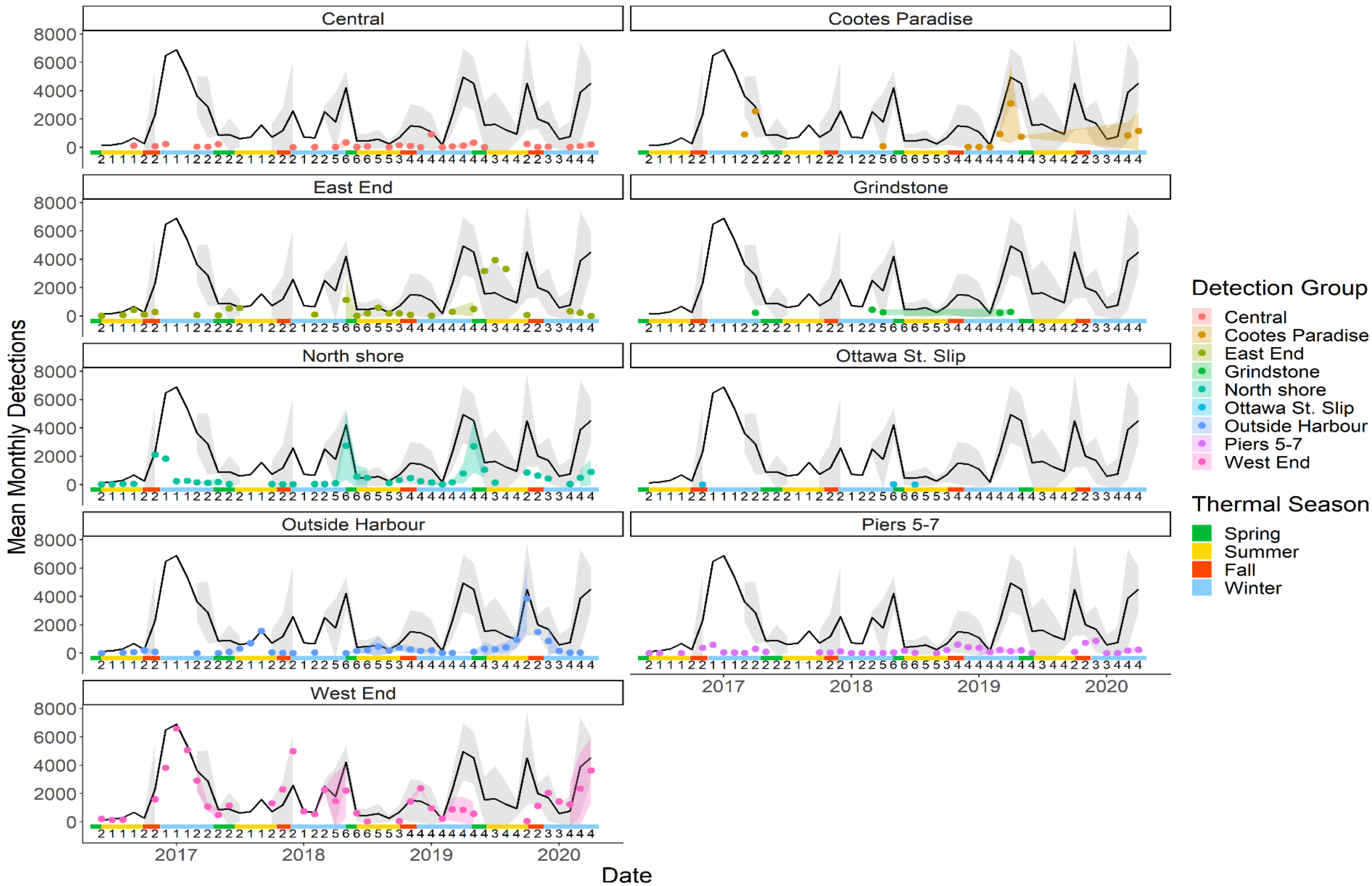


**Figure K1.** Mean (± SD) monthly detections of acoustically tagged White Sucker at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of White Sucker at that time.

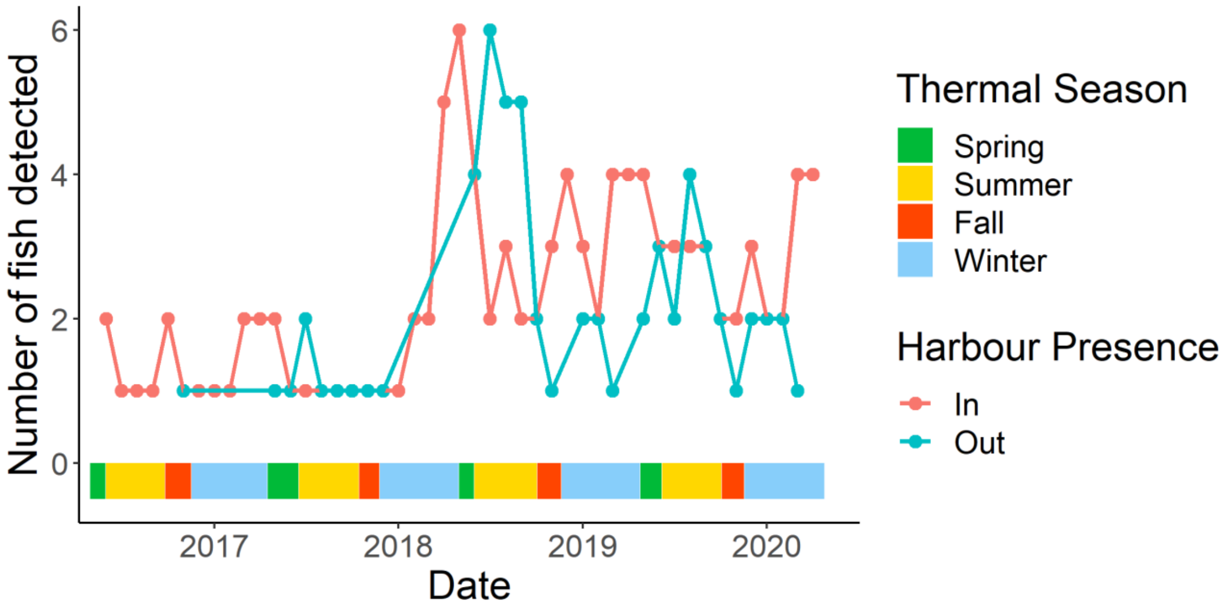


**Figure K2.** Monthly total of acoustically tagged White Sucker detected in or out of Hamilton Harbour over time. The coloured bar indicates the season over time.


**Figure K3**. Mean (± SD) monthly detections of acoustically tagged White Sucker at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of White Sucker during that month.

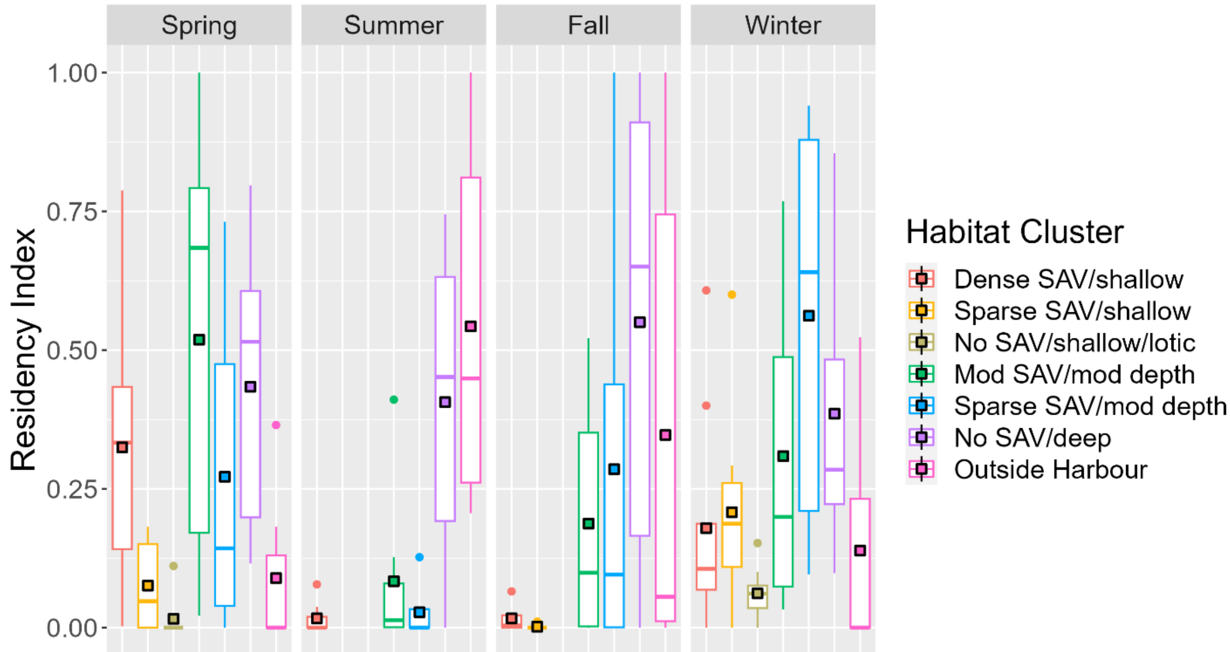


**Figure K4.** Boxplot of individual tagged White Sucker residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

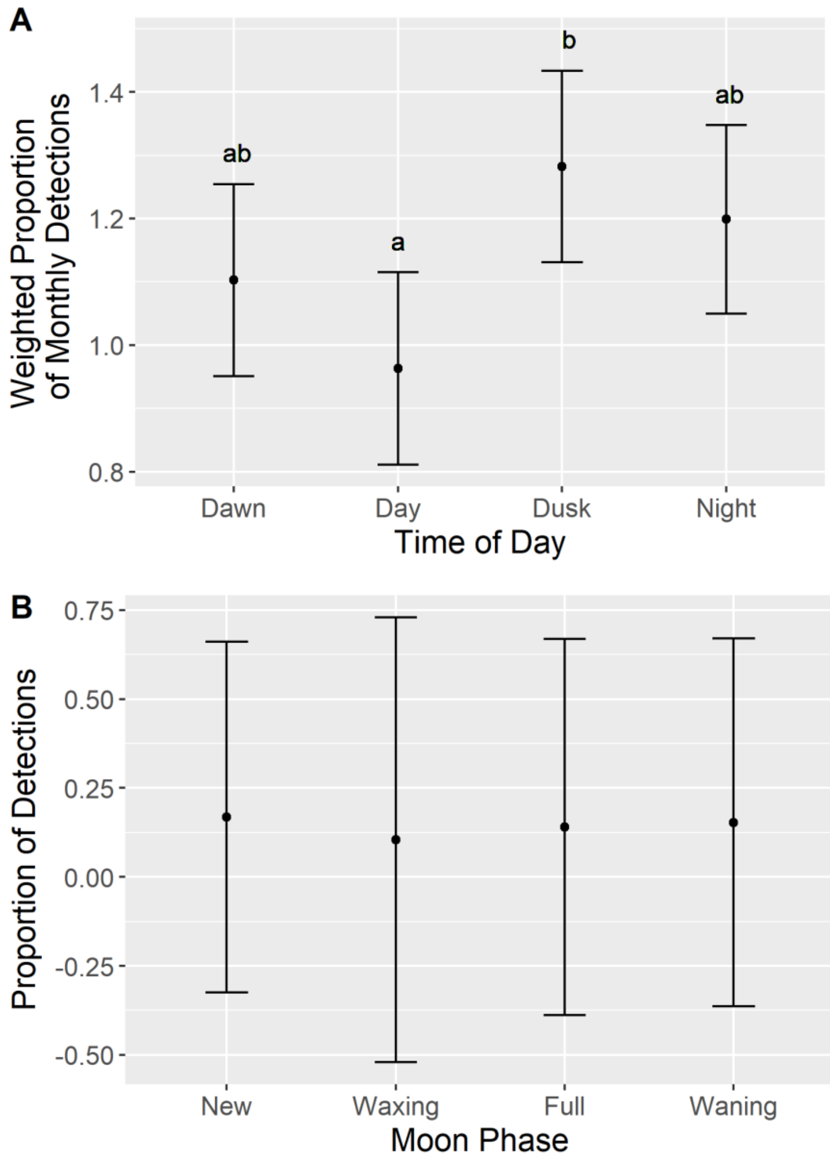


**Figure K5**. A) Mean (± SE) proportion of monthly detections of White Sucker at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly White Sucker detections occurring at different moon phases in Hamilton Harbour, 2016 – 2020.

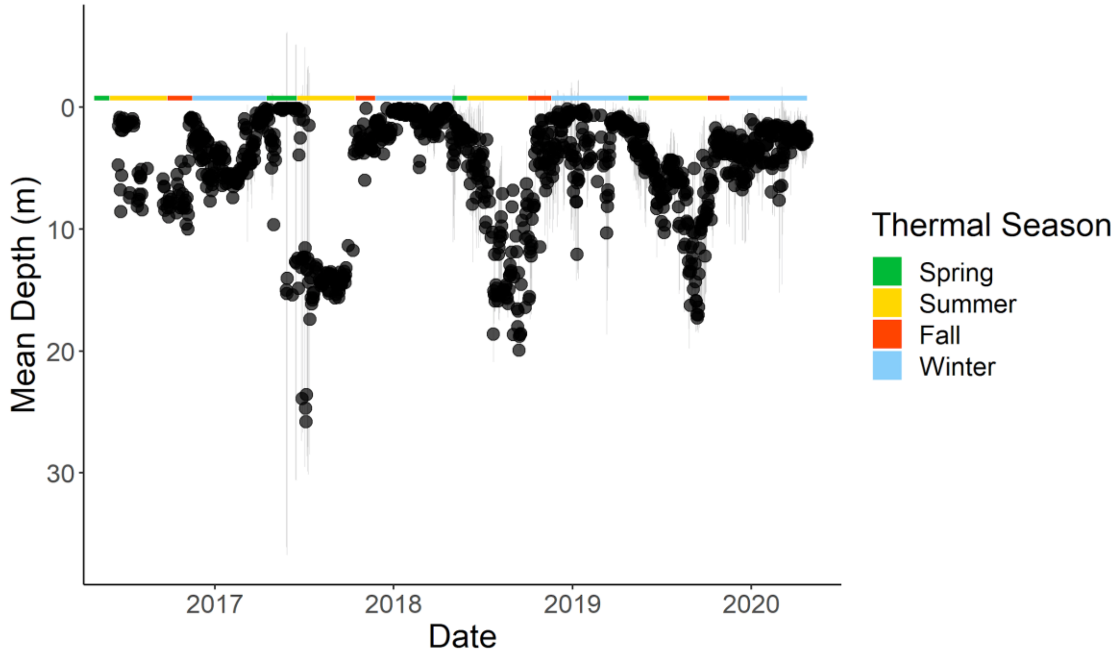


**Figure K6**. Mean (± SD) daily depth use of acoustically tagged White Sucker in Hamilton Harbour over time. The coloured bar indicates the season over time.

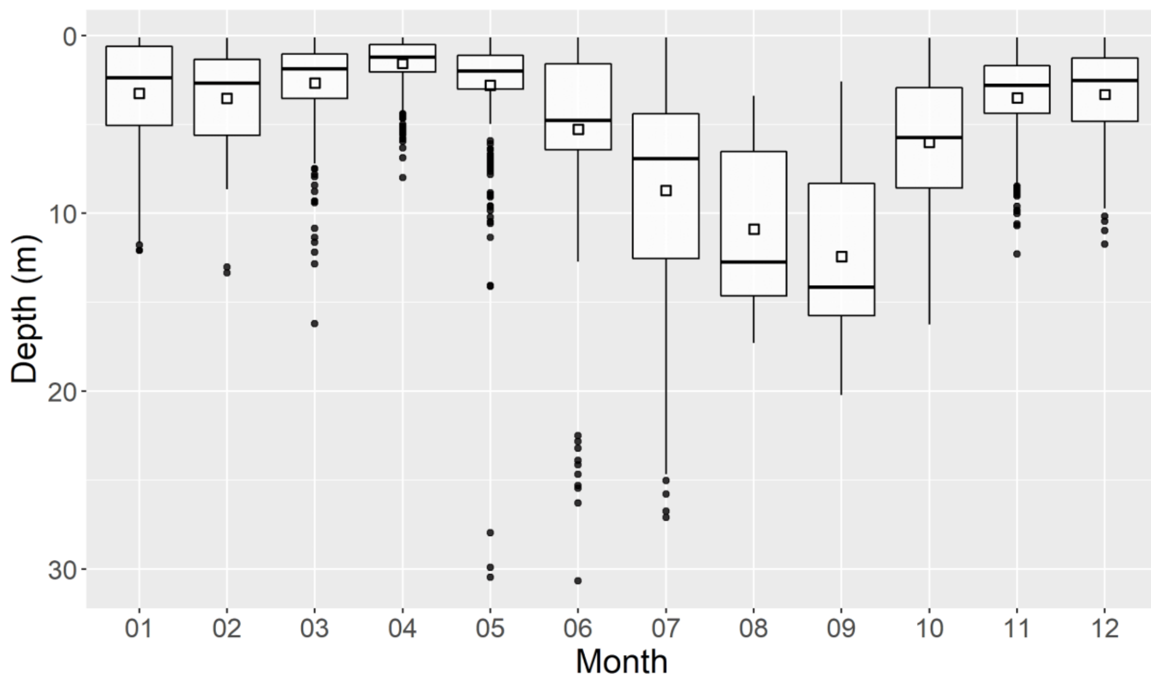


**Figure K7.** Boxplot of monthly depth use based on mean daily depths of acoustically tagged White Sucker in Hamilton Harbour, 2016 – 2020. Squares indicate the mean.

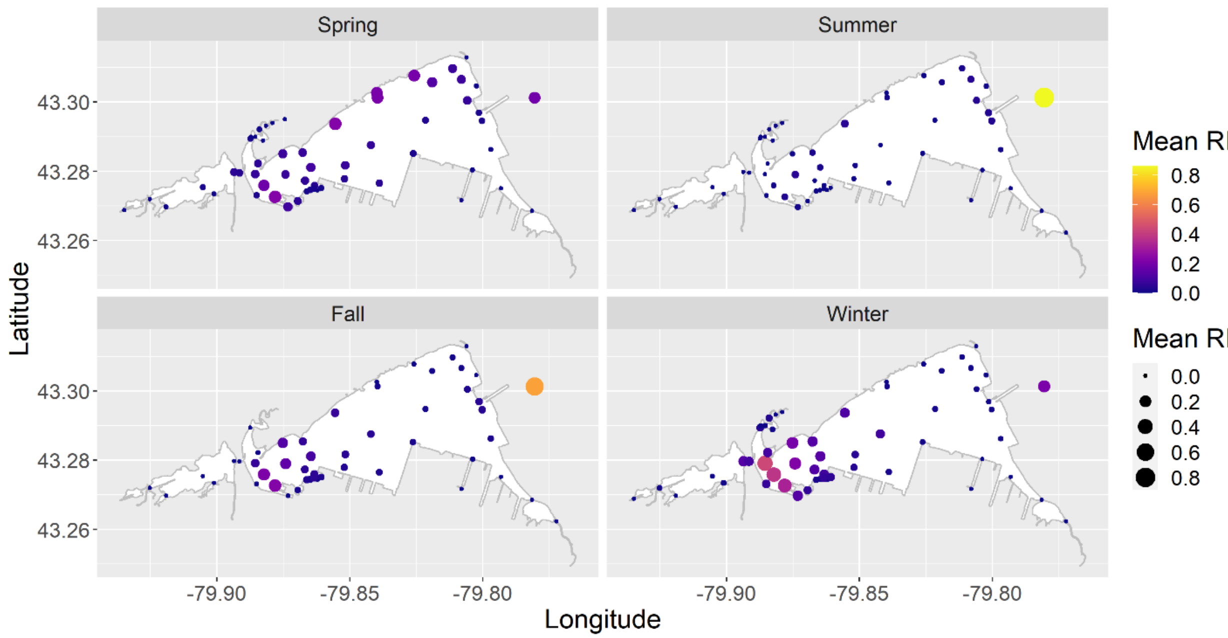


**Figure K8.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged White Sucker (N = 8). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

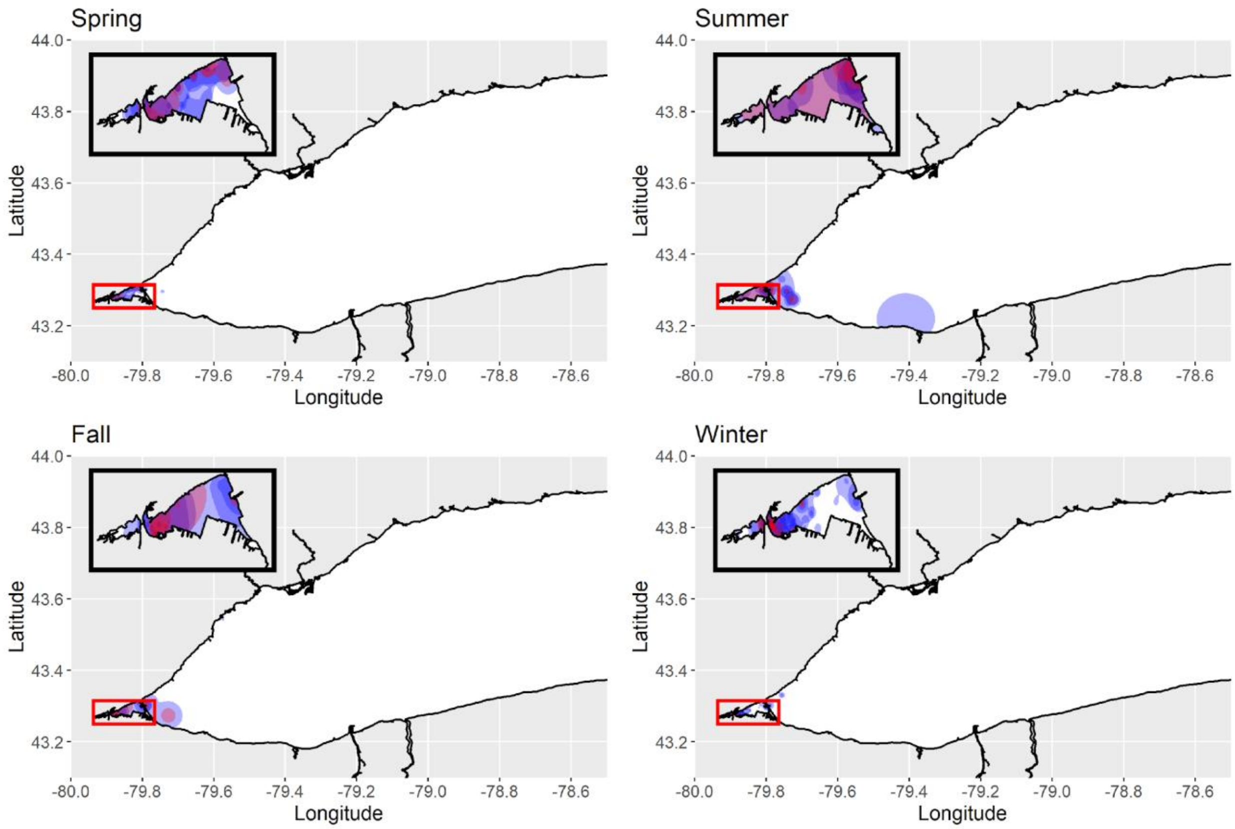


**Figure K9**. Seasonal 50% (red) and 95% (blue) home ranges (via kernel utilization distribution) of individual White Sucker tagged in Hamilton Harbour, 2016 – 2020. Darker colours indicate overlapping home ranges of individuals. All White Sucker left the harbour at some point during the study but individual duration and distance varied.

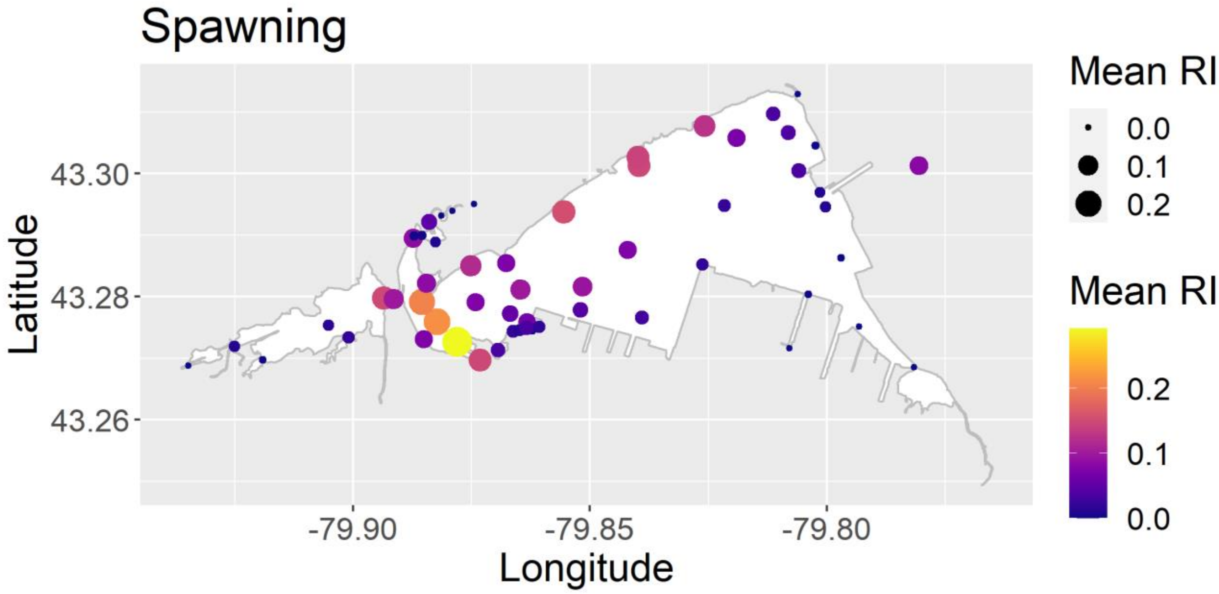


**Figure K10.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged White Sucker (N = 8) during their spawning window (April 1 to May 31). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

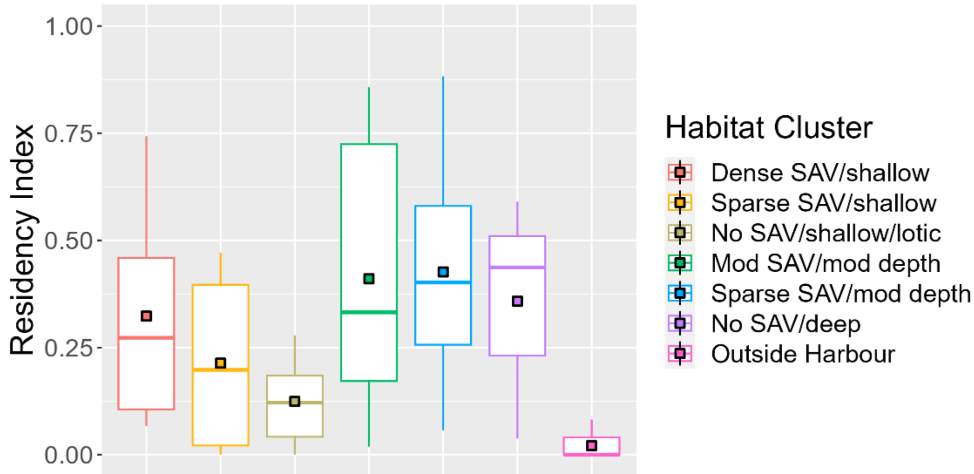


**Figure K11**. Boxplot of individual tagged White Sucker residency during the spawning window (April 1 to May 31) at associated habitat clusters within Hamilton Harbour, 2016 – 2020. Coloured squares are the means.

# APPENDIX L: YELLOW PERCH

## DETECTIONS AND HABITAT USE

Ten Yellow Perch (*Perca flavescens*) were acoustically tagged and monitored in Hamilton Harbour from August 2016 to April 2017 (**Table L1**). Based on mean monthly detections, Yellow Perch had more detections in summer than in winter (**Figure L1**). Yellow Perch detections indicated a general affinity towards the west end in the summer and fall, with an increase in detections in the east end in the fall, and with detections in the west end, Piers 5-7, north shore, and east end in winter (**Figure L1**). Two Yellow Perch entered Cootes Paradise Marsh in April and soon returned to the harbour that same month. No Yellow Perch left the harbour during the study period.

Based on mean monthly detections at habitat clusters, Yellow Perch were primarily detected in areas of dense SAV at shallow depths in the summer, fall, and winter (**Figure L2**). However, habitat trends were different when assessed based on seasonal residency by habitat clusters (**Figure L3**). Seasonal residency indicated that Yellow Perch were primarily located in areas of sparse SAV at moderate depths in spring, summer, and fall, and in areas of no SAV at deep depths in spring, fall, and winter. However, to a lesser extent Yellow Perch also used areas of dense SAV in shallow waters year-round, areas of moderate SAV at moderate depths in spring, fall, and winter, areas of sparse SAV in shallow waters in spring and winter, and lotic areas in the spring (**Figure L3**).

There was an increase in detections during dawn compared to dusk and daytime (relative to the duration of time of each daylight category; $\chi^2_3 = 10.645$, $p = 0.013$), but no change in the relative number of detections based on moon phase ($\chi^2_3 = 5.641$, $p = 0.130$; **Figure L4**).

## DEPTH USE

Yellow Perch did not have depth sensor tags to determine depth use patterns.

## RESIDENCY

Spatially, Yellow Perch had the greatest residency in the west end, year-round (**Figure L5**). However, residency was highly focused in the Bayfront area in the summer, where tagging Yellow Perch had occurred. In fall, residency shifted into slightly deeper waters and towards the southern part of the east end. By winter, Yellow Perch residency was in deeper waters of the west end, and in spring, residency was spread throughout the west end, towards Cootes Paradise Marsh, Grindstone, and the north shore (**Figure L5**).

## SPAWNING

April 1 to May 31 was the spawning window used for Yellow Perch (**Table 2**). Based on the residency index, during the spawning window, Yellow Perch appear to be in the west end and towards Cootes Paradise Marsh (**Figure L6**). However, the receiver array had not yet expanded into areas like Piers 5-7 or further in Grindstone and Cootes Paradise Marsh to give a more definitive location of Yellow Perch during spawning. Habitat-associated residency of Yellow Perch during the spawning window was in areas of no SAV at deep depths as well as sparse SAV in shallow depths, and sparse and moderate SAV at moderate depths (**Figure L7**). Again, due to the array placement during 2016, there was less ability to detect Yellow Perch in the nearshore areas that likely skewed the habitat-associations during the spawning period.

**Table L1.** Tagging and detection summary of acoustically tagged Yellow Perch (*Perca flavescens*) in Hamilton Harbour, ON. Life status refers to whether fish were considered A = alive, AD = alive and later died, or U = unknown, based on the detection/depth profiles.

| Tag ID | Total Length (mm) | Mas s (g) | Date Tagged | Release Location | Tag Type | Depth Sensor (T/F) | Life status | Date of First Detection | Date of Last Detection | Detection Window (days) | Number of Detections | Number of Days with Detections |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 45357 | 295 | 359 | 7/21/2016 | Bayfront Boat Launch | V7-2L | FALSE | A | 7/24/2016 | 10/9/2016 | 77 | 5103 | 61 |
| 45360 | 181 | 59 | 7/21/2016 | Bayfront Boat Launch | V7-2L | FALSE | A | 8/12/2016 | 4/15/2017 | 246 | 11660 | 157 |
| 45361 | 187 | 71 | 7/21/2016 | Bayfront Boat Launch | V7-2L | FALSE | A | 7/24/2016 | 4/23/2017 | 273 | 10562 | 201 |
| 45362 | 201 | 94 | 7/21/2016 | Bayfront Beach | V7-2L | FALSE | U | 7/29/2016 | 2/18/2017 | 204 | 611 | 49 |
| 45363 | 175 | 51 | 7/21/2016 | Bayfront Beach | V7-2L | FALSE | AD | 8/8/2016 | 9/29/2016 | 52 | 2489 | 45 |
| 45365 | 239 | 152 | 7/26/2016 | Bayfront Beach | V7-2L | FALSE | A | 7/26/2016 | 4/23/2017 | 271 | 5211 | 154 |
| 45366 | 242 | 179 | 7/26/2016 | Bayfront Beach | V7-2L | FALSE | A | 7/26/2016 | 4/18/2017 | 266 | 10421 | 184 |
| 45367 | 248 | 193 | 7/26/2016 | Bayfront Marina | V7-2L | FALSE | AD | 8/3/2016 | 9/11/2016 | 39 | 6240 | 40 |
| 45368 | 235 | 230 | 7/26/2016 | Bayfront Marina | V7-2L | FALSE | A | 8/3/2016 | 4/22/2017 | 262 | 27033 | 220 |
| 45371 | 214 | 113 | 7/21/2016 | Bayfront Beach | V7-2L | FALSE | AD | 7/21/2016 | 8/21/2016 | 31 | 1158 | 31 |

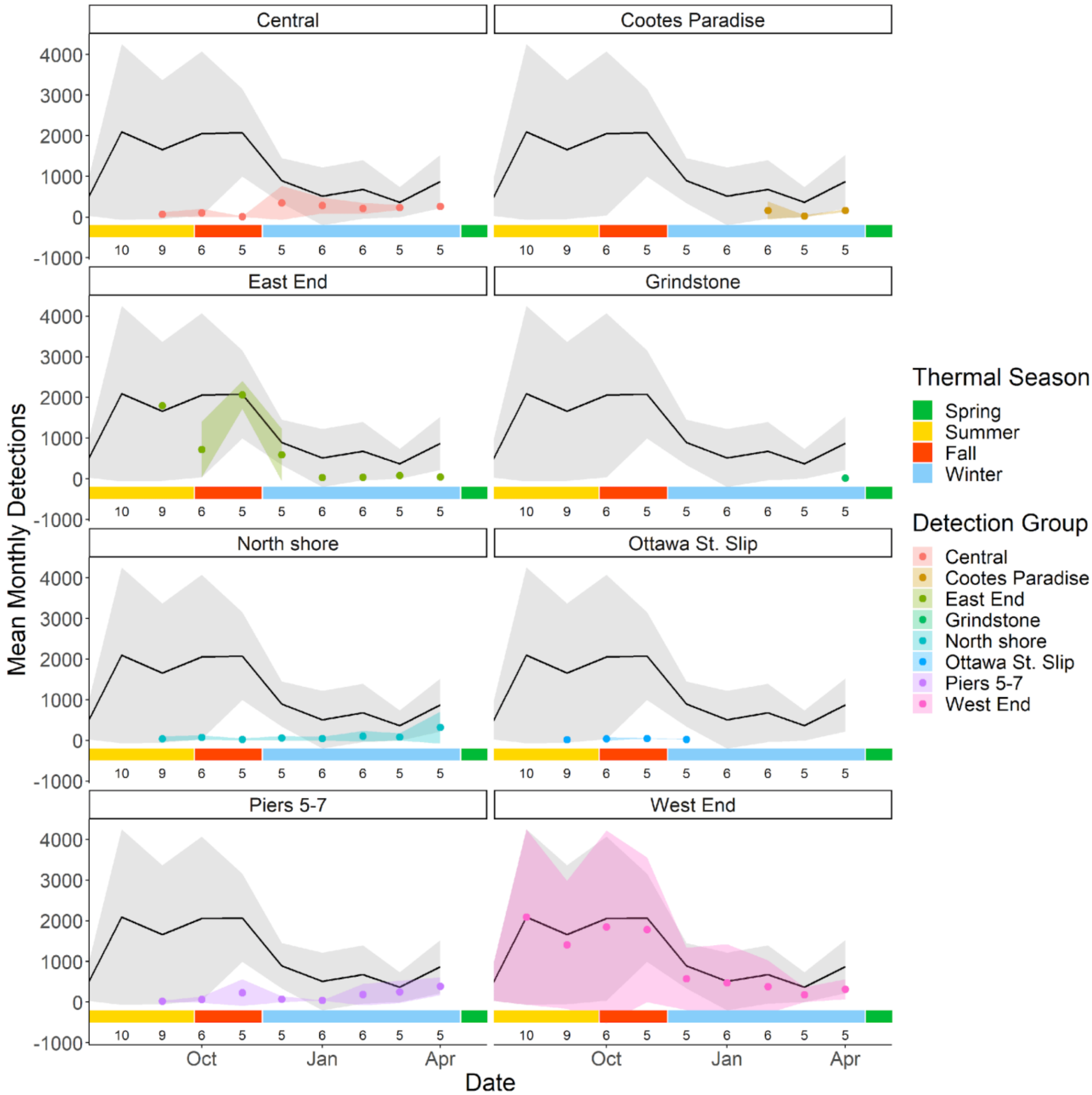


**Figure L1.** Mean (± SD) monthly detections of acoustically tagged Yellow Perch at general locations within Hamilton Harbour over time. Black line is the total mean monthly detections with SD. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Yellow Perch at that time.

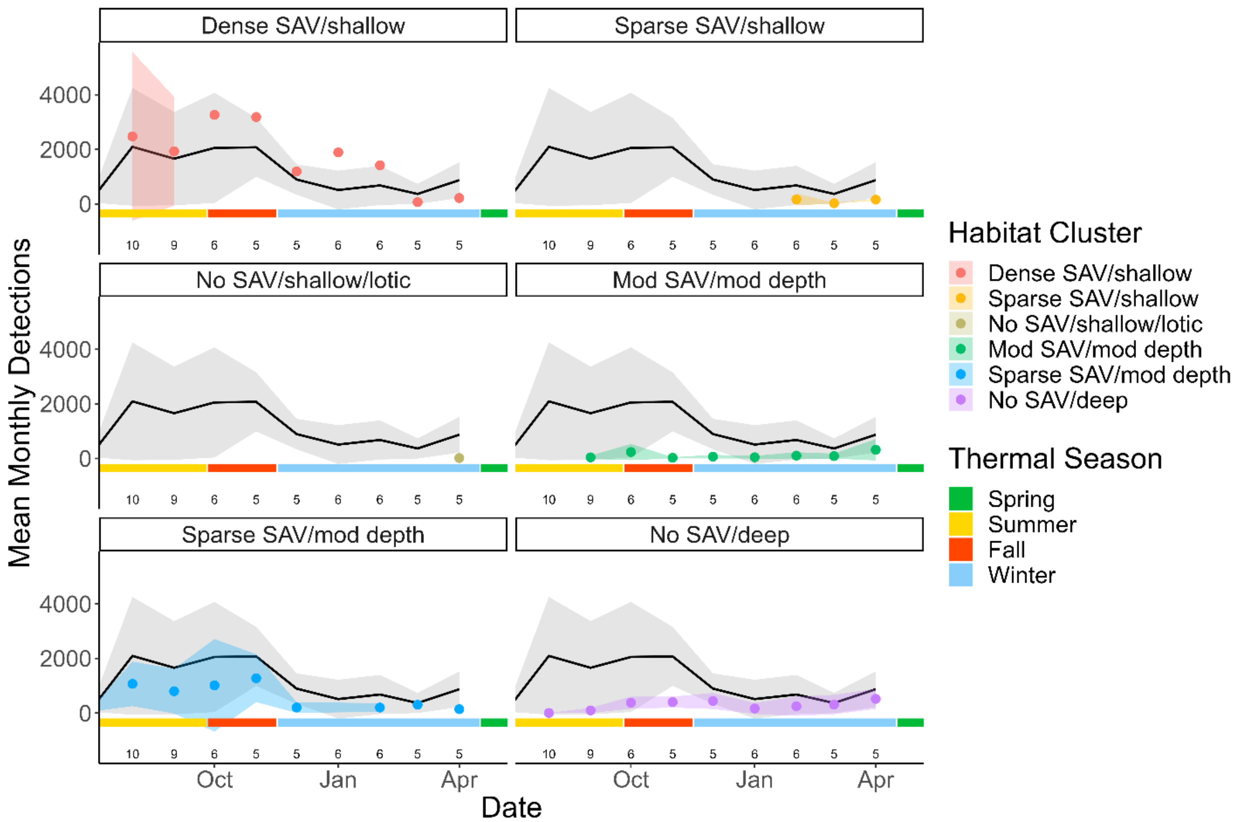


**Figure L2**. Mean (± SD) monthly detections of acoustically tagged Yellow Perch at the different habitat clusters within Hamilton Harbour over time. Black line is the total mean monthly detections. The coloured bar indicates the season over time and the values below the seasons are the sample sizes of Yellow Perch.

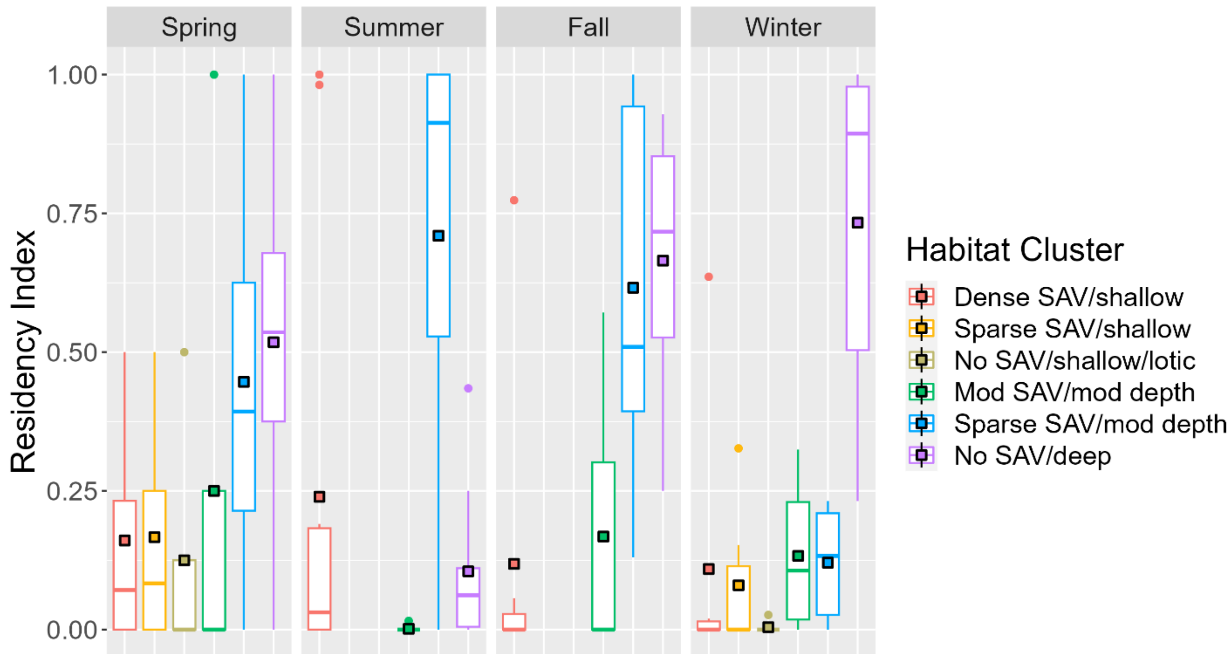


**Figure L3.** Boxplot of individual tagged Yellow Perch residency by season at associated habitat clusters within Hamilton Harbour, 2016 – 2017. Coloured squares are the means.

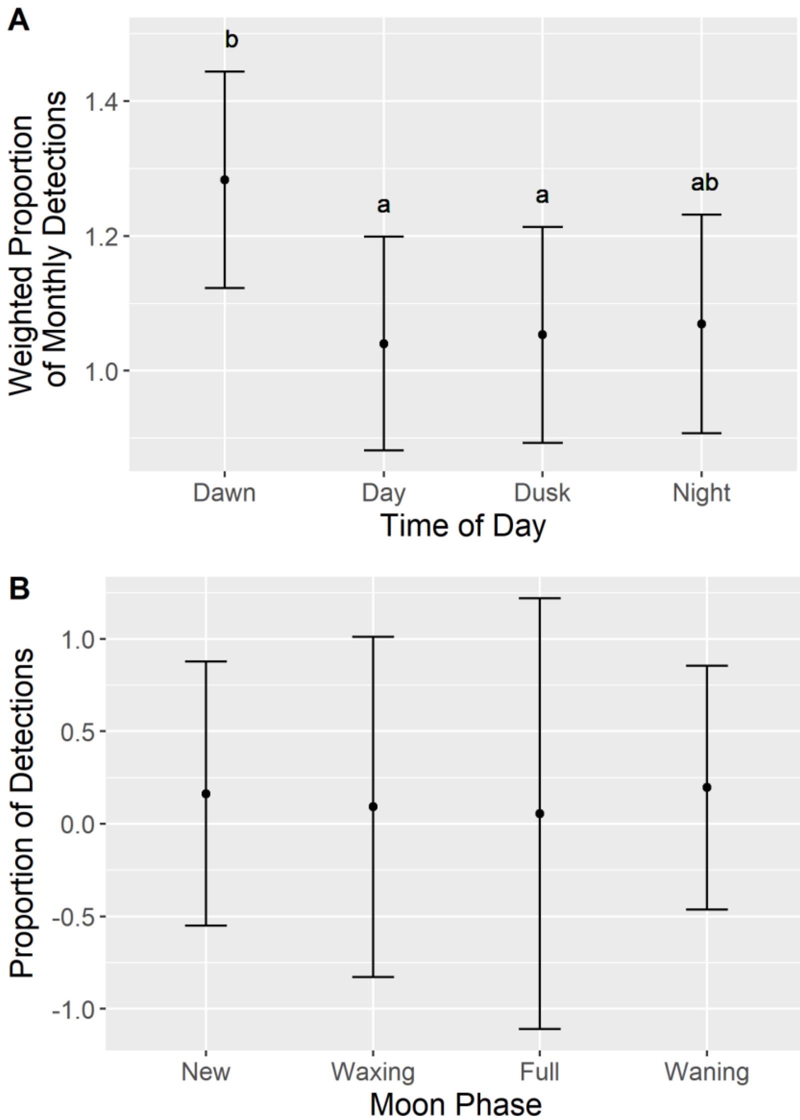


**Figure L4**. A) Mean (± SE) proportion of monthly detections of Yellow Perch at different periods of the day, weighted by the duration of each period of the day and B) mean (± SE) proportion of monthly Yellow Perch detections occurring at different moon phases in Hamilton Harbour, 2016 – 2017.

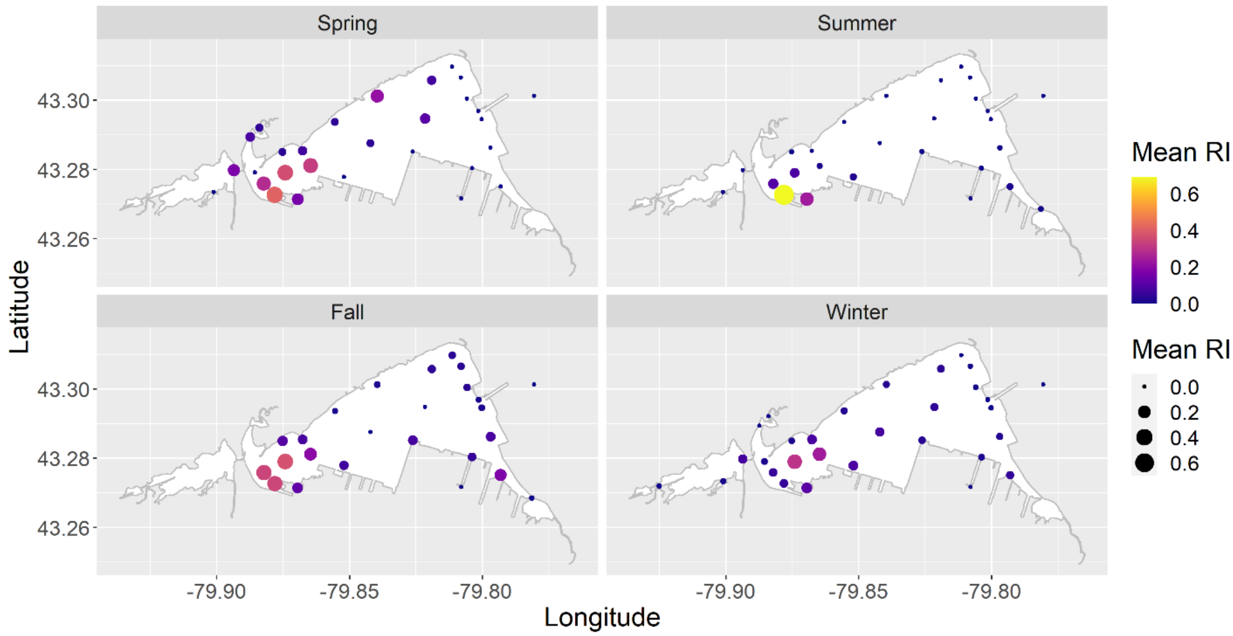


**Figure L5.** Seasonal mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Yellow Perch (N = 10). Size increases and colours are brighter/warmer with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

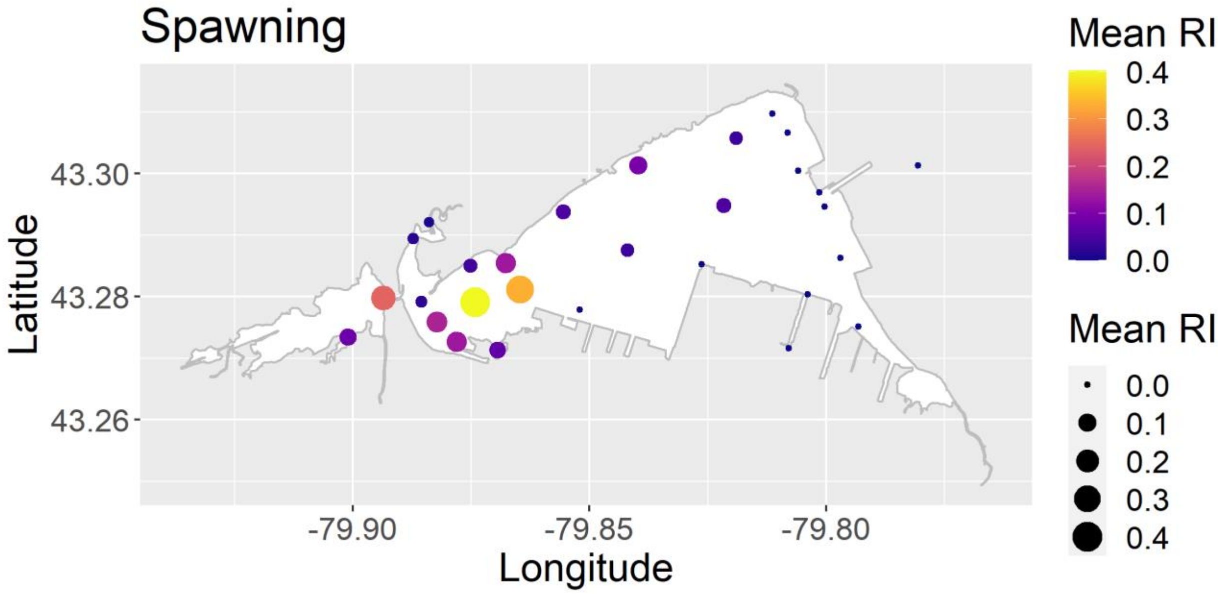


**Figure L6.** Mean residency index (RI) at each receiver location in Hamilton Harbour based on detections of acoustically tagged Yellow Perch (N = 5) during their spawning window (April 1 to May 31). Size increases and colours are warmer/brighter with increased RI. Mean RI was calculated by averaging RI values across individuals within each season.

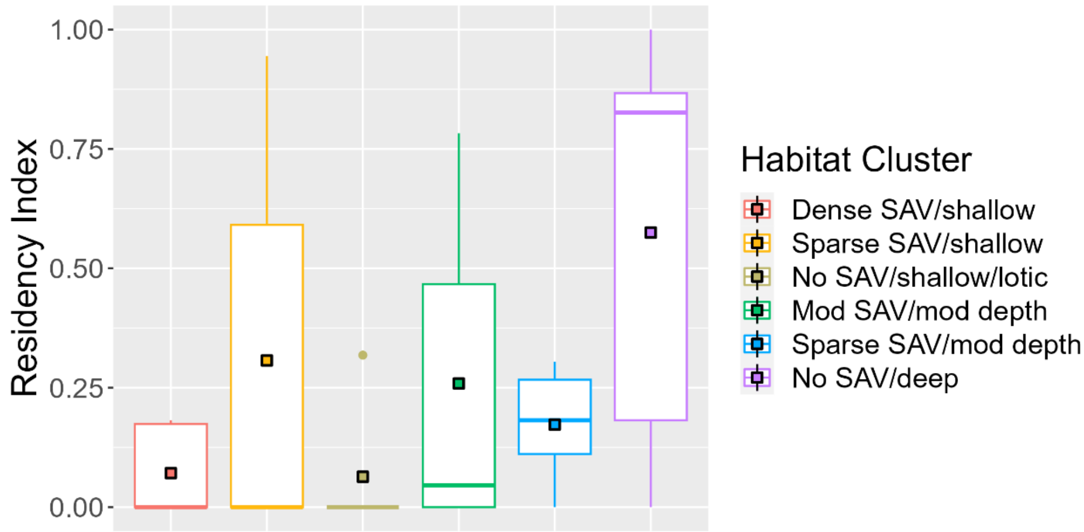


**Figure L7**. Boxplot of individual tagged Yellow Perch residency during the spawning window (April 1 to May 31) at associated habitat clusters within Hamilton Harbour, 2016-2017. Coloured squares are the means.