Seasonal Spatial Ecology of juvenile Muskellunge and Northern Pike in upper St. Lawrence River Nursery Bays: Applied Perspectives

By

Sarah Elizabeth Walton

BSc in Biology with Specialization in Conservation Biology, Trent University, 2012

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Dedication

First and foremost, I dedicate this thesis to my husband, who has encouraged and supported me every step of the way. You pushed me to apply, despite knowing it would mean long-distance for two years because you knew it would it benefit our relationship in the long-run. You were a consistent source of inspiration, and an ear when I needed to vent, especially when I hit moments where I felt I was not good enough to continue. You found me such a wonderful little apartment, I do not want to leave its breathtaking view of Gatineau Park and its sunsets, but I cannot wait to snuggle you each night once again. You became my husband half way through graduate school, and while we have been apart for most of our first year of marriage, it has only made us stronger. I so look forward to the next chapters of our lives and the joys a young family will bring. Thank you for your constant belief and supporting my life pursuits. I hope I can make you proud.

To my parents, who inspired me as a young child to pursue my dreams, regardless of how untraditional they were. First, it was a meteorologist, one that chased tornadoes. I will admit, the idea of studying weather is still intriguing; however, it was our inaugural Algonquin Provincial Park camping trip where a unique interaction with a black bear started me down my path to work with wild animals. Moreover, your push for me to attend a Girl Guide canoe camp solidified my need to be outdoors, and an absolute love for canoe tripping. You empowered me to pursue an adventurous life, one in which every experience, and those with whom I established close friendships along the way, made me the woman I am today.

Abstract

Nursery habitat requirements for age-0 *Esox* spp. in the upper St. Lawrence River are well understood; however, little is known about the influence of environmental variables (i.e., depth, temperature, habitat) on their spatiotemporal ecology during fall and winter periods. A hatchery study evaluated biologically relevant endpoints post-implantation of a mini-acoustic transmitter in age-0 Muskellunge. Neither tag expulsion nor mortality were observed, nor influence of tag presence on short-term growth rates. Applying this tool to evaluate their ecology, I captured and tagged age-0 Muskellunge (*Esox masquinongy*) and Northern Pike (*Esox lucius*) from August to October in natal bays. Detection data, modeled against environmental covariates, found deeper littoral regions were used by both species, and complex interactions between covariates influenced spatial trends during this critical period. With similar overwintering spatial ecology between these congeneric competitors, overwintering microhabitat use studies in association with water level management may confirm habitat overlap and inform wetland restoration efforts.

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Co-Authorship

Chapter 2. Evaluation of acoustic transmitter implantation on tag retention, healing, growth and behaviour of juvenile muskellunge. Sarah Walton, Mark Newell, Amanda Jeanson, Elodie Lédée, John Farrell, and Steven Cooke.

While this study is my own, the research was undertaken as part of a collaborative effort and each co-author played a role in its completion. The project was conceived by Walton. Data were extrapolated by Walton and Ledee. All figure construction and analyses were conducted by Walton. Data were interpreted by Walton and Ledee. All writing was conducted by Walton. All co-authors provided comments and feedback on the manuscript. This manuscript has been prepared as a management brief submission to the North American Journal of Fisheries Management.

Chapter 3. Spatiotemporal ecology of juvenile Muskellunge (*Esox masquinongy*) and Northern Pike (*Esox lucius*) in upper St. Lawrence River nursery bays over fall and winter seasons. Sarah Walton, Elodie Lédée, John Paul Leblanc, Petra Szekeres, Jon Midwood, Austin Gallagher, John Farrell, and Steven Cooke.

While this study is my own, the research was undertaken as part of a collaborative effort and each co-author played a role in its completion. The project was conceived by Farrell and Cooke. Data were collected by Walton, Leblanc, Szekers, and Gallagher. The figures were constructed by Walton with the assistance of Lédée and Graham Raby. Data interpretation and analysis were conducted by Walton with direction from Lédée. All writing was conducted by Walton. All co-authors provided comments and feedback on the manuscript. This manuscript has been prepared for submission to Ecology of Freshwater Fish.

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CHAPTER 1: General Introduction

Riverine fish are amongst the most threatened taxa due to persistent environmental stressors and anthropogenic pressures including shoreline development, migration barriers, habitat degradation, overfishing, pollutants, and climate change (Dudgeon et al. 2006, Cooke et al. 2012). Where and when riverine fish distribute themselves over time to reside, forage, avoid predation, and reproduce - their spatiotemporal ecology - is markedly influenced by such stressors and natural variability in physio-chemical characteristics of their environment, as are their interactions with other species. Insight into the spatiotemporal patterns of juvenile fish may elucidate how early life stages distribute themselves as environmental conditions fluctuate and the subsequent influence on source and sink population dynamics. Studying these patterns may illuminate factors that trigger variation in space use and dispersal patterns (e.g. emigration, transient movement) and elucidate how and why variation may exist (Chapman et al. 2012, Radinger and Wolter 2014). Such insight may aid in characterizing seasonal habitat use and inform *in-situ* habitat protection and management to promote recruitment and enable self-sustaining populations (Warfe and Barmuta 2004, Jewell et al. 2014) amongst such persistent stressors and anthropogenic pressures.

1.1 Spatiotemporal Fish Ecology

Understanding the mechanisms that influence distribution and subsequent habitat use, and the ability to predict changes in spatiotemporal patterns based on environmental fluctuations, using statistical analysis, is at the core of aquatic ecological studies (Planque et al. 2011). Measuring and modeling how environmental drivers may influence spatial distribution enables researchers to predict where organisms are likely to reside, interspecific interactions, and variability between stocked and native individuals (Cooke et al. 2016). Data may illustrate core habitat use areas at earlier-life stages (i.e. nursery rearing, foraging, winter residency), and elucidate ontogenetic shifts

in habitat use (e.g. Cunjak 1996, Shuter et al. 2012, Huusko et al. 2007).

1.2 Rehabilitation Efforts for Early-Life Stages

Restoration, recovery or rehabilitation of habitats, as witnessed in projects throughout Areas of Concern in the Great Lakes - St. Lawrence River basin (Kelso and Hartig 1995, Brooks et al. 2017), exemplify the importance and success of *in-situ* initiatives to promote natural recruitment of self-sustaining fish populations. Success stories include reconnecting coastal wetlands in the upper St. Lawrence River, to encourage residency and population growth by aquatic biota and use of restored wetlands by juvenile fish like larval Northern Pike (*Esox lucius*; Augustyn et al. 2018). Several case studies throughout the Great Lakes basin focus on the need to determine seasonal fish-habitat associations for the purpose of habitat restoration within large-riverine systems like the St. Mary's, St. Clair, Detroit and Niagara Rivers (Brooks et al. 2017). Though these case studies focused on whether restoration and use of spawning habitats for native and invasive species had occurred, using acoustic telemetry to follow the fish in real-time, work and subsequent adjustments to habitat availability may have direct implications on juvenile fishes.

1.3 Tracking Aquatic Creatures in the Field

Telemetry is a well-recognized tool for addressing knowledge gaps associated with spatiotemporal distributions of aquatic and terrestrial organisms by investigating the relationship of individuals with their environment (Grimm 1999, Cooke et al. 2013, Hussey et al. 2015). Understanding how fish habitat associations and environmental drivers are correlated and influence spatiotemporal ecology are key research topics elucidated by acoustic telemetry, and the postulates from such applied science are used to inform fisheries managers (Donaldson et al. 2014). Indeed, the focus of data collection is often premised on informing *in-situ* conservation science plans for declining populations and at-risk species (e.g. Simpfendorfer et al. 2010).

Individual movements are tracked, and collective patterns are analyzed to permit a better understanding of spatial occupancy and habitat requirements (Jackson et al. 2001, Cooke et al. 2004) of fish at various life-stages, which may advise habitat restoration and stock enhancement initiatives (Lucas and Baras 2000).

Development of smaller, efficient, coded acoustic transmitters (e.g. McMichael et al. 2010) have enabled researchers to tag and track smaller species and earlier life stages of large-bodied fish (Cooke et al. 2013). Within riverine environments, early life stage studies have focused on elucidating coarse and fine-scale movements of salmonids (e.g. Juanes et al. 2000). For instance, McMichael et al. (2010) tracked juvenile salmon (*Oncorhynchus sp.)* and steelhead using mini-acoustic transmitters to examine migration and survival through multiple hydroelectric facilities on Canada's west coast, while Laurel et al. (2007) tracked juvenile Atlantic Salmon (*Salmo salar*) to examine whether age- or stage- habitat suitability and subsequent distribution may be relative to season and ontogeny. Use of mini-acoustic tag technology (e.g. JSAT tags) may therefore elucidate the spatiotemporal ecology of other recreationally valuable fish whose basic juvenile ecology remains unknown (Murry and Farrell 2007), such as esocids.

Telemetry studies often presume that the behaviour, condition, and fate of tagged fish are not influenced by transmitter presence or tagging process, suggesting that tagged fish are representative of untagged conspecifics (e.g. Skalski et al. 2001). Yet, the extent to which that presumption is correct has been questioned, particularly, when transmitters are implanted in the coelom (Brown et al. 2011). Therefore, validating tagging procedures to minimize welfare impacts on tagged fish is important to consider (Walsh et al. 2000), as well as the suitability of mini-acoustic tags to collect spatiotemporal data for early-life stages in field studies. (e.g. and long-term physical consequences associated with the tag presence). Validation studies have shown that implanting passive integrated transponder (PIT) tags are suitable for age-0 fish (e.g. Acolas et al.

2007, Richard et al. 2013, Tiffan et al. 2015), including esocids like Muskellunge (Wagner et al. 2007, Younk et al. 2010) and Northern Pike (Hühn et al. 2014), however, the influence of surgical implantation and presence of these new mini-acoustic tags on these cryptic and declining species must be evaluated.

1.4 Muskellunge and Northern Pike Ecology and Knowledge Gaps

Muskellunge (*Esox masquinongy*), the largest piscivorous fish in North America, are restricted to eastern waters of North America (Scott and Crossman 1998). This species, one of five in the *Esox* genus (Harvey 2009) derived from a single glacial refuge (Crossman 1986) and includes three major stocks: the upper Mississippi River, Ohio River, and Great Lakes (Koppelman and Phillip 1986). Within the Great Lakes and their connecting channels, Muskellunge live in sympatry with Northern Pike, an older relative and competitor which exhibits a circumpolar distribution (Scott and Crossman 1998). In their sympatric range, Northern Pike are likely more common than Muskellunge due to their spawning phenology and subsequent predation on young Muskellunge, and tolerance to varying temperature and oxygen ranges (Harvey 2009).

Bi-national management of these well-known sportfish in the St. Lawrence River has shifted from a harvest focus to catch-and-release, with objectives to conserve and sustain spawning and nursery habitat requirements in coastal embayments (Farrell et al. 2007). Juvenile and sub-adult ecology, however, remains poorly understood (Midwood et al. 2015). Much effort has been devoted to restoration of fish habitat in the upper St. Lawrence River system, due to hydroelectric operations and shoreline alteration, but there remain many questions about the effectiveness of past restoration efforts or basic understanding of esocid-environment relationships needed to inform future restoration activities.

Pragmatic research needs for Muskellunge include critical habitat identification and core ecology for juvenile Muskellunge (ages 0-5; Farrell et al. 2007); the ability to support early-life

stages through habitat associations is imperative when population restoration is a key management goal (Farrell et al. 1999). Notably, fine-scale assessments of a small sample of stocked, sub-adult Muskellunge (age-1) and wild age-1 Northern Pike in the upper St. Lawrence River bay noted ecological separation observed in summer months (Farrell et al. 2014). Targeted research on the spatiotemporal ecology and habitat use of riverine age-0 Muskellunge and Northern Pike in summer months has further elucidated movement activities for stocked individuals at varying latitudes (Hanson and Margeneau 1992, Wagner and Wahl 2011), observed persistent use of nearshore regions with low water velocity, fine substrates, and habitat complexity (Murry and Farrell 2007) in addition to woody debris (DeBoom and Wahl 2012, Owensby et al. 2017), supported conservation of well-vegetated habitat which support abundant fusiform fish for strong year class formation (Kapincinski and Farrell 2014), and modeled how variation in water temperature and community dynamics may influence recruitment and survival (Eslinger et al. 2010). Given that many restoration and rehabilitation efforts have focused on early life stages, information on the spatiotemporal ecology of juvenile esocids in fall and winter months remains a significant research gap.

1.5 Research Rationale and Objectives

My thesis provides insight on an important life stage of esocids and the potential impacts of riverine conditions on their behaviour and survival. Indeed, the significant decline in self-sustaining Muskellunge and Northern Pike populations inhabiting the upper St. Lawrence River (Farrell et al. 2007) and no understanding of the role of winter phenology on juveniles prompted collection of real-time dispersal and residency data, using mini-acoustic tags, to identify spatiotemporal trends, core habitat feature use, and elucidate how environmental mechanisms (e.g. temperature, water levels) may drive spatiotemporal patterns during fall and winter periods. My thesis includes two data chapters (Chapters 2 and 3).

Chapter two evaluated the effects of surgical procedures and tag implantation on captive-reared age zero Muskellunge. Tag retention, survival, growth rates, rate of healing due to surgical wounds, and flight initiation behaviour associated with chemical anesthetic exposure using three treatment groups - tagged, sham, and control - were quantified, to assess whether rates differed significantly treatment groups, and how behaviour post-anesthetic exposure may influence vulnerabilities to predators, post release in field studies.

Chapter three characterized the spatiotemporal ecology of age-0 and age-1 Muskellunge and Northern Pike in the upper St. Lawrence River, and compared their collective dispersal patterns, core winter residencies and habitat use to environmental covariates to elucidate overwintering habitat requirements for these early life stages, and how interspecific overlap with Northern Pike may influence survival of Muskellunge beyond their first winter.

CHAPTER 2: Evaluation of acoustic transmitter implantation on tag retention, healing, growth and behaviour of juvenile muskellunge

2.1 Abstract

Acoustic telemetry is an increasingly common tool used in fisheries science. The development of small acoustic transmitters has enabled researchers to target earlier life stages and smaller fish species than was previously possible. The underlying assumptions of any telemetry study are minimal tag loss and negligible effects on the behaviour and survival of tagged individuals. To that end, tag retention, healing, survival, growth, and behaviour were evaluated in age-0 Muskellunge (*Esox masquinongy*) (205 ± 10 mm total length [TL]) implanted with one of the smallest commercially available acoustic transmitters (Pacific Northwest National Laboratory JSAT tag; 12.0 × 5.3 × 3.7 mm, 0.217-g in air) in an overwinter hatchery experiment. Tagged fish were compared to untagged controls and sham fish (fish that had undergone surgery, but not transmitter implantation). MS-222 was used for anesthesia, the incisions were closed with a synthetic absorbable monofilament, and all surgeries were conducted by a single trained researcher. All tags were retained throughout the experiment; surgical wounds healed within 30 days, and 32% of sutures were retained 120-d post-surgery. Growth was similar among the three groups (tagged, untagged and sham fish), and 98% of fish survived the experiment. Minor behavioural differences were observed in the tagged fish hours after the tagging procedure as well as sham fish, relative to controls, seven days post chemical anesthesia. Results validate the utility of surgically implanted small acoustic transmitters in juvenile Muskellunge (>150 mm) in future ecological studies.

2.2 Introduction

Telemetry has become a mainstream tool for studying the spatial ecology and survival of fish (Donaldson et al. 2014, Hussey et al. 2015). Early telemetry studies focused on larger bodied fish species and adult life stages, but enhancements (e.g. smaller tag size, longer battery life) have enabled tracking and collection of real-time movement data for smaller life stages and species. In telemetry studies it is often presumed that the behaviour, condition, and fate of tagged fish are not influenced by transmitter presence or tagging process, suggesting that tagged fish are representative of untagged conspecifics (Skalski et al. 2001, Deriso et al. 2007). Yet, the extent to which that presumption is correct has been questioned, particularly, when transmitters are implanted in the coelom (Brown et al. 2011). Therefore, validating tagging procedures to identify methods that minimize welfare impacts on tagged fish is important to consider (Walsh et al. 2000). The ratio of tag size (the volume, shape, and mass) to fish body size seems to be particularly influential (e.g., on healing, retention, behavioral impairments, survival; Jepsen et al. 2004). Nonetheless, other aspects such as suture material, incision location, surgeon experience, and tag type (e.g. presence of antenna for radio tags, tag coating) are also important considerations (reviewed in Bridger and Booth 2003, Cooke et al. 2011, Thorstad et al. 2013). Clearly, there is a large degree of interspecific variation in responses, that are further mediated by environment (Cooke et al. 2011).

Researchers use telemetry tools to explore and assess recreational fishes' spatial behaviour in their natural environment (Lucas and Baras 2000), often to develop a mechanistic understanding of spatial patterning (e.g., Cooke et al. 2008). Researchers efforts are expanding to study the spatial ecology and survival of juvenile fish, including Muskellunge (e.g. Hanson and Margenau 1992, Farrell et al. 2014, Owensby et al. 2017), and Northern Pike (Hühn et al. 2014). Validating how telemetry tools may influence the welfare of fish, or limit data interpretation, is therefore

imperative. Implanting passive integrated transponder (PIT) tags, for instance, was not found to impair the welfare or produce sublethal effects for age-0 fish (e.g. Acolas et al. 2007, Richard et al. 2013, Tiffan et al. 2015), including age-0 Muskellunge (Wagner et al. 2007, Younk et al. 2010), and Northern Pike (Hühn et al. 2014). However, these studies are limited in their capacity to capture fine-scale (e.g. daily) movements. Radio telemetry has been used to estimate mortality, dispersal, and habitat use of stocked age-0 Muskellunge (Hanson and Margenau 1992, Wagner and Wahl 2011, Owensby et al. 2017), though no validation studies were performed. Deters et al. (2010) evaluated implantation and retention associated with the smallest, commercially available, coded transmitter (e.g. Juvenile Acoustic Salmon Telemetry (JSAT) tag; McMichael et al. 2010) and found neither tag expulsion nor mortality associated with implanting tags in juvenile Chinook Salmon (*Oncorhynchus tshawytscha*; FL range = 96–121 mm; tag 2–6% body weight). With acoustic telemetry growing in popularity as tool for research on juvenile life stages and small fish (Hussey et al. 2015), there is merit in studying effects of surgical implantation and presence of these new mini-acoustic tags on other species.

With research gaps related to the spatial ecology of juvenile Muskellunge (e.g., Crane et al. 2015), and no publications evaluating the influence of acoustic telemetry tools for this species, this paper focuses on the influence of surgical procedures, tag presence, and anesthesia on captive reared, age-0 Muskellunge. Fish implanted with JSAT transmitters were compared to untagged controls and sham fish (fish that have undergone surgery but not transmitter implantation) with 1) survival, 2) tag retention, 3) tag burden, 4) tag encapsulation, 5) incision healing, and 6) growth rates for each sampling interval (day 0-30, 30-60, 60-90, and 90-120 days post-tagging) and full experiment duration of 120-d (Hühn et al. 2014), as well as individual flight response post-anesthetic recovery and seven days post-surgery as end points.

2.3 Methods

2.3.1 Fish source and rearing

Muskellunge used in this study were reared at the Fleming College Muskellunge Hatchery (Lindsay, Ontario) in 2.4 (l) x 1.2 (w) x 1.2 (h) m tanks with a normal operating volume of 3000 L with recirculated water. Eggs were collected as gametes from a native, wild stock in Gloucester Pool, Lake Huron (Wilson et al. 2016) and fertilized on April 27. Eggs were incubated between 15ºC to 17ºC in early rearing units. Fish were transferred to intermediate rearing units, six to seven weeks post-hatch, for eight to 10-weeks, where rearing temperatures were ~22ºC. Fish were fed a manufactured salmonid Skretting diet; Nutra ST 0.3 mm crumble feed (58% protein, 18% lipid) as fry, Nutra RC NP 1.8 mm (50% protein, 20% lipid), and Europa 15 4.0 mm (55% protein, 15% lipid) food pellets as juveniles grew. Muskellunge (n = 96) were processed in November 2017 over three days.

2.3.2 Environmental and physical fish measurements

Water temperature and dissolved oxygen levels were documented daily for each tank post-processing. Every 30 days, body size (total length, nearest 1 mm; weight, nearest 0.1 g) was measured to estimate growth (Table S.2.1). Average temperatures (based on sampling intervals) declined after 60-d (14.3, December; 11.4 ºC, January), then increase to 16.9ºC in February (90-d) and 18.1ºC in March (120-d). Both the incision site and fins (caudal, dorsal, pelvic) were photographed for each fish. If a fish died, a necropsy was performed to assess if peritoneal infection (presence of viscous pale-pink fluid in a sack around the transmitter or in the body cavity) was present or absent (Walsh et al. 2000) and whether the tag was encapsulated or free-floating.

2.3.3 Missing data

Fish that were missing a measurement for one or more sampling intervals related to overall body size (n = 2), healing rate (n = 3), or activity response (n = 17) were omitted from their

respective statistical analyses. Analyses were conducted in R Studio 3.4.1 (R Studio Team, 2016). Significance was identified if $\alpha \leq 0.05$.

2.3.4 Individual identification

All fish were handled with electrosedation gloves (TENS 3000 unit, DT3002 Roscoe Medical, low voltage setting; as per Ward et al. 2017) and implanted with two visible implant elastomer (VIE) tags for group and individual identification. Colors (red, orange, and green) were selected by recommendation of Northwest Marine Technology (Shaw Island, Washington). Tags were administered with handheld 0.3-mL tuberculin syringes (29-gauge needle) coupled with syringe holders. The elastomer and curing agent were mixed several minutes prior to injection. Ink was kept on ice to reduce coagulation during injections, and tag codes were implanted in a systematic order. Tags were injected in the transparent tissue where each fin (pectoral, pelvic, anal, caudal, and dorsal) met the body cavity, rather than the lower-jaw (Younk et al. 2010). All fish were weighed (nearest 0.1 g) and measured (fork length; nearest 1 mm) post VIE implantation. As natural body markings are known as an effective identification tool (e.g. Wilson et al. 2006, Brooks et al. 2010, Pablo Barriga et al. 2015), the dorsal, caudal, and pelvic fins were photographed as a form of secondary identification by spot pattern.

2.3.5 Anesthetization

A total of 96 Muskellunge were selected at random from their source tanks and were assigned to one of three treatment groups for a total of 32 per treatment group (Younk et al. 2010): tagged (anesthetized and implantation with acoustic tag), sham (anesthetized, no tag implantation), and control (no anesthetic or tag implantation, measurements only). Sham controls were used to isolate the effects of surgical procedure from the presence of the transmitter following Cooke et al. (2011). For control fish to be processed (that is, held in anesthetic and recovery bins) in the same fashion as sham and tagged fish, the average time sham and tagged fish underwent anesthesia

and recovered was calculated and used to time control fish. To achieve this, all fish from each treatment were processed at the same time (e.g. all sham, all tagged, all control), rather than rotational order (sham, tagged, control), which is often used to remove biases associated with processing fish. Neither length (TL) nor weight (W) of fish processed at the start of the study were normally distributed ($W = 0.95985$, $P = 0.005$), so both parameters were transformed to their log natural (lnTL and lnW) and met assumptions of normality (Gaussian distribution) and homoscedasticity, and to calculate specific (or relative) growth rates.

2.3.6 Surgery Procedures

Fish were not fasted prior to surgery to mimic *in-situ* field surgery conditions. Before implantation, sham and tagged fish were anesthetized (70 mg/L solution of tricaine methanesulfonate (MS-222) in hatchery water) until opercular rates slowed and fish were unresponsive to touch (see Carter et al. 2011, Wagner et al. 2011, Wagner et al. 2014). Fish were placed supine on a surgery table in recirculating water and received a maintenance anesthetic dose (70 mg/L MS-222) by placing a small-diameter (size) silicone rubber tube from a pump (in the recirculating tank) inside the mouth so water gently flowed over the gills. A ~5 mm lengthwise incision was made between the pelvic and pectoral fins and closed with one simple interrupted suture (PDS II, 3/0, Ethicon Inc.) following tag insertion. Tagged fish were implanted with a sterilized (Virkon), JSAT tag (Pacific Northwest National Laboratory; 12.0 × 5.3 × 3.7 mm, 0.20 g in air) into their coelom. Surgical tools were sterilized in a diluted solution of Virkon between each surgery.

2.3.7 Processing considerations

Fish were tagged by the same researcher, to reduce surgeon bias on survival (Cooke et al. 2003, Richard et al. 2013, Tiffan et al. 2015). To compare healing rates, the ventral side of each fish that received surgery was photographed. Any abnormalities associated with fish and

deviations from the tagging process were noted. Post-surgery, fish were held in a recovery cooler with aerated water. Surgically processed fish (both tagged fish and sham fish) were kept under sedation (knock out and laparotomy or surgery) between two to six minutes and recovered in two to three minutes. Individuals were systematically assigned to one of four replicate holding tanks, so as each tank contained eight fish per treatment group (Tiffan et al. 2015). Fish were removed from their tanks at specific sampling intervals (7, 30, 60, 90 and 120-d) to measure endpoints, and were rotated between tanks once processed to ensure individuals were not sampled twice (Fig. 1).

2.4 Statistical Analysis

2.4.1 Data preparation and considerations

To quantify how tag burden may influence growth (body size in length or specific growth rates in weight), tag weight (0.2 grams) was removed from the total weight of tagged fish measured each sampling interval. To determine whether final body size of fish after 120-d from each treatment group may have been biased by their initial size, total lengths of fish randomly picked for each group at the start of the study were compared using a one-way ANOVA. The potential effect of treatment group (sham, tagged and control) and time under anesthesia on recovery time was evaluated using an ANCOVA, with treatment the categorical variable, and time continuous.

2.4.2 Survival, Internal Tag Assessment, Tag Retention, & Tag Burden

Fish health was monitored daily by hatchery staff to assess survival, and individuals that suffered mortality were frozen until a necropsy could identify the location of the transmitter and level of peritoneal infection due to the presence of the transmitter. Tanks were visually scanned for expelled tags during daily, routine cleaning, and the lone drain for all hatchery effluent was covered by a small-mesh net, to ensure expelled tags would be located, if not observed upon initial inspection. Survival and tag retention were calculated as a percentage (the total number of fish that survived and retained their tags, respectively, per treatment group; Gries and Letcher 2002). Tag

burden, or body-to-weight ratio (%), was calculated as 100 × (tag weight) / *W*, where tag weight was 0.2 grams and *W* was an individual fish weight when tagged (Wooton 1990) (Table S.2.2).

2.4.3 Growth Rates

Specific (or relative) growth rates (SGR) for individual fish were calculated as 100 × (lnW2 −lnW1) / (t2 −t1), where W2 and W1 were body weights at sampling intervals t2 and t1 (Ricker 1975); SGR calculations were made between each sampling interval and the full experiment duration (Table S.2.2). The overall difference in body length (lnTL) between treatment groups 120-d post-processing and SGR's at each sampling interval were evaluated with linear mixed effect models (*lme,* R package 'nlme'; Pinherio et al. 2018). Collinearity between biological and temporal factors (time, treatment, lnTL, lnW, temperature, and tank fish was housed over a specific sampling interval), were compared using Pearson correlation coefficients and variance inflation factors (*vif,* R package "car"; Fox and Weisburg 2011). Time and lnW had *vif* value >3, indicating time was collinear with temperature and lnW with lnTL (Table S.2.3). Despite the correlation of time with temperature, two nested linear mixed effect models were compared (Fig. S.2.4), and one model included time and temperature. Both models included a time:lnTL interaction to control for size over time. Temperature and lnTL (fixed variables) were centralized to simplify interpretation and facilitate comparison of their relative importance (Schielzeth, 2010).

Temporal autocorrelation was tested, confirmed, and accounted for in the repeated measures ANOVA for overall growth in body size, and SGR (Eq. S.1). The best fit SGR model was fit using the *corARMA* function, relative to *corCAR1* and *corAR1* functions (R package 'nlme'; Pinherio et al. 2018). The model included the average temperature across tanks for each respective sampling interval (TM), treatment group (TR), rearing tank at the specified sampling interval (TK), and the log natural total length of individual fish (lnTL) (Table S.2.4).

2.4.4 Incision Healing

Macroscopic inflammation (redness) and wound closure (amount of open dermal tissue) was scored from 0 to 1 (see Schoonyan et al. 2017 Table 1 for rating system) by two researchers independently to account for variability. Due to the large variation in wound closure scores between each researcher for the 90-d and 120-d sampling interval, when sutures caused additional dehiscense (rupture), the more conservative scores were selected for analysis. Generalized linear mixed models (*glm*, R package 'nlme'; Pinherio et al. 2018) compared the number of Muskellunge scored for each wound type (openness and inflammation) over time, using a Poisson distribution and log link function. Two models for each wound type were compared using AICc to determine whether temperature or sampling interval were appropriate, as they were collinear; wound category and treatment group were included in all models as main effects and interaction terms.

Suture retention over time was assessed using the same generalized liner mixed effect model described for incision healing, but with a binomial distribution, log link function, a "bobyqa" optimizer, maxfun of 1e5, and an nAGQ value of seven. Time and treatment groups were fixed factors and fish ID the random factor. Interaction terms were removed, as none were significant. Multiple comparisons were tested using Tukey's (*glht*, R package 'multcomp'; Hothorn et al. 2017).

2.4.5 Flight Initiation Response

The sedation level of each fish was established by lightly touching the fish every 30 seconds to determine its response stage. Fish were no longer considered sedated when they became upright and displayed regular opercular and fin movement (Wagner et al. 2014). Activity and reaction time were recorded using a Hero 3 GoPro, mounted above a 40L aquarium (51 x 25 x 30). A Styrofoam sheet with 2.54 x 2.54 cm grid squares was placed under the aquarium, to quantify movement. Fish were placed in the aquarium once they reached Stage 1 anesthesia in their recovery

cooler and were permitted to acclimatize for five minutes. Fish activity was recorded between five and 10-minutes. A moving object (76.5-cm plastic, hollow, hexagonal cross section control rod from a set of horizontal mini-blinds with a square, silicate aquarium air-stone attached by white electrical tape; total length of 79-cm or 31-in) was then immediately placed in the fish's line of sight, on the opposite end the aquarium from the fish, and was slowly moved towards the fish. Video recordings of activity responses post-anesthetic were randomly viewed and blindly scored, to avoid observer bias associated with treatment. Active movement and response to a moving object, including flight initiation distance, were scored based on movement during the acclimation period (1 or 2; fish crossed < or ≥ 2 grid squares in 5-minutes), flight initiation reaction (1 to 4; fish did not react, reacted < or ≥ 2 grid squares from object, or before object entered tank), and reaction post exposure (1 to 4; fast, moderate, slow or no reaction) were included as fixed factors.

A two-way repeated measures ordinal ANOVA (*clmm*) was used to analyze the ordinal, dependent variable (reaction to moving object) for flight initiation response post-anesthesia, with time (repeated measurement) and treatment as fixed factors and activity and speed as independent, ordered factors. The proportional odds assumption was checked using the *nominal_test* function. Fish was a random factor to account for their selection from a randomly sampled population (i.e., Gloucester Bay), and temperature was centralized for both incision healing and flight response analyzes. The best models selected had the lowest AICc accounting for small sample size. Multiple comparisons were tested using (R package "lsmeans", Lenth 2016).

2.5 Results

2.5.1 Size of fish per treatment group

Fish selected for tagging had statistically significant larger body sizes than those selected for control at the study's start (Tukey's, $t = 2.912$, $p = 0.0124$) and post 120-d (Tukey's, $z = 2.829$, $p = 0.0114$; Fig. 2), but the actual mean difference was small (e.g., mean difference of TL, 7-mm

(201 ± 9.7-mm [mean ± SD], control; 206 ± 10.3-mm, sham; 208 ± 10-mm, tagged) and 3-grams body mass (29 ± 5.4-g, control; 32 ± 5-g, sham; 32 ± 4.6-mm, tagged). Average overall size (*TL*) of Muskellunge at 120-d ranged from 261- to 264-mm (Table 2).

2.5.2 Surgery Procedures

Though this study aimed to process sham and tagged fish similarly, the amount of time under sedation between treatment groups (368 ± 102 seconds, sham; 280 ± 47 seconds, tagged) differed significantly ($F = 10.9313$, $df = 1$, $p = 0.002$). Recovery time (241 ± 93 seconds, sham; 183 ± 44 seconds, tagged) post anesthetic exposure ($F = 8.6589$, $df = 2$, $p = 0.0005$) was also significantly different between treatment groups.

2.5.3 Survival, Internal Tag Assessment, Tag Retention & Tag Burden

All tagged fish retained their acoustic tags. Two tagged fish died as tank escapees, and no peritoneal infection was observed for either mortality. Tags were encapsulated in the serous membrane between the liver and stomach (Fig. 2). Tag burden was low, from initial processing day (<0.8%) to the end of the study 120-d post tagging (Table 2).

2.5.4 Body Size & Specific Growth Rates

Specific growth rates (SGR) ranged over time from an average of 0.08 g^{-1} day^{-1} (30- to 60-d) across treatment groups to 1.05 g^{-1} day^{-1} by 120-d (Table 2). Rates ranged from negative growth (weight loss of -0.5 g^{-1} day^{-1}) during the first seven days to 2.93 g^{-1} day^{-1} between the 60- and 90-d mark; both were control fish. SGRs for all treatment groups decreased in the first 60-d from 0.59 ± 0.31 g^{-1} day^{-1} (30-d) to 0.10 ±0.14 g^{-1} day^{-1} (60-d), considerably increased to 1.07 ±0.8 g^{-1} day^{-1} at 90-d (likely due to the substantial increase in temperature and thus metabolism), then decreased to 0.81 ±0.34 g^{-1} day^{-1} at 120-d (Table 2, Fig. 3). Growth rates did not significantly differ between treatment groups over the full four-month study ($x^2 = 3.4926$, $p = 0.1744$); however, control fish grew significantly longer and heavier the first 7-d ($t = 8.40$, $p = <0.001$), and between 60- and 90-

d (t = 2.40, p = <0.001). Sham fish (t = -5.67, p = <0.001) grew significantly less between 7-d and 30-d (Fig. 2.4, Table S.2.5), as did SGR of tagged fish (t = -2.37, p = <0.001) relative to control and sham between 60-d and 90-d (Fig. 2.4, Table S.2.5). Total length of all fish significantly increased over time (t = 3.25, p = <0.001), as anticipated; however, growth rates of all fish in tank 5 were significantly lower (t = -3.25, p = <0.001), reiterating the challenges associated with controlling for all environmental variables (Table S.2.5).

2.5.5 Incision Healing

Wound dehiscense (dermal tearing or rupture) scores decreased throughout the study for both sham and tagged fish. Sham fish exhibited low levels of dehiscense (0-0.3%); tagged fish ranged from 0-0.15% (categories 1 to 3; see Schooynan et al. 2017; Fig. 2.5). Level of inflammation ranged from 0-0.45% (category 1 to 4) for both treatment groups. Incisions healed by 60-d; however, 32% (n = 29 fish) of sutures were retained by both groups 120-d post-surgery. The rate at which sutures fell out significantly declined with each sampling interval, starting at 60-d (z = -2.22, p = 0.02; 90-d [z = -3.08, p = 0.002]; 120-d [z = -3.34, p = 0.001]).

The number of Muskellunge scored in each dehiscense (LR x^2 = 40.46, p = <0.001) and inflammation (LR x^2 = 31.05, p = <0.001) category was not independent of sampling interval (Fig. 2.5, 2.6). Significantly fewer fish exhibited open wounds (90-d, z = -4.20, p = <0.001; 120-d, z = -3.63, p = <0.001), or inflammation later in the study (90-d, z = -5.00, p = <0.001; 120-d, z = -5.23, p = <0.001). Sampling interval was a better predictor of when inflammation was noticeably reduced (interval, AICc = 133.90; temperature, AICc = 149.05) while temperature influenced wound closure (interval, AICc = 282.70; temperature, AICc = 113.70).

2.5.6 Flight Initiation Response

Nearly 25% of fish responded immediately to the moving object post-processing (post-sedation for sham and tagged fish). The reaction of sham fish post-object exposure (slow vs.

moderate, scores 2 and 3) declined seven-days post sedation, while the reaction of tagged fish was significantly faster (LR $\chi^2 = 7.8387$, $df = 2$, $p = 0.01985$) relative to that post-recovery (Fig. 2.7). No variation in behaviour was noted during the acclimation period or flight initiation distance test.

2.6 Discussion

The present study suggests mini acoustic transmitter implantation did not impair short-term growth (120-d) juvenile Muskellunge. Similarly, growth was not impaired for free-ranging, multi-tagged (external and internal) age-0 Northern Pike, or conspecifics >480-mm TL implanted solely with radio transmitters (Hühn et al. 2014). Though the mean length of tagged age-0 Muskellunge was larger than control fish at the start in our study, reduced size and growth rates of tagged fish (an anticipated result of an invasive procedure) was not observed after four months (120-d).

Control fish grew significantly longer and heavier than sham and tagged fish the first week (Fig. 2.4) as groups which underwent laparotomy may have allocated more energy to initiate wound closure than to somatic growth. Declines in SGR between 30- and 60-d for all treatment groups is likely attributed to the decline in average water temperatures below preferred values (≥12ºC; Kerr and Lasenby 2011) during the first 60-d of the study. By 120-d, all fish were growing 0.8 ±0.04 g^{-1} day^{-1} and by 60-d; comparable to the size of those of intensively reared age-0 Muskellunge in Chautauqua hatchery ponds after 50-d (Colesante and Bubnack 1992).

Low burden (<0.8%), high retention (100%), and high survival (98%) suggest micro acoustic tags are not harmful for juvenile Muskellunge studies. Burden was lower than most micro-acoustic and PIT tag implantation studies (1% to 9%; e.g. Winter 1983, Tiffan et al. 2015, Panther et al. 2018), and high retention rates mimic studies assessing PIT tag retention (>95%) previously reported for age-0 Muskellunge (Younk et al. 2010) and JSAT tag retention (>99%) for juvenile Chinook Salmon (Wagner et al. 2014) and Bloater (*Coregonus hoyi;* Klinard et al. 2018). Moreover, no tagging-induced mortalities up to 325-d post-tagging and full tag retention was

observed for multi-tagged (PIT, fin clip, external tag) age-0 Northern 195-325-d (Hühn et al. 2014). These age-0 Northern Pike suffered substantial overwintering mortality in this pond experiment, suggesting mesocosm studies may elucidate whether our high Muskellunge survival rates were due to a captive environment, consistent food supply, or elevated water temperatures.

Similar to Atlantic salmon (*Salmo salar*) tagged with dummy acoustic transmitters (Lacroix 2004), a lack of peritoneal inflammation or infection, along with a clearly encapsulated tag were observed in two age-0 Muskellunge, post-necropsy. Tags within the juvenile Atlantic Salmon became encapsulated in a thick membrane prior to expulsion 142 and 217-d post-surgery (Lacroix 2004). Protracted suture retention was observed in 25% of juvenile Muskellunge 120-d post-surgery, possibly due to lower water temperatures (<20ºC; Deters et al. 2010). Despite increased vertical (dorsal to ventral) tearing of dermal tissue in the ~25% of tagged Muskellunge (induced by protracted suture retention) 60-d into the study, >75% of incision wounds fully healed (fully closed, no suture, or erythema) within 120-d post-surgery. This suggests that expulsion post-stocking into Gloucester Pool (wild source) is unlikely. Suture retention for juvenile Muskellunge did not vary between treatment groups, but significantly decreased at after 60-d, similar to free-ranging Walleye (*Sander vitreus*), of which 50% healed approximately 60-d post-release (Schoonyan et al. 2017), and 100% after 90-d.

This study used MS-222 concentrations within acceptable limits (60 - 100 mg/L), and fish were induced and sedated within recommended timelines and manufacturer guidelines (see Wagner et al. 2011, Wagner et al. 2014); however, increased exposure to MS-222 (relative to tagged fish) may have influenced short-term (30-d) recovery for sham fish. Though no published studies indicate short-term growth impairment associated with MS-222 exposure on juvenile fish, alterations in physiology may reduce feed intake or nutrient uptake. A significant interaction was observed between decreased Na^+, Ca^{2+}, and K^+ blood levels in juvenile Chinook Salmon over a

two-week period, after increased MS-222 exposure (Wagner et al. 2014), suggesting stress response patterns observed post-surgery may have been amplified when exposed to increased anesthetic (Wagner et al. 2014). Similar physiological stress may have been experienced by sham Muskellunge in the first month, due to increased MS-222 exposure (relative to tagged fish); this may have been amplified by electrosedation (prior to chemical anesthetization) and laparotomy. To this end, tag implantation and increased MS-222 exposure may have short-term, sublethal implications (i.e., predator avoidance) post-release. The reduced distance sham fish maintained between themselves and the object, one-week post-sedation, may have been a delayed reaction attributed to lingering effects of increased exposure to MS-222. With no difference in acclimation activity or flight response to sham fish, the short-term influence of tag presence on behaviour post-sedation requires additional research.

In summary, small variation in growth rates at the end of this short-term study between treatment groups, negligible mortality, low body mass ratio and 100% transmitter retention observed in this study suggests that juvenile Muskellunge can successfully be implanted intracoelomically with mini-acoustic transmitters, though sedation methods and level of exposure, confounded by laparotomy, may influence short-term growth and behavioural responses.

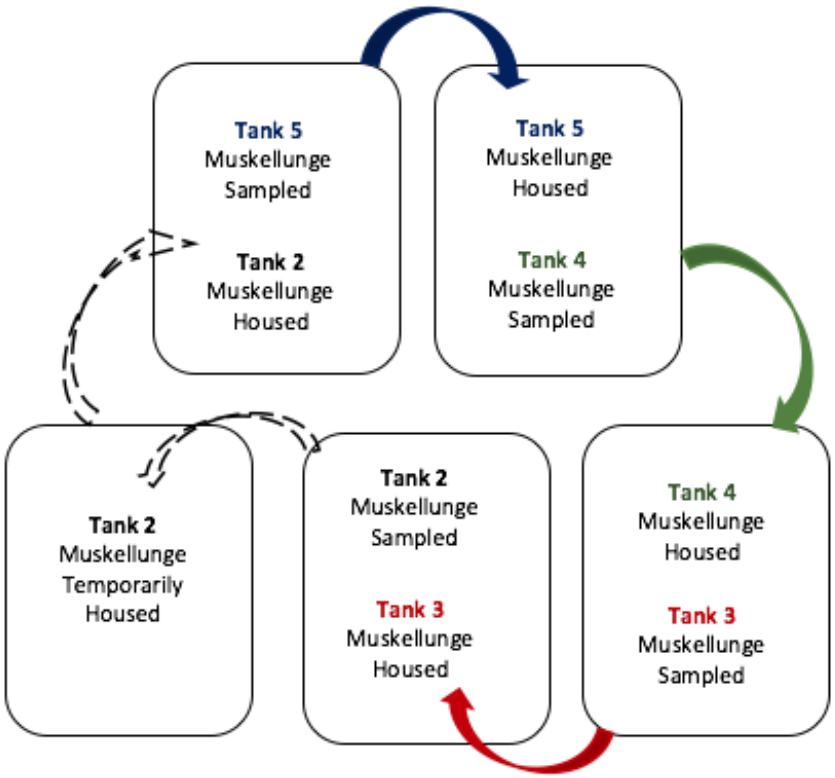


Figure 2.3. A diagram describing the order in which captive reared, age-0 Muskellunge were sampled and rotated through five 2.4 (l) x 1.2 (w) x 1.2 (h) m tanks at the Fleming College Muskellunge Hatchery. All fish were first sampled from Tank 2, and temporarily housed in Tank 1. Fish from Tank 3 were sampled (weighed, measured, and photographed) and moved to Tank 2. This process continued with Tank 4 fish moved to Tank 3 (post-sampling), and Tank 5 fish to Tank 4. Once processing was complete after as specific sampling interval, all fish in Tank 1 were moved to Tank 2, as Tank 1 did not have the same dimensions as Tanks 2 through 5.

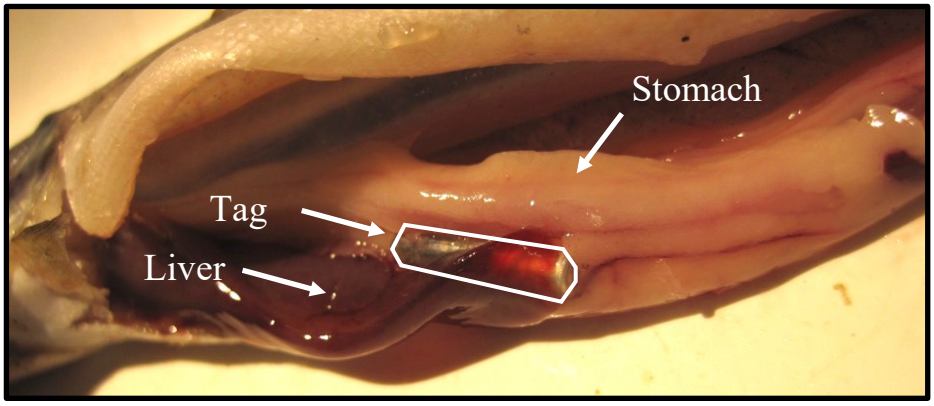


Figure 2.2. JSAT tag (white) location inside of a 250-mm, 64.6 gram (including tag) juvenile Muskellunge, 90-d post-implantation. This fish jumped from its tank and was found the morning of March 11, 2018. Necropsy was performed on March 16, 2018. The tag was found encapsulated between the stomach and the liver within the coelom, with no peritoneal infection.

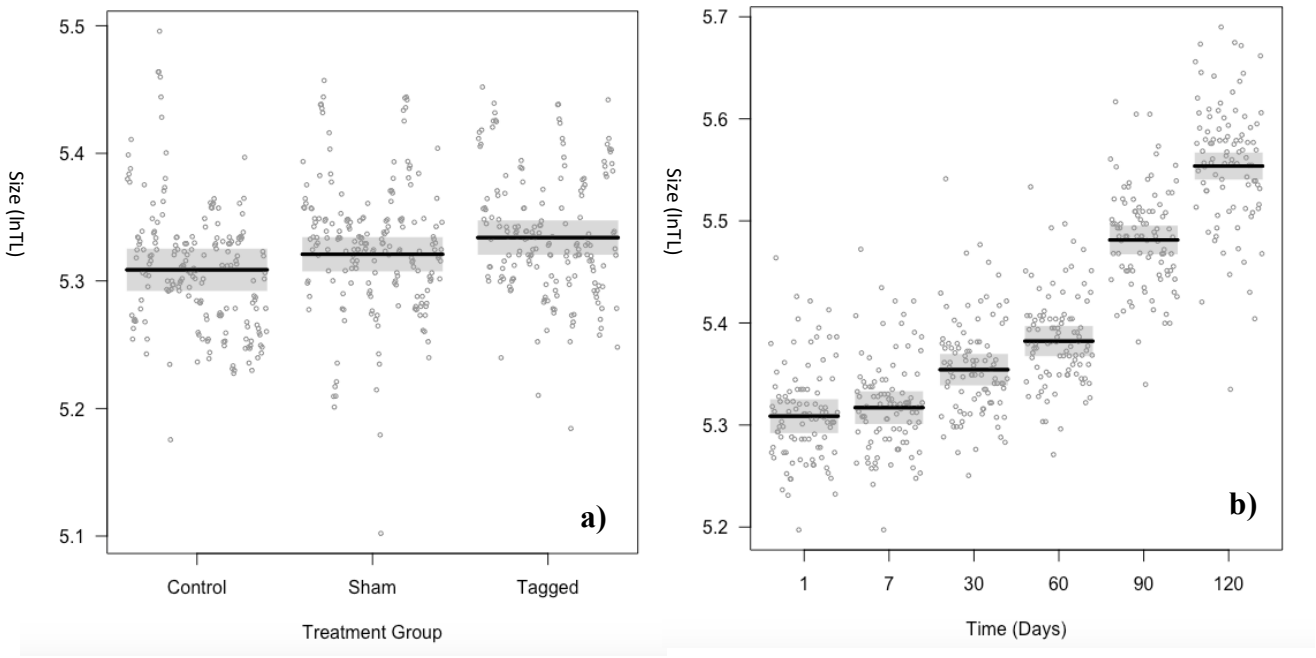


Figure 2.3. Presence of mini-acoustic transmitters had no effect on growth of age-0 Muskellunge in a hatchery experiment. The average size as natural log total length (ln*TL,* mm) of control, sham and tagged juvenile Muskellunge relative to treatment group 120-days post anesthesia, laparotomy, and surgical implantation of a mini acoustic tag (Treatment Group, a), and sampling interval in days (Time, b). Tagged fish were found to be significantly larger in average size at the start and end of the study, indicated by average length (ln*TL*) at the end of the study, relative to sham and control fish.

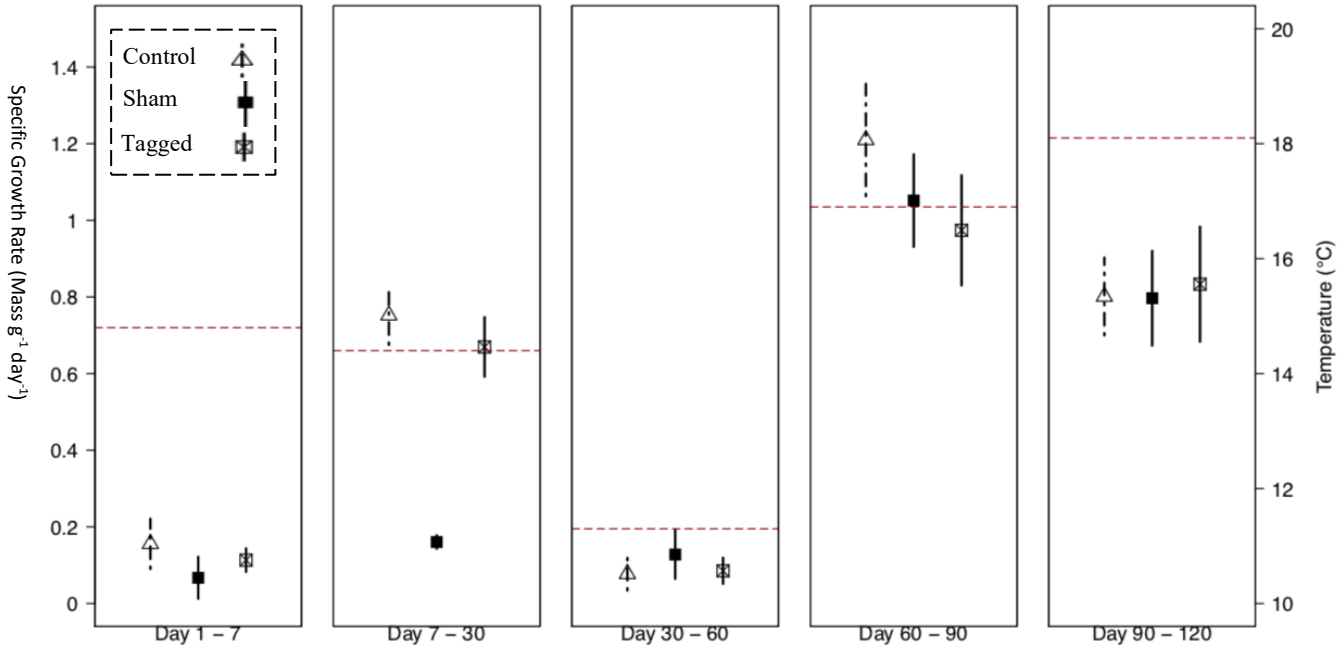


Figure 2.4. Specific (or relative) growth rates by weight (SGR, g^{-1} day^{-1}) of control, sham, and tagged age-0 Muskellunge over five sampling intervals. Error bars represent the SEs of treatment-specific means. Average water temperature for each sampling interval (horizontal dash line) is presented by the secondary Y axis. Sham fish had a significantly lower SGR between 7 and 30 days (t = -5.67, p = <0.001), as did tagged fish between 60 and 90 days (t = -2.37, p = <0.018). Control fish had significantly higher SGR between 7 and 30 days (t = 8.87, p = <0.001), 60 and 90 days (t = 9.07, p = <0.001) and 90 to 120 days (t = 2.73, p = <0.001).

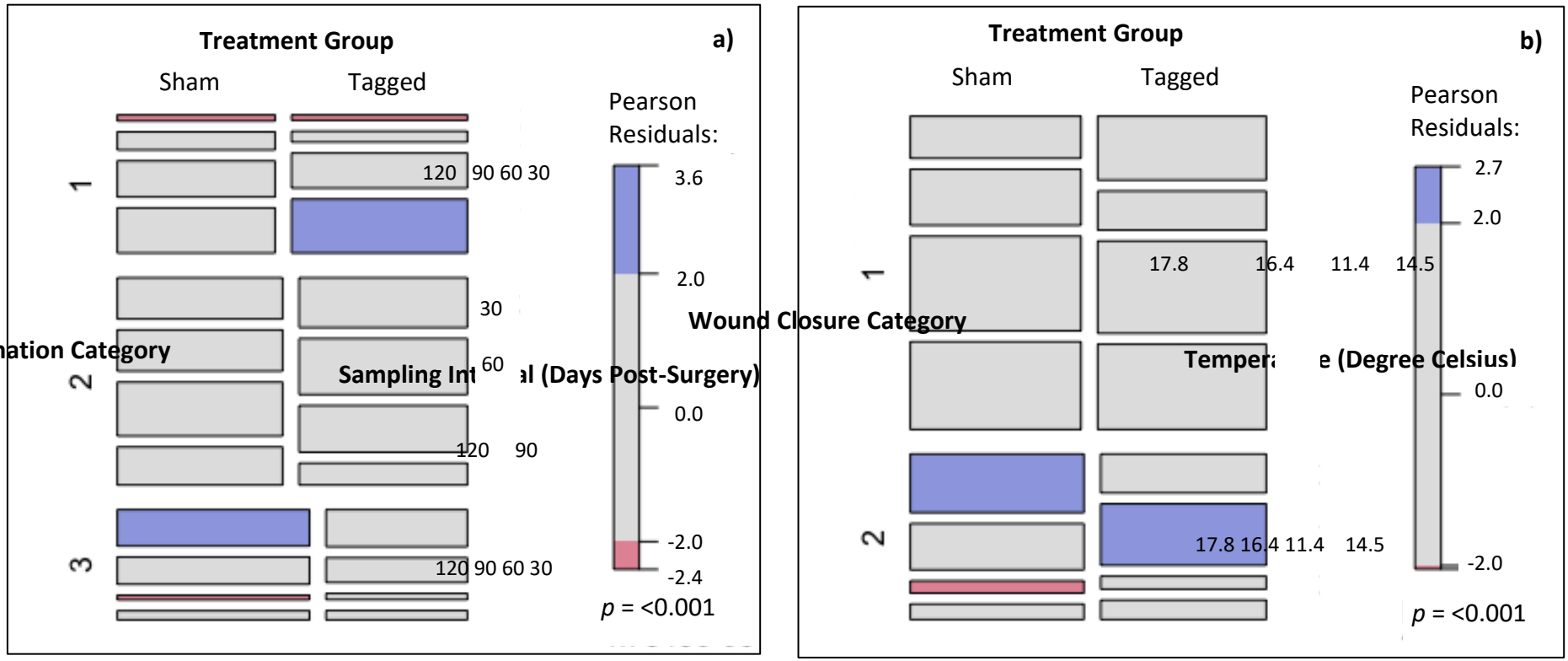


Figure 2.5. Mosaic plots showing the number of fish (sham and tagged) per inflammation (a) and wound closure category (b) over four sampling periods and temperature ranges (30-d / 14.5ºC, 60-d / 11.4ºC, 90-d / 16.4ºC, and 120-d / 17.8ºC). The same number of observations were made between the two treatment levels (sham and tagged fish) and wound closure categories (1 and 2), as seen by its symmetrical design. A significant effect was found between the (a) sampling interval and inflammation interaction (LR $x^2 = 66.85$, $p = <0.001$) where inflammation levels were not independent of time, and (b) sampling interval and wound closure interaction (LR $x^2 = 66.85$, $p = <0.001$), where level of dehiscence was not independent of temperature. Pink rectangles indicated significantly fewer fish scored per category and sampling interval, while blue rectangles indicated more fish. Significantly few fish exhibited low levels of inflammation at the start of the study (as wounds had not yet begun to heal), and significantly fewer sham fish showed high levels of inflammation or dehiscence after 90-d at 16.4 ºC, relative to tagged fish, though differences were minimal. Significantly more tagged fish exhibited cases of dermal rupture after 60-d when temperature dropped and inflammation after 120-d, relative to sham fish. Though few fish exhibited low levels of inflammation those first 30-d, significantly more sham fish exhibited high levels inflammation and dermal rupture during this period, relative to tagged fish.

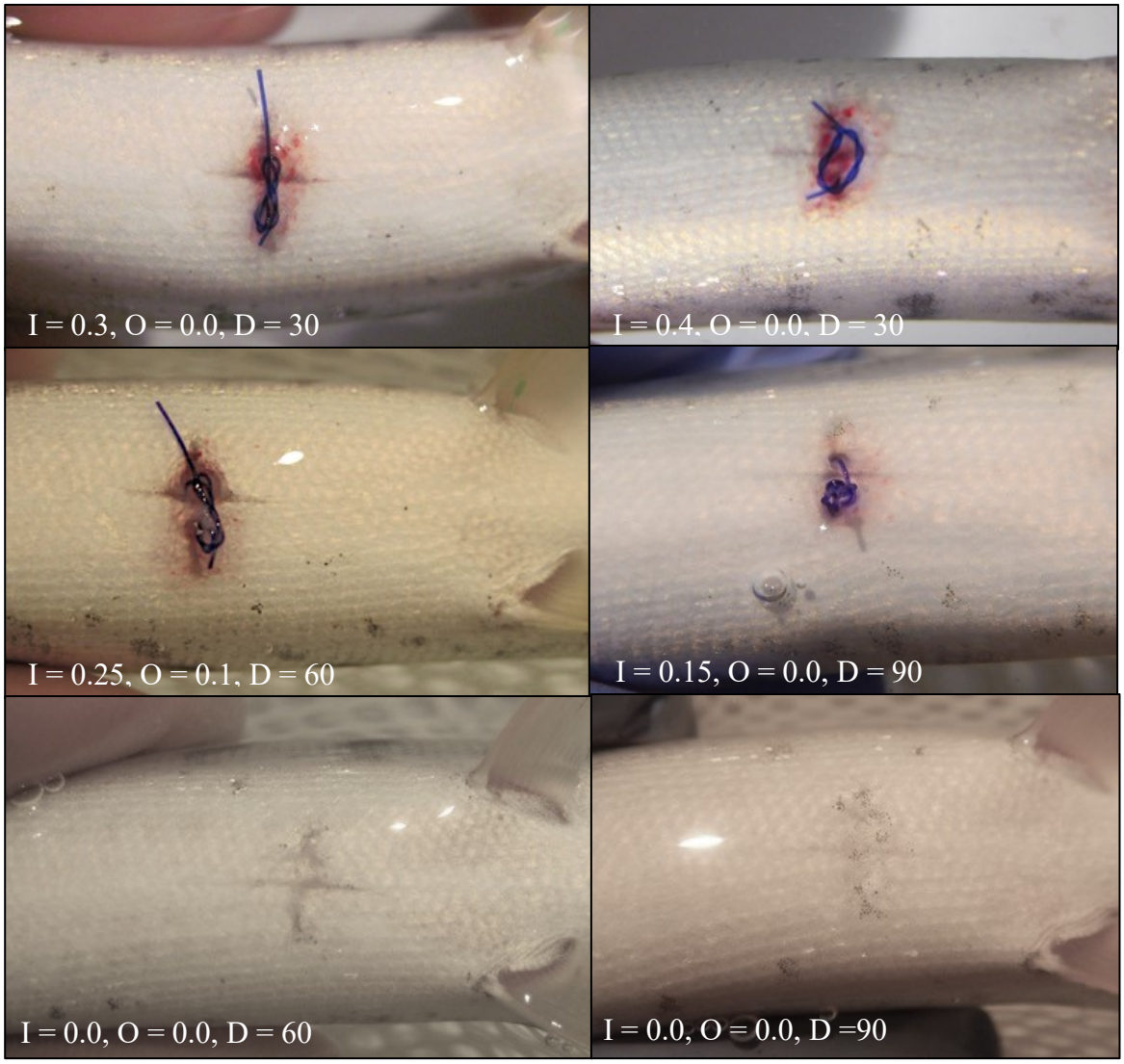


Figure 2.6. Representative photographs of six different juvenile Muskellunge, illustrating ranges of inflammation and wound openness. The key on each panel designates scores for inflammation (I) and wound openness (O) from 0 to 1, and days post-surgery (D). Score were based on six different percent categories (see Schoobyan et al. 2017 Table 1).

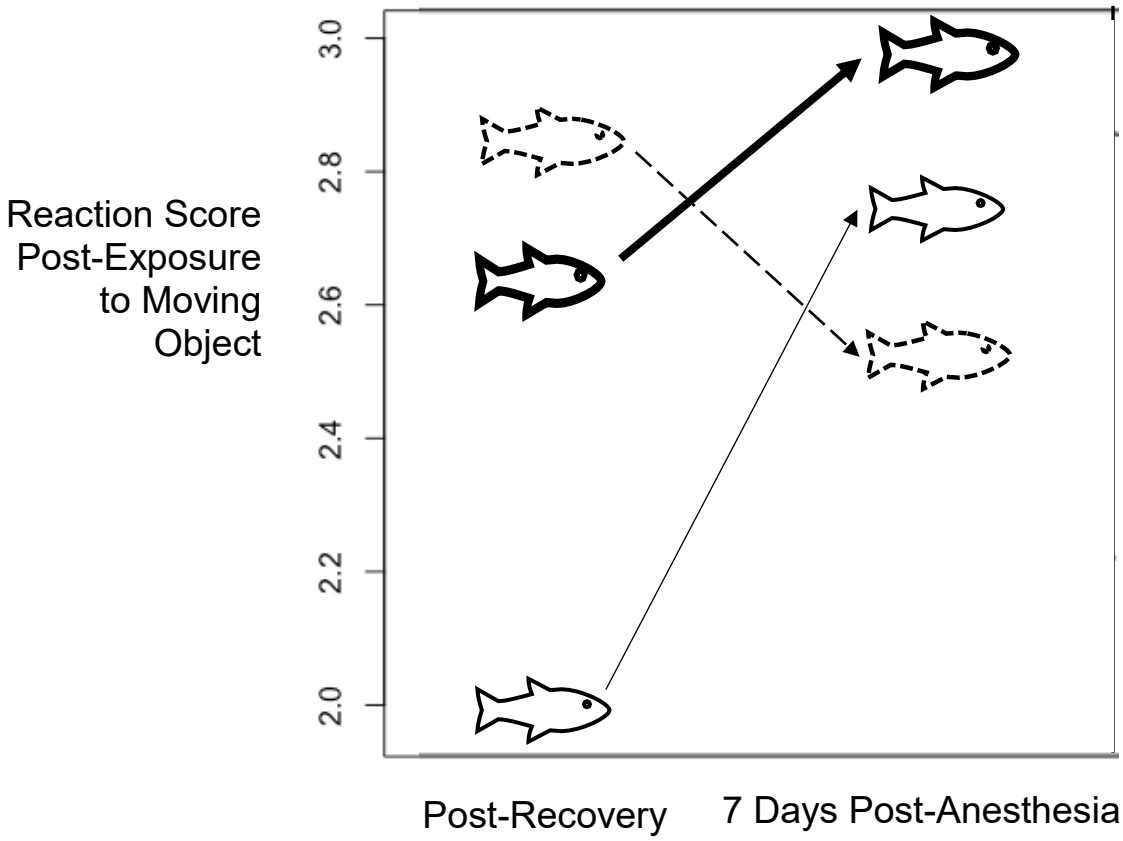


Figure 2.7. The average reaction post-exposure to the move object (movement relative to grid squares) by control (thick line), sham (dashed line) and tagged fish (thin line), post-recovery and seven days post-surgery. Tagged fish reacted significantly slower than sham or control fish post-recovery; their 95% confidence interval (with respect to their reaction score) did not cross zero. Moreover, tagged fish reacted significantly faster (LR χ^2 = 7.8387, *df* = 2, *p* = 0.02) seven days after chemical anesthesia exposure compared to their initial reaction.

Table 2.6. How juvenile Muskellunge were scored, post-anesthetic recovery. Individual fish were scored based on active movement during the five-minute acclimation interval in the aquarium, the flight initiation distance and reaction with respect to a moving object (aerator bubbler attached to a long rod), and the speed of the reaction response once the object was within two grid squares.

Activity	Response Description	Score
Acclimation Period	Crossed ≥ 2 grid squares during 5-minute acclimation interval	2
	Crossed < 2 grid squares during 5-minute acclimation interval	1
Flight Initiation Reaction	Reacted (swam around tank) before object hit water	4
	Moved when object came within ≥ 2 squares (far)	3
	Moved when object came within < 2 squares (close)	2
	Fish did not react or move	1
Reaction Post Object Exposure	**Fast** - Fish crossed tank in 1 second, once object was ≤ 2 square away or object had been in water less than 5 seconds	4
	Moderate - Fish swam to maintain a minimum distance of 2 squares	3
	Slow - Fish swam slowly as object pursed fish (less than 2 squares distance)	2
	None - Fish exhibited no speed through a swim response	1

Table 2.2. Mean total length (TL) and weight (W) with standard deviations (SD) of juvenile Muskellunge by treatment group (Treat) over the six sampling intervals (Time), and the average water temperature between tanks over each sampling interval, and evaluation of the tag burden and effects of 0.2 g JSAT acoustic tags on their growth (SGR) between November 2017 and March 2018 at the Fleming College Muskellunge hatchery. Significant values are bolded (e.g. SGR weight differences from sham and tagged fish relative to control fish) and starred (SGR of sham fish 7-30d, SGR of tagged fish 60-90-d; final total length of tagged fish relative to control fish).

Treat	N	Time (Days)	TL ± SD (mm)	W ± SD (g)	Tag Burden (%)	SGR ln*w* ± SD (g^{-1} day^{-1})	SGR lntl ± SD (mm^{-1} day^{-1})	Avg. Temp (ºC)
Control	32	1	201 ± 9.7	29 ± 5.4	-	-	-	-
	32	7	203 ± 10.1	31 ± 6.0	-	**0.16 ± 0.2**	0.16 ± 0.2	-
	32	30	212 ± 11.5	37 ± 6.8	-	**0.75 ± 0.2**	0.37 ± 0.2	14.4
	32	60	217 ± 10.6	38 ± 6.8	-	**0.08 ± 0.1**	0.18 ± 0.1	11.3
	32	90	242 ± 11.6	55 ± 10.4	-	**1.21 ± 0.4**	0.80 ± 0.2	16.9
	32	120	***261 ± 14.6**	71 ± 15.5	-	**0.80 ± 0.3**	0.64 ± 0.2	18.1
Sham	32	1	206 ± 10.4	32 ± 5.0	-	-	-	-
	32	7	207 ± 9.6	34 ± 5.6	-	**0.07 ± 0.2**	0.08 ± 0.2	-
	32	30	215 ± 10.4	39 ± 7.1	-	**0.66 ± 0.4**	0.34 ± 0.1	14.4
	32	60	221 ± 10.5	42 ± 7.0	-	**0.13 ± 0.2**	0.21 ± 0.1	11.3
	32	90	245 ± 13.1	58 ± 11.2	-	**1.05 ± 0.3**	0.79 ± 0.2	16.9
	32	120	264 ± 17.4	75 ± 17.6	-	**0.80 ± 0.3**	0.62 ± 0.2	18.1
Tagged	32	1	208 ± 10.0	32 ± 4.6	0.6 ± 0.08	-	-	-
	32	7	211 ± 12.8	33 ± 5.6	0.6 ± 0.08	**0.11 ± 0.1**	0.11 ± 0.1	-
	32	30	217 ± 10.2	39 ± 5.5	0.5 ± 0.07	**0.67 ± 0.2**	0.31 ± 0.1	14.4
	32	60	224 ± 9.6	42 ± 6.8	0.5 ± 0.06	**0.08 ± 0.1**	0.21 ± 0.1	11.3
	30	90	246 ± 11.3	56 ± 10.4	0.4 ± 0.07	***0.97 ± 0.4**	0.71 ± 0.2	16.9
	30	120	***264 ± 16.1**	72 ± 18.2	0.3 ± 0.08	**0.83 ± 0.4**	0.62 ± 0.2	18.1

Table 2.3. Percent of juvenile Muskellunge from each treatment group that scored 4, 3, 2, or 1 (see Table 1) in response to a moving object in the behavioural experiment. The reactions of fish were scored immediately after their recovery from anesthesia (post-recovery), and seven-days after surgery. The number of fish (No. Fish) does not equal the original number assigned to each group (n = 32), as fish that did not have a matching score (post recovery or seven-days post-surgery) due to processing difficulties, or lack of video, were eliminated from the analysis. No significant differences were found between the percent of fish per reaction group over time.

		Post-Recovery (%)				Post-Seven Days Post Surgery (%)			
Group	No. Fish	4	3	2	1	4	3	2	1
Control	31	6.5	51.6	22.6	19.4	9.7	71.0	9.7	9.7
Sham	20	10	65	25	0	10	55	30	5
Tagged	28	10.7	28.6	28.6	32.1	11	46	29	14

2.7 Supplementary

Table S.2.1 Total length (TL) and weight (W) of all sham (Group "S"), tagged (Group "T") and control fish (Group "C") studied in the Fleming College Muskellunge Hatchery mini-acoustic transmitter tagging study. TL and W are provided for day one (start) and six sampling intervals of 30, 60, 90, and 120 days.

Fish No.	Group	Start_TL	30_TL	60_TL	90_TL	120_TL	Start_W	30_W	60_W	90_W	120_W
1	S	207	216	224	247	262	32	39.2	43.1	59.6	71.7
2	S	210	220	225	243	263	32	44.6	46	58.8	74.2
3	S	215	225	231	258	281	36	47.1	50.8	70.6	93
4	S	200	209	217	239	251	30.5	37.2	38.4	53.3	59.3
5	S	205	220	226	250	267	32.5	40.4	45	62.3	77.2
6	S	229	242	247	275	295	41.5	57.2	56.9	83	101
7	S	203	213	221	244	265	28.6	40.9	38.2	48.3	67.7
8	S	210	216	223	250	269	32.5	39.4	42	63.3	77.4
9	S	205	215	222	247	272	32.2	39.1	43	60	85.3
10	S	200	208	213	232	250	27.9	34.5	37.9	49.5	61.9
11	S	205	213	217	231	235	31.2	36.5	38.9	42.9	43
12	S	195	198	202	211	210	24	30.2	27.3	30.5	30
13	S	225	228	233	249	256	37.7	42.9	43.8	54.5	58
14	S	183	193	197	220	240	21.2	29.3	28.2	39.7	54
15	S	207	218	223	251	274	32.2	41.5	44.9	63	85.8
16	S	196	205	209	240	262	27.9	34	36.4	59.2	74
17	S	210	220	225	248	268	32.7	38.5	40.6	58	70.5
18	S	200	213	220	244	264	30.4	38.1	39.9	54.3	73.2
19	S	220	222	230	253	276	37.7	42.1	46.6	57.6	85
20	S	200	205	213	246	271	31	35	40.2	64.1	87.6
21	S	212	217	225	250	268	31.4	39.7	44.2	64.4	78.5
22	S	206	216	220	250	278	33.5	23.3	41.2	63.8	95.8
23	S	230	240	246	275	299.5	47.6	59.2	63.1	84.4	116.9
24	S	210	218	223	244	258	34.7	39.1	42	55.8	65.6
25	S	196	205	213	240	262	28	33.8	37	53.3	70
26	S	195	206	213	229	246	25.3	32.6	35.7	44	57.7
27	S	195	206	214	227	241	28.7	35.1	40.6	44.7	53.4
28	S	201	210	217	245	265	28.5	37	39.6	56	73.5
29	S	207	216	225	254	284	33.8	41.9	45.5	69.2	97.3
30	S	204	210	219	244	268	30.4	36.8	38.4	57.2	83
31	S	220	229	236	259	276	37.9	48.5	52.3	71.3	86.9
32	S	204	213	218	250	268	29.7	w3	38	59.6	76.1

Fish No.	Group	Start_TL	30_TL	60_TL	90_TL	120_TL	Start_W	30_W	60_W	90_W	120_W
33	T	230	238	244	258	271	40.3	46.9	48.3	58.5	72.5
34	T	224	231	236	249	261	37.6	48.2	46.2	53	67
35	T	205	210	215	227	228	29.7	32.5	33.8	37.7	36.3
36	T	195	203	210	239	261	26.2	31.8	34.9	53	71.3
37	T	206	214	221	243	269	30.7	37.1	40	55.7	78.7
38	T	215	227	232	258	276	33.2	43.6	44.6	63.6	79.9
39	T	203	214	224	244	265	31.6	38.6	43.2	55.4	74.8
40	T	209	215	218	227	234	32.5	37.2	37.6	39.6	43
41	T	208	219	226	253	275	33.3	41.8	45.6	68.2	89.9
42	T	197	207	215	229	252	25.7	30.6	33.4	40	55.5
43	T	206	214	220	239	265	33	41	43.3	60.6	80.9
44	T	196	205	214	238	253	26.1	32.5	36	50.3	60
45	T	209	217	220	237	254	32.3	37.1	38.3	49	59.9
46	T	199	210	216	241	267	28.9	35.9	37.8	55.9	77.3
47	T	208	217	225	243	262	31.5	38.2	42.3	51.4	67
48	T	219	229	233	252	271	37.6	43	44.9	58.1	75.4
49	T	197	206	214	243	NA	28.7	37.1	38.5	62.4	NA
50	T	207	218	223	243	260	28.7	36.8	37.2	49.1	61.4
51	T	224	233	240	268	298	42.3	49	53.9	78.4	114.8
52	T	212	222	228	249	273	31.8	39.5	41.2	43.3	78.9
53	T	201	212	218	246	269	31.8	38.3	41.7	64.1	83.8
54	T	226	241	246	270	290	42.3	54.6	54.3	72.2	98.1
55	T	215	220	225	238	241	31.8	36.9	38.8	44.3	43.5
56	T	201	210	219	255	278	30.3	37.9	43	71	91.1
57	T	203	216	226	253	NA	28.8	39.2	43.9	63.8	NA
58	T	200	207	214	234	255	27.9	42.5	36.8	49	66.3
59	T	192	202	211	237	259	24.2	30.3	34.7	48.6	63.8
60	T	220	228	234	265	295	36.9	43.1	45.6	73.5	110.9
61	T	224	232	239	261	279	38.7	44.3	48.3	64.8	80.3
62	T	208	215	220	233	243	29.9	35	34.2	42.6	48.4
63	T	206	214	222	247	260	32.2	40.1	41.5	56.5	70.1
64	T	206	213	218	240	254	31.7	35.8	37.1	51.8	60.9

Fish No.	Group	Start_TL	30_TL	60_TL	90_TL	120_TL	Start_W	30_W	60_W	90_W	120_W
65	C	195	200	206	224	242	26.2	29.8	33.1	44.1	54.2
66	C	213	222	229	253	273	35.4	43.1	45.1	62.3	82.8
67	C	206	215	223	249	271	32.3	39.6	44	63.1	83.5
68	C	195	204	210	241	264	25.2	32.6	35.5	55.1	73.4
69	C	191	200	207	233	259	23.8	29.3	32.7	49.4	71
70	C	205	217	222	241	264	31.9	39.8	41.4	54.9	76.5
71	C	200	212	216	241	259	28.7	36	36.9	55.1	70.4
72	C	205	213	222	243	258	31.8	39.7	42.4	58.7	68.7
73	C	198	211	217	244	265	29	36.4	40.3	65	85.2
74	C	201	216	216	240	252	28.2	39.9	34.1	50.9	58.3
75	C	188	201	212	234	252	24.4	37.8	35.3	48.2	60.8
76	C	200	210	220	250	267	28.7	36.8	40.2	59.4	73.5
77	C	208	216	223	244	268	31.9	36.1	40.1	57	79.5
78	C	236	255	253	275	291	48.2	59	60.1	77.9	87.9
79	C	211	225	232	258	283	37.2	48.1	52	74.4	99
80	C	199	208	214	223	226	26.7	33.2	34.4	35.1	35
81	C	199	209	215	243	262	28.8	35.5	39.2	63.3	75.3
82	C	206	217	221	237	254	31.2	37	37.2	49.2	59.9
83	C	217	228	233	260	286	40.3	51.2	52.4	76.3	107.3
84	C	195	202	209	231	248	25.6	30.9	32.5	47.2	55.3
85	C	204	217	223	245	264	29.7	37.1	40	54.7	68.5
86	C	196	218	217	244	276	26.2	36	37.2	57.7	84.3
87	C	194	198	206	237	257	25.3	30.4	33.1	54.6	74.6
88	C	203	213	220	250	272	31	36.8	30.7	61.8	80.4
89	C	207	221	224	254	282	31.3	43.4	41.1	66.6	90.4
90	C	190	203	208	226	240	23.8	30.7	33.1	39.1	49.5
91	C	190	200	201	234	256	23.7	29.4	31.5	52.3	67.8
92	C	198	207	211	230	241	26.5	31.4	35.6	46.4	53.1
93	C	193	201	205	225	243	23.9	30.1	31.1	41.8	54.7
94	C	205	210	217	233	246	27.8	31.4	33.7	41	49.7
95	C	187	195	201	233	260	22.6	28.2	31.6	51.2	73
96	C	203	216	223	253	265	30.8	39.6	42.8	61.2	71

Table S.2.2 Specific growth rates (sgr) for sham (Group "S"), tagged (Group "T") and control fish (Group "C") studied in the Fleming College Muskellunge Hatchery mini-acoustic transmitter tagging study for 10 sampling intervals. There was no significant difference in sgr over the full study period (sgr_1_120).

Fish No.	Group	sgr_1_30	sgr_1_60	sgr_30_60	sgr_1_90	sgr_30_90	sgr_60_90	**sgr_1_120**	sgr_30_120	sgr_60_120	sgr_90_120
1	S	0.164	0.496	0.158	0.691	0.698	1.080	0.672	0.671	0.848	0.616
2	S	0.202	0.605	0.052	0.676	0.461	0.818	0.701	0.566	0.797	0.775
3	S	0.198	0.574	0.126	0.748	0.675	1.097	0.791	0.756	1.008	0.919
4	S	0.148	0.384	0.053	0.620	0.599	1.093	0.554	0.518	0.724	0.356
5	S	0.265	0.542	0.180	0.723	0.722	1.084	0.721	0.720	0.900	0.715
6	S	0.240	0.526	-0.009	0.770	0.620	1.258	0.741	0.632	0.956	0.654
7	S	0.188	0.482	-0.114	0.582	0.277	0.782	0.718	0.560	0.954	1.126
8	S	0.143	0.427	0.107	0.741	0.790	1.367	0.723	0.750	1.019	0.670
9	S	0.144	0.482	0.158	0.692	0.714	1.110	0.812	0.867	1.142	1.173
10	S	0.171	0.511	0.157	0.637	0.602	0.890	0.664	0.650	0.818	0.745
11	S	0.124	0.368	0.106	0.354	0.269	0.326	0.267	0.182	0.167	0.008
12	S	0.066	0.215	-0.168	0.266	0.016	0.369	0.186	-0.007	0.157	-0.055
13	S	0.076	0.250	0.035	0.409	0.399	0.729	0.359	0.335	0.468	0.207
14	S	0.231	0.476	-0.064	0.697	0.506	1.140	0.779	0.679	1.083	1.025
15	S	0.183	0.554	0.131	0.746	0.696	1.129	0.817	0.807	1.079	1.030
16	S	0.107	0.443	0.114	0.836	0.924	1.621	0.813	0.864	1.182	0.744
17	S	0.161	0.361	0.089	0.637	0.683	1.189	0.640	0.672	0.920	0.651
18	S	0.188	0.453	0.077	0.645	0.591	1.027	0.732	0.726	1.011	0.996
19	S	0.160	0.353	0.169	0.471	0.522	0.706	0.677	0.781	1.002	1.297
20	S	0.064	0.433	0.231	0.807	1.008	1.555	0.866	1.019	1.298	1.041
21	S	0.205	0.570	0.179	0.798	0.806	1.255	0.764	0.757	0.957	0.660
22	S	0.143	0.345	0.950	0.716	1.679	1.458	0.876	1.571	1.406	1.355
23	S	0.147	0.470	0.106	0.636	0.591	0.969	0.749	0.756	1.028	1.086
24	S	0.121	0.318	0.119	0.528	0.593	0.947	0.531	0.575	0.743	0.539
25	S	0.151	0.465	0.151	0.715	0.759	1.217	0.764	0.809	1.063	0.909
26	S	0.172	0.574	0.151	0.615	0.500	0.697	0.687	0.634	0.800	0.904
27	S	0.172	0.578	0.243	0.492	0.403	0.321	0.517	0.466	0.457	0.593
28	S	0.169	0.548	0.113	0.750	0.691	1.155	0.789	0.763	1.031	0.906
29	S	0.185	0.495	0.137	0.796	0.836	1.398	0.881	0.936	1.267	1.136
30	S	0.084	0.389	0.071	0.702	0.735	1.328	0.837	0.904	1.285	1.241
31	S	0.194	0.537	0.126	0.702	0.642	1.033	0.692	0.648	0.846	0.660
32	S	0.164	0.411	0.156	0.774	0.906	1.500	0.784	0.876	1.157	0.815

Fish No.	Group	sgr_1_30	sgr_1_60	sgr_30_60	sgr_1_90	sgr_30_90	sgr_60_90	sgr_1_120	sgr_30_120	sgr_60_120	sgr_90_120
33	T	0.506	0.302	0.049	0.414	0.368	0.639	0.489	0.484	0.677	0.715
34	T	0.828	0.343	-0.071	0.381	0.158	0.458	0.481	0.366	0.620	0.781
35	T	0.300	0.216	0.065	0.265	0.247	0.364	0.167	0.123	0.119	-0.126
36	T	0.646	0.478	0.155	0.783	0.851	1.393	0.834	0.897	1.191	0.989
37	T	0.631	0.441	0.125	0.662	0.677	1.104	0.784	0.836	1.128	1.152
38	T	0.908	0.492	0.038	0.722	0.629	1.183	0.732	0.673	0.972	0.761
39	T	0.667	0.521	0.188	0.624	0.602	0.829	0.718	0.735	0.915	1.001
40	T	0.450	0.243	0.018	0.220	0.104	0.173	0.233	0.161	0.224	0.275
41	T	0.758	0.524	0.145	0.797	0.816	1.342	0.828	0.851	1.131	0.921
42	T	0.582	0.437	0.146	0.492	0.446	0.601	0.642	0.662	0.846	1.092
43	T	0.724	0.453	0.091	0.675	0.651	1.120	0.747	0.755	1.042	0.963
44	T	0.731	0.536	0.170	0.729	0.728	1.115	0.694	0.681	0.851	0.588
45	T	0.462	0.284	0.053	0.463	0.464	0.821	0.515	0.532	0.745	0.670
46	T	0.723	0.447	0.086	0.733	0.738	1.304	0.820	0.852	1.192	1.080
47	T	0.643	0.491	0.170	0.544	0.495	0.650	0.629	0.624	0.767	0.884
48	T	0.447	0.296	0.072	0.484	0.502	0.859	0.580	0.624	0.864	0.869
49	T	0.856	0.490	0.062	0.863	0.867	1.610	NA	NA	NA	NA
50	T	0.829	0.432	0.018	0.597	0.481	0.925	0.634	0.569	0.835	0.745
51	T	0.490	0.404	0.159	0.686	0.783	1.249	0.832	0.946	1.260	1.271
52	T	0.723	0.432	0.070	0.343	0.153	0.166	0.757	0.769	1.083	2.000
53	T	0.620	0.452	0.142	0.779	0.858	1.433	0.807	0.870	1.163	0.893
54	T	0.851	0.416	-0.009	0.594	0.466	0.950	0.701	0.651	0.986	1.022
55	T	0.496	0.332	0.084	0.368	0.305	0.442	0.261	0.183	0.191	-0.061
56	T	0.746	0.583	0.210	0.946	1.046	1.672	0.917	0.974	1.251	0.831
57	T	1.028	0.703	0.189	0.884	0.812	1.246	NA	NA	NA	NA
58	T	1.403	0.461	-0.240	0.626	0.237	0.954	0.721	0.494	0.981	1.008
59	T	0.749	0.601	0.226	0.775	0.787	1.123	0.808	0.827	1.015	0.907
60	T	0.518	0.353	0.094	0.766	0.890	1.591	0.917	1.050	1.481	1.371
61	T	0.450	0.369	0.144	0.573	0.634	0.980	0.608	0.661	0.847	0.715
62	T	0.525	0.224	-0.039	0.393	0.328	0.732	0.401	0.360	0.579	0.425
63	T	0.731	0.423	0.057	0.625	0.571	1.028	0.648	0.621	0.874	0.719
64	T	0.405	0.262	0.059	0.546	0.616	1.113	0.544	0.590	0.826	0.539

Fish No.	Group	sgr_1_30	sgr_1_60	sgr_30_60	sgr_1_90	sgr_30_90	sgr_60_90	sgr_1_120	sgr_30_120	sgr_60_120	sgr_90_120
65	C	0.429	0.390	0.175	0.579	0.653	0.956	0.606	0.665	0.822	0.687
66	C	0.656	0.404	0.076	0.628	0.614	1.077	0.708	0.725	1.013	0.948
67	C	0.679	0.515	0.176	0.744	0.776	1.202	0.791	0.829	1.068	0.934
68	C	0.858	0.571	0.142	0.869	0.875	1.465	0.891	0.902	1.211	0.956
69	C	0.693	0.529	0.183	0.811	0.871	1.375	0.911	0.983	1.292	1.209
70	C	0.738	0.434	0.066	0.603	0.536	0.941	0.729	0.726	1.023	1.106
71	C	0.755	0.419	0.041	0.725	0.709	1.336	0.748	0.745	1.077	0.817
72	C	0.740	0.479	0.110	0.681	0.652	1.084	0.642	0.609	0.804	0.524
73	C	0.758	0.548	0.170	0.897	0.966	1.593	0.898	0.945	1.248	0.902
74	C	1.157	0.317	-0.262	0.656	0.406	1.335	0.605	0.421	0.894	0.452
75	C	1.459	0.615	-0.114	0.756	0.405	1.038	0.761	0.528	0.906	0.774
76	C	0.829	0.562	0.147	0.808	0.798	1.301	0.784	0.769	1.006	0.710
77	C	0.412	0.381	0.175	0.645	0.761	1.172	0.761	0.877	1.141	1.109
78	C	0.674	0.368	0.031	0.533	0.463	0.865	0.501	0.443	0.634	0.403
79	C	0.857	0.558	0.130	0.770	0.727	1.194	0.816	0.802	1.073	0.952
80	C	0.726	0.422	0.059	0.304	0.093	0.067	0.226	0.059	0.029	-0.010
81	C	0.697	0.514	0.165	0.875	0.964	1.597	0.801	0.835	1.088	0.579
82	C	0.568	0.293	0.009	0.506	0.475	0.932	0.544	0.535	0.794	0.656
83	C	0.798	0.438	0.039	0.709	0.665	1.253	0.816	0.822	1.195	1.137
84	C	0.627	0.398	0.084	0.680	0.706	1.244	0.642	0.647	0.886	0.528
85	C	0.742	0.496	0.125	0.679	0.647	1.043	0.696	0.681	0.897	0.750
86	C	1.059	0.584	0.055	0.877	0.786	1.463	0.974	0.945	1.363	1.264
87	C	0.612	0.448	0.142	0.855	0.976	1.668	0.901	0.997	1.354	1.040
88	C	0.572	-0.016	-0.302	0.767	0.864	2.332	0.794	0.868	1.605	0.877
89	C	1.089	0.454	-0.091	0.839	0.714	1.609	0.884	0.815	1.314	1.018
90	C	0.849	0.550	0.125	0.552	0.403	0.555	0.610	0.531	0.671	0.786
91	C	0.718	0.474	0.115	0.879	0.960	1.690	0.876	0.928	1.278	0.865
92	C	0.566	0.492	0.209	0.622	0.651	0.883	0.579	0.584	0.666	0.450
93	C	0.769	0.439	0.054	0.621	0.547	0.986	0.690	0.664	0.941	0.897
94	C	0.406	0.321	0.118	0.432	0.445	0.654	0.484	0.510	0.648	0.641
95	C	0.738	0.559	0.190	0.909	0.994	1.609	0.977	1.057	1.396	1.182
96	C	0.838	0.548	0.130	0.763	0.726	1.192	0.696	0.649	0.844	0.495

Table S.2.3 Fixed factors were compared against each other to test for correlation. Factors included the sampling period in days (time), treatment group (treat), the log natural total length (lnTL) and weight (lnW) of each fish, the average temperature across tanks for each respective sampling period (temp), and the rearing tank a fish was housed during the time of sampling (tank). The final model (M4) did not include lnW as it was collinear with lnTL. Time was collinear with temperature; however, time was included in the full model as a main effect and interaction.

Model	Factor	DF	VIF
M1	time	4	2.439057
	treat	2	1.025702
	lnTL	1	4.62346
	lnW	1	4.166168
	temp	1	16.539776
	tank	1	2.090229
M2	time	4	2.033027
	treat	2	1.025635
	lnTL	1	4.621708
	lnW	1	4.15857
	temp	1	16.533774
M3	treat	2	1.008971
	lnTL	1	1.018744
	lnw	1	4.198557
	temp	1	4.093027
	tank	1	1.28277
M4	treat	2	1.00277
	lnTL	1	1.004112
	temp	1	1.285687
	tank	1	1.282055

Table S.2.4 Two nested linear mixed effect models, which examined the effects of fish size, temporal factors, and treatment group on *Esox masquinongy* specific growth rates in a hatchery experiment, had the exact same AIC value. M2 (time included) was used for further analysis. Models accounted for autocorrelation using the ARM correlation function. Both models included a random effect for individual fish and parameters were standardized. SGR, or specific growth rate, is the response variable. "TM" is time in days post-processing, "TR" is the assigned treatment group of fish (tagged, sham, or control), "TK" is the tank a fish was sampled from (fish were rotated between tanks), "TP" is the temperature averaged all tanks over each sampling period (e.g. 7-to 30-d), and "lnTL" is the log natural total length.

Model	Formula	df	AIC
M1	SGR ~ TP + TR + TK + lnTL + TR:TM + TR:lnTL	26	18.15406
M2	SGR ~ TP + TR + TK + lnTL + TP + TR:TM + TR:lnTL	26	18.15406

Table S.2.5 Time, temperature, tank, treatment, and fish size effects on *Esox masquinongy* specific growth rates (SGR) from the M2 nested linear mixed effect model. Main effects and interactions are compared to SGR (Intercept) of Control fish. Environmental parameters were standardized for comparison. Asterisks indicate a significant effect ($p < 0.05$) on specific growth rates. Bolded values indicate those that are significant.

Factor/Interaction	Standard Error	t value	p value	Significant
(Intercept)	0.07015449	5.329483	0	
time30	**0.07190379**	**8.398987**	**0**	*
time60	0.27807149	0.954392	0.3404	
time90	**0.18601327**	**3.041311**	**0.0025**	*
time120	0.28037931	-0.327784	0.7432	
sham	0.08819845	-0.726523	0.4679	
tagged	0.08550528	-0.288635	0.773	
tank3	0.02837011	0.76947	0.442	
tank4	0.02719946	-0.876093	0.3815	
tank5	**0.02833862**	**-3.246788**	**0.0013**	*
temperature	0.18108627	1.594982	0.1115	
lntl	**0.04189588**	**3.246942**	**0.0013**	*
time30:sham	**0.09066982**	**-5.842954**	**0**	*
time60:sham	0.09573712	1.122781	0.2622	
time90:sham	0.13056057	-1.135345	0.2569	
time120:sham	0.16456165	-0.156263	0.8759	
time30:tagged	0.08554125	-1.079111	0.2812	
time60:tagged	0.09314405	0.015901	0.9873	
time90:tagged	**0.12881855**	**-2.407509**	**0.0165**	*
time120:tagged	0.16473483	-0.369157	0.7122	
sham:lntl	0.05783128	0.867509	0.3862	
tagged:lntl	0.06080476	1.24869	0.2125	

Eq S.2.1 Autocorrelation was observed, and AR, CAR, and ARM autocorrelation models were fitted. The ARMA model provided the best fit. As temperature was highly correlated, the AIC of three models using the ARM were compared using the following lme function:

y <- lme(response~ fixed factors + interactions, random = ~1|x, correlation = corARMA(p = 1, q = 1,form = ~ 1| x), data= z, method="ML", control=list(lmeControl(opt = "optim"), maxIter=10000, msMaxIter=10000)

Chapter 3 - Spatiotemporal ecology of juvenile Muskellunge (*Esox masquinongy*) and Northern Pike (*Esox lucius*) in upper St. Lawrence River nursery bays over fall and winter seasons

3.1 Abstract

Knowledge of the spatial ecology of juvenile freshwater fish is often lacking, particularly during the winter period. A decline in self-sustaining populations of sympatric, congeneric predators - Muskellunge (*Esox masquinongy*) and Northern pike (*Esox lucius*) - in the upper St. Lawrence River prompted study of spatiotemporal patterns and habitat requirements associated with earlier life stages in fall and overwintering periods. Age-0 Muskellunge (n = 38) and Northern pike (n = 38) were tagged and passively monitored using acoustic telemetry in four nursery embayments between 2015 and 2017 in fall and winter months to elucidate basic ecology and inform restoration activities and population management. Presence, residency, space and habitat use, developed from kernel utilization densities, were assessed and modeled against key environmental (e.g. water temperature and levels) and biological (total length) parameters using mixed effect models to identify how biotic and abiotic factors may influence spatiotemporal patterns and habitat use. Deeper littoral regions with submergent aquatic vegetation (SAV) were used by both species, and complex interactions between temperature and water levels were found to influence spatiotemporal trends during this critical period. Future analyses may elucidate fine-scale use of restored or manipulated habitats in nearshore and deeper regions with canopy forming SAV and delineating fine-scale variation in depth use between these juveniles esocids during overwintering periods, in accordance with new water level management plans aimed at producing natural riverine cycles.

3.2 Introduction

Freshwater fish generate many ecosystem services (Lynch et al. 2016), yet this group confronts a multitude of environmental stressors and anthropogenic pressures (i.e., dispersal barriers, development, pollution; Brunton 1995, Ricciardi and Rasmussen 1999, Dudgeon et al. 2006). For many freshwater species, little is known about their basic biology (see Cooke et al. 2016), despite the need for science-based management and habitat restoration (Lorenzen et al. 2016). Of particular importance is understanding how fish are distributed in space and time – their spatial ecology – a prerequisite to protecting critical habitats and the corridors that connect them (Bond and Lake 2003). Relationships between fish, their environment, and habitat use are fundamental to fish ecology as the environment influences growth, fecundity, and survival (Fry 1971). Owing to widespread anthropogenic habitat alterations and noted declines in fish populations, efforts to restore degraded fish habitats have increased (Cowx and Gerdeaux 2004). Yet, most of this work has focused on creation of spawning habitat rather than accounting for the habitat features required for all life stages. In particular, information on the ecology and seasonal habitat use of juvenile fish remains a significant research gap and has impeded habitat conservation and restoration activities.

Although occurring at naturally low densities as top predators (Cook and Solomon 1987), a substantial decline in the self-sustaining Muskellunge (*Esox masquinongy*) population of the upper St. Lawrence River have been recently reported (Farrell et al. 2017). In addition, population declines of their sympatric congener, Northern Pike (*Esox lucius*), have also been observed in the region (Smith et al. 2007), but abundances of Northern Pike greatly exceed those of Muskellunge in the region; young Muskellunge are often preyed on by their earlier spawning congener (Harvey

2009). This has prompted additional study to better understand spatial ecology and habitat requirements of the earlier life stages of both species.

Summer nursery habitat requirements for age-0 Muskellunge in the upper St. Lawrence River are well understood and are generally described by the presence of low to moderate cover of submerged aquatic vegetation (SAV) (Werner et al. 1996, Farrell 1998, Farrell and Werner 1999, Murry and Farrell 2007, Kapuscinski and Farrell 2014, Farrell et al. 2014). Likewise, well-oxygenated (Inskip 1982), deeper littoral areas with floating, emergent (Engstedt et al. 2018), and submerged aquatic vegetation (Cucherousset et al. 2009, Pierce et al. 2013) are preferred summer nurseries for age-0 Northern Pike (Grimm and Backx 1990). Most inferences about species-habitat relationships of juvenile esocids are restricted to seine or electrofishing surveys that provide a single point in time and space, typically for age-0 in the summer (July to August; e.g. Murry and Farrell 2007). Although this provides valuable information, these presence/absence surveys typically fail to account for seasonal movement patterns and habitat use, particularly into the fall and winter. For juvenile esocids in north temperate regions, little is known about habitat use and behaviour into late-fall and winter (Cunjak 1996), a period of time that imposes important selective pressure (i.e., survival) on fish populations during early life. Important to this understanding is how two congeneric predators that overlap in their early life histories and habitats exist in sympatry during the juvenile stage, a stage where juvenile Muskellunge can be easily preyed on by larger age-0 Northern Pike. With such information, the conservation and restoration of core habitat(s) can provide for reduced predation risk of juvenile Muskellunge by their competitively superior early-life congener (e.g. Crane et al. 2015).

Knowledge of the spatial ecology of early life stages was historically hampered by technical limitations of telemetry equipment (e.g. large tag size, short battery life). Recent

technological innovations, however, have made it possible to tag and track juvenile esocids over extended time periods. Thus, to better understand the ecology of esocids during a critical period of their early-life, the most recent telemetry technology was used to study the spatiotemporal trends associated with fall and overwintering behaviour and quantify core habitat features, and to determine the influence of environmental and biological variables on the presence, residency, and habitat use of age-0 Muskellunge and Northern Pike. Although maximizing edge habitat in littoral zones with moderate densities of SAV has been recommended to benefit multiple esocid life-stages (Crane et al. 2014), without a better understanding of habitat-by-species relationships, balancing the potential different habitat needs of sympatric Muskellunge and Northern Pike juveniles lacks precision.

3.3 Methods

3.3.1 Study location

This study took place in the Thousand Islands region of upper St. Lawrence River between Cape Vincent (43.30048 N, 79.80591 W) and Alexandria Bay, NY (43.30048 N, 79.80591 W). The upper St. Lawrence River is an oligotrophic system that is the effluence of eastern Lake Ontario and flows through the Eastern Great Lakes Lowland Forest (Thorp et al. 2005). Water levels in the upper St. Lawrence River are regulated by the International Joint Commission (IJC) at the Moses Saunders power dam that have artificially suppressed the magnitude and periodicity of water level fluctuations under plan-1958D (Farrell et al. 2010). The IJC has, however, implemented a new water level regulation regiment, plan-2014, to better reflect natural hydrology of the system.

The Thousand Islands region is characterized by its complex archipelago (>1,800 islands), rocky shorelines, shoals, and extensive littoral community and coastal wetland embayments

dominated by emergent and submergent vegetation (Farrell et al. 2010). The upper St. Lawrence River has also been the foci of a long-term monitoring program for esocids (Farrell et al. 1999; 2007; 2017) that has inventoried and evaluated critical early-life habitats of Muskellunge and Northern Pike. Like many coastal regions of the Great Lakes, those in the upper St. Lawrence River have experienced degradation of nearshore spawning and nursery habitats among many embayments (Carmignani & Roy 2017) and would benefit from science-based restoration and protection of critical habitat. For this study, four embayments with a mix of open-water and vegetated nearshore coastal habitats were examined. These included Rose Bay (44.185872 ºN -76.225169ºE), Buck Bay (44.253241ºN -76.136121ºE), Flynn Bay (44.25324ºN -76.136121ºE), and Grass Point. These sites were selected based on monitoring surveys that indicated an increase probability of catching sufficient numbers of age-0 Muskellunge and Northern Pike.

3.3.2 Embayment Habitats

Rose is a 9-hectare (ha) sheltered bay near Cape Vincent, NY (Fig. 1), and its mouth slopes steeply into the main channel. Buck (18-ha; Cooper 2016) is a narrow, shallow and sheltered bay that is adjacent to Flynn, a 74-ha system off Grindstone Island with a drowned river mouth tributary (Fig. 1; Farrell et al. 2014). Grass Point (47-ha), a New York State Park, was the least sheltered embayment that had a wide interface with the main channel (Fig. 1). Although exposed to the main channel, Grass Point exposure to prevailing westerly winds was limited by outcrops of islands and mainland shoreline that extends north into the river.

3.3.3 Fish capture

Age-0 Muskellunge and Northern Pike were captured using a standardized seining protocol where a 36.6 m seine net (6.4 mm mesh, stretch measure) with a 12.2 m bag was deployed in water depths less than 1.5 m for 18.3 m; one full transect encompassed 449 m^2 (Farrell and Werner

1999). When age-0 Muskellunge and Northern Pike were caught by seine, they were transferred to a cooler with aerated water from the site of capture. Water temperature in the cooler was monitored and periodically exchanged to prevent thermal stress to fish. Muskellunge were captured in all four bays from September-11-2015 to September-15-2015 and September-06-2016 to October-06-2016. In 2015, Muskellunge caught in Rose and Buck were of wild and stocked origin (e.g. Farrell et al. 2017). All age-0 Northern Pike were of wild origin, and those used for telemetry were all caught in in Flynn Bay between September-26-2015 and September-28-2015 and on September-21-2016. One Muskellunge captured in Flynn Bay in 2015 was translocated to Buck Bay.

3.3.4 Tags & Surgical implantation

Individuals were anesthetized in an aerated basin using a concentration of 75 mg/L tricaine methanesulfonate (MS-222). When loss of equilibrium was observed, anesthetized fish were weighed (nearest 0.1 g), measured for total length (TL; nearest 1 mm), and photographed. Fish were placed supine on the surgery table and received a maintenance dose of aerated anesthetic (75 mg/L MS-222) through a silicone rubber hose placed in the fish's mouth so water gently flowed over gills. Persistent opercular movement of anesthetized fish was used to monitor their condition during surgery. Because of multiple surgeons, surgery time ranged from <3 minutes for all fish in 2015 to between 3.5 and 12 minutes in 2016. Muskellunge were anesthetized (total time, knock out and surgery) on average for 12-min. while Northern Pike average of 14-min. in 2016. Times were not recorded in 2015. A sterilized (betadine) mini-acoustic JSAT tags (either a Lotek Wireless, L-AMT-1.416, 0.28 g, 10.7 x 5.4 x 3.1 mm or PNNL JSAT, 0.20 g, 15.0 x 3.4 mm) was implanted into fish following the procedure described by Gallagher et al. (2018). The tags used in this study represent two of the smallest commercially available acoustic telemetry devices (i.e., L-

AMT-1.416 and PNNL JSAT). Both tag types emitted a coded signal at a frequency of 416.7 kHz, with signal strengths of approximately 156 to 158 dB (re: µPA @ 1 meter) using a BPSK (binomial phase shift key) 16-bit tag code. Following surgery, fish were allowed to recover in fresh, aerated water from the site of capture and release once fish regained full equilibrium.

3.3.5 Receiver deployment

In the fall of 2015, 38 receivers (Lotek WHS4250 416.7 KHz, Newmarket, Ontario) were deployed in Rose, Buck, and Flynn Bays. A grid system in Rose and Buck bays was used to maximize residency and detection capacity with the assumption that fish remained in the shallow (<1 m) back portion of bays in the fall. A loose gate of receivers was positioned in deeper waters (1.5-3.0 m) of both bays to assess outward movement and residency as fall progressed to winter from October to December (Fig. 1). In Flynn, receivers were deployed to maximize coverage of the bay's shallow interior and deeper (>1 meter) regions. In 2016, twenty-one receivers were deployed in the nearshore region of Rose and Grass Point and the mouth of Flynn in October to assess fall residency. In November, all 21 receivers were removed and downloaded. All 21 receivers (plus three more) were redeployed in the mouth or perimeter of Rose, Grass and Flynn until March 2017 (Fig. 1). In every instance that receivers were deployed, their location was recorded with a handheld GPS unit.

Receivers deployed in shallow waters were mounted to rebar using zip ties and electrical tape and buried in the substrate. The top of the receiver, which detected the signal, remained several inches above the substrate to prevent attenuation issues. Receivers deployed in waters >2 m were secured between two sandbags filled with cobble-sized rocks and attached to twisted polypropylene rope that was buoy at the surface (Fig. S.1). Receivers set at depths >3 meters were rigged so that the receiver was near the substrate and the connected buoy was 2 m below the water's

surface to ensure that water level fluctuations would prevent adverse contact with boats and that ice did not form around the buoy and move the receiver.

The effective range at which implanted fish could be detected (ratio of true to expected detections captured by receivers) was calculated by dividing the observed number of detections by the number expected per hour from sentinel tags (n = 180) and receiver beacon signals (n = 60). Both implanted and sentinel tags emit a series of bursts (herein known as a ping) with a digital ID every 20 seconds. Sentinel tags were placed 30-, 70-, and 120-meters from receivers in the nearshore region of Buck and Rose in 2015, to determine the furthest distance tagged fish would be detected 50% and 100% of the time. In 2016, sentinel tags were not deployed, therefore each receiver was also set to emit a ping (beacon signal) with similar power to real tags (Wigglesworth, *pers. comm*) every 60 seconds. Variation in pings/hour between signal sources (beacon vs. sentinel tag) was accounted for by multiplying observed beacon signals by three. Effective detection range for both sentinel tags and beacon signals were 100% of signals received at 30-meters and 50% of signals received at 75-meters.

3.3.6 Environmental variable sources

HOBO Pro v2 water temperature loggers were attached to receivers deployed in the interior of Rose and Buck in 2015, at Rose and Grass Point in 2016, and within the mouth of Flynn (2016). New loggers were deployed in deeper waters associated with the winter Rose array (>3 meters), and waters ~2 meters deep in the Flynn and Grass Point arrays. Mean monthly water level data were sourced from the International Great Lakes Datum (Canadian Hydrographic Service 2017) from Port Weller, Toronto, Cobourg, and Kingston, Ontario, and Rochester and Oswego, New York stations. Water depths were documented in meters above sea level, as per IGLD 1985. Daily air temperature data, used as a proxy for water temperature in Buck and Flynn (2015) and Rose

(2016/17), was sourced from Environment and Natural Resources Canada (2018) historical weather and climate data for October to December 2015 and October 2016 to March 2017. Hourly water temperatures (Rose 2015, Grass and Flynn 2016/17) which were condensed to daily values and compared against daily air temperatures values using Pearson's correlation coefficient, were not highly correlated (<0.70). If they were highly correlated, water temperature from one bay (i.e. Grass) would have been used for another bay monitored within the same year (i.e. Rose).

3.3.7 Analytical approach

Detection data were filtered so that double detections and detections < 5min apart at the same receiver were excluded. Detection data were then separated by year (2015 vs. 2016); October was excluded from the 2016 data set due to differences in array designs. Independent analyses were performed on the age-0 cohorts tagged for both species in 2015 and 2016/17, age-1 Muskellunge detected overwinter in Rose 2016/17, and age-1 Northern Pike detected in Flynn 2016/17. Differences in overall body size, represented by total length, was compared for each species between years using a one-way ANOVA, with year as a fixed factor.

3.3.8 Diel data

Detections over the full study period were categorized into four diel times: dawn (0500-0859), day (0900-1559), dusk (1600-2059), and night (2100-0459). Dusk and dawn were selected based on the earliest and latest hour that sunrise and sunset was observed in October. A generalized linear mixed model (*glm*, R package "lme4"; Bates et al. 2015) with a Poisson distribution and a least regression test ("LR") was used to analyze the total number of detections per diel period from sentinel tags, beacon signals, and tagged fish. Tagged data included the total number of detections per diel period from all receivers per embayment. Models included bay and year as fixed factors, with fish as the random factor. Pairwise comparisons were evaluated using a Tukey test (*glht*, R

package “multcomp”; Hothorn et al. 2008) when significance occurred.

3.3.9 Monthly residency

Abacus plots of acoustic detections were examined to visually assess spatial and temporal residency of fish in the arrays for the duration of each study period (three months 2015, six months 2016 to 2017; R package “glatos”; Holbrook et al. 2016). The presence/absence of a fish was identified on a monthly basis; a fish was considered present and assigned a value of one if it was detected ≥ 7 days in a given month. If not, they were considered absent and given a value of zero for that month. A monthly residency index ranging from 0 to 1 (where values close to 1 indicated high residency in the array; Espinoza et al. 2014) was calculated for each fish classified as present by dividing the number of days a fish was detected within an array by the number of days the array was active during that month. To compare residency of fish detected from October 2016 to March 2017, monthly RI values were divided by the number of receivers active each month (e.g. seasonality) to ensure a reduction in detections was not due to the reduction in number of receivers, and to confirm a natural pattern rather than an artefact of the array.

3.3.10 Space Use

Space use was calculated based on center of activity (COA) locations and kernel utilization distribution (KUD) values. COA locations were calculated using method from Simpfendorfer et al. (2002), where mean fish positions, based on detections from all receivers within sequential two-hour intervals, were calculated throughout the study period to reduce spatial and temporal autocorrelation (Rooney et al. 1998). KUD values (50% core and 95% extent) were then estimated for individual fish by using the kernelUD function (R package “adehabitatHR”; Calenge 2006). The kernelUD function included a smoothing parameter (h, which controls the width of the kernel functions), a grid size (on which the KUD should be estimated, and its resolution) and an extent

value (the extent of the grid used for the estimation). The UD (van Winkle, 1975) considers the space use described by bivariate probability density based on relocation coordinates (the COA locations) and the kernel method (Silverman 1986; Wand and Jones 1995), which averages the relocation values. The smoothing parameter was determined by calculating the "h" value for each fish within an embayment (per year) and using the median value (Hollensead et al. 2016). The size of the grid was established by increasing grid values in increments of 250 (starting at 500) until the error message of "grid too small" no longer appeared, and extent values were increased starting at one. A consistent grid value of 1000 (appropriate across all bays and years), and extent value of four were used. Finally, variation in core space use and extent among individuals in the same embayment were assessed using linear models.

3.3.11 Habitat features

Habitat types within each bay were determined using an image classification of raster files representing each bay in ArcGIS (ArcMap 10.5.1; ESRI 2017) to compare embayments in a consistent manner. NY GIS Clearinghouse orthoimage raster files from 2015 of each embayment (NYS Information Technology Services 2018) were merged using the *Mosaic Data Management* tool, and clusters associated with physical habitat types (e.g. vegetation, exposed substrate, depth) were identified for each embayment mosaic map using the *Iso unsupervised image classification* tool (20 classes), in which the Iso Cluster and Maximum Likelihood Classification tools are combined and classify individual pixels based on the raster bands (red, green, blue) associated with the raster files. Habitat types were established by comparing clusters to vegetation survey data in published literature (Farrell et al. 2014) and an Ontario submerged aquatic vegetation (SAV) shapefile, which provided coarse resolution of exposed sand regions, low and high SAV (Shuchman et al. 2013). Mosaic maps for each bay were reclassified (*Reclassify* tool) based on

like habitat features (see Fig. 1 legend) and converted into polygon features (*Raster to Polygon* tool). To calculate the percent of each habitat type within each fish's core range per month, monthly core use (50% KUD) were first converted to ESRI shapefiles (*writeOGR*, R package "rgdal"; Bivand et al. 2017) then imported into file geodatabases (*Feature Class to Geodatabase* tool). Individual monthly core use ranges were intersected (each separately) to the habitat polygons, using the intersect tool. The percentage of each habitat type used within an individual's core space was divided by the total core area to calculate habitat proportions used.

3.3.12 Mixed effect models

A series of mixed effect models (R packages "nlme", Pinheiro et al. 2018; "lme4, Bates et al. 2015) were applied to explore the influence of water level, air and/or water temperature, and fish size (fixed factors which may elicit differences among response levels; Bolker et al. 2009) on residency, space and habitat use within deployed arrays for each species, per embayment, per year. Fixed factors were centred to simplify interpretation and facilitate comparison of their importance (Schielzeth 2010). Fish ID was a random factor to enable population-level prediction and account for the repeated-measures nature of the data (Bolker et al. 2009). Collinearity between fixed factors, were compared using Pearson correlation coefficients and variance inflation factors (*vif,* R package "car"; Fox and Weisburg 2011), and residual and auto-correlation plots evaluated models' goodness of fit (Bolker et al. 2009; Zuur 2010). If auto-correlation was present, models were fitted to account for spatial (e.g. corExp) or temporal (e.g. corAR1, corARMA) correlations, and heteroscedasticity. Akaike's information criterion (AICc) was calculated, and the models with the lowest AIC corrected for small sample sizes were selected (Burnham and Anderson 2004; see Supplementary Tables). Linear models (LME) for space use were analyzed using maximum likelihood, an "optim" lmeControl and a value of 10,000 for both maxIter and msMaxInter.

Generalized models (GLMM) were fitted with a binomial error distribution using a logit link and an nAGQ value of seven (e.g., Bolker et al. 2009). The nAGQ (Adaptive Gauss-Hermite Quadrature) model is more accurate than Laplace estimations (Bolker et al. 2009) and increased the accuracy of the model's residency estimation (Pinheiro et al. 2006). Due to convergence failure, two separate optimisers were used: the "bobyqa" for Flynn, Buck, and Grass Point and "nloptwrap" for Rose Bay.

3.4 Results

3.4.1 Descriptive

Over the course of the study, nearly all age-0 fish tagged were detected (2015: 98% Muskellunge and 100% Northern Pike (Table 3.2, 3.3); 2016/17: 100% Muskellunge and 98% Northern Pike; Table 3.4), and consistent detections on multiple receivers indicated high survival in fall and overwintering periods. Total length) of age-0 Muskellunge was greater in 2016 (177 ± 36.8-mm) than 2015 (154 ± 20.8-mm) but this difference was statistically indistinguishable ($F_{1, 37}$ = 3.7464, p = 0.06). Similarly, Northern Pike did not differ in total length between 2015 (234 ± 55.2-mm) and 2016 (227 ± 38.3-mm; $F_{1, 37}$ = 1.2429, p = 0.27). One Muskellunge originally caught and tagged in Rose Bay in 2016 was subsequently recaptured four weeks later and had grown 78-mm and gained 49.3-g in four weeks (Fig. S.3.13). Water depths fluctuated from 74.56 m (above sea level, October 2015) to 74.47 m (November 2015) to 74.74 m (December 2015) and increased from 74.48 to 75.00 meters (November 2016 and March 2017).

3.4.2 Diel detections

The temporal variation in detections of sentinel tags appeared to indicate an environmental influence on detection rate, rather than variation in fish movement among the diel periods. More detections were captured at night (33%; z = 2.486, p = 0.01) and day (30%; z = 2.376, p = 0.02)

relative to the dusk and dawn diel periods. Fish detections followed a similar pattern to the sentinel tags between years; more detections occurred at night (30-40%), while detections during the day (4-19%), dusk (14-19%) and dawn (15-32%) were more evenly distributed.

3.4.3 Detections, Residency & Space Use

3.4.3.1 Muskellunge

Rose Bay

Twenty age-0 Muskellunge were initially tagged in Rose Bay in 2015, and all fish were frequently detected (577 ± 1,125 [mean detection of all fish ± SD], Fig. S.3.8). In contrast, of the five Muskellunge tagged in 2016, individuals were detected less frequently over winter (143 ± 127), likely a product of differences in receiver array design and sample sizes between years.

In 2015, residency index was highest during early fall (>0.50), and higher residency index was significantly correlated with warmer water temperatures (>10ºC) in both 2015 and 2016 (x^2 = 7.5242, p = 0.006, 2015, Fig. 3.2a; x^2 = 7.5242, p = 0.006, 2016, Fig. 3.2d; Table S.2). Residency index was significantly higher with body size (x^2 = 4.4903, p = 0.03) in 2016, but no effect was found in 2015 (Table S.21). Covariates had no effect on presence/absence in either season.

Four Muskellunge detected in 2015 exhibited significantly smaller ($F_{19,56}$ = 3.3319, p = 0.001) core spaces, relative to conspecifics (Fig. 3.4). Space use between individual fish was similar each month in 2015 (core, 0.04 km^2 ± 0.002 SE, extent 0.16 km^2 ± 0.004 SE; Table 3.1; Fig. 3.3a). In 2016, all fish detected (n = 3) shared the exact same core space use size of 0.02 km^2, likely as a product of the array design, which drove small utilization distribution outputs.

Water temperature and water level were significant variables contributing to the fit of the data for core space. In 2015, Muskellunge had smaller core space use ranges between water temperatures of 9.5ºC and 11.5ºC (x^2 = 4.59, p = 0.03; Fig. 3.2b) and at lower water levels (x^2 =

4.189, p = 0.04; Fig. 3.2c). Over the 2016 winter season, Rose Muskellunge retracted their core space use when water levels increased (x^2 = 5.07, p = 0.024, Fig. 3.2e) and increased their extent size (95% KUD) with warmer air temperatures (x^2 = 14.363, p = <0.001, Fig. 3.2f).

Buck, Flynn & Grass Bays

All eight Muskellunge tagged in Buck Bay were present during fall (100% in October and November), and residency index remained high each month. Fish were not often detected (81 ± 42, [mean detection of all fish ± SD]), however, all fish exhibited similar use of Buck Bay (Fig. 3.3a) with a core space use size of <0.15 km^2. Extent sizes averaged 0.50 km^2 ± 0.01 SE (Table 3.1). Covariates had no effect on spatial responses among the factors examined.

The lone Muskellunge tagged and transported to Buck from Flynn was infrequently detected in Buck; however, it was detected in Flynn in 2016/17 for a brief period, demonstrating it migrated to its original site of capture. The sole Muskellunge tagged in Flynn in 2016/17 was also infrequently detected in October and over winter.

Grass Point Muskellunge tagged (n = 5) maintained a consistent presence within the embayment perimeter, as did residency index (0.38 ± 0.27 SD). Space use was consistent (0.11 km^2 ± 0.004 SE, core; 0.49 km^2 ± 0.01 SE, extent) among fish, though their individual use of the embayment perimeter where waters drop of varied extensively; space use did not overlap visually (Fig. 3.3b). No effects from biological or environmental variables on presence/absence, residency index, or space use were observed.

3.4.3.2 Northern Pike

All 24 age-0 Northern Pike tagged in 2015 were detected at some point, and 17 fish (788 ± 812, [mean detection of 17 fish ± SD]) were considered present (Table 3.3). Of these 17 fish, three were found to have significantly larger core use areas ($F_{16,39}$ = 4.2165, p < 0.001; Fig. 3.4) relative

to conspecifics. Core use space for all fish (0.06 km^2 ± 0.005 SE) was often restricted to the embayment interior (Fig. 3.3a), while extent included both interior and mouth regions (0.32 km^2 ± 0.02 SE). Residency index was higher in the shallow interior of the bay (>0.50) relative to the deeper water habitat of the embayment's mouth (0.05).

Of 15 age-0 Northern Pike tagged in 2016/17, all 15 were detected (80 ± 102, [mean detection of fish ± SD]), and 50% (seven) were considered present (Table 3.5). Core space (0.18 km^2 ± 0.01) and extent (0.62 km^2 ± 0.008) doubled relative to age-0 fish monitored in 2015, likely due to the change in array size. Residency index was low (~0.05) indicating that fish used other regions (nearshore or deep waters) more often than the mouth.

Water level significantly contributed to the fit of the data for residency index in 2015, as did air temperature for residency index and core space in 2016. Presence significantly increased as water levels rose, from 52% of fish to 96% of fish monitored (x^2 = 6.7064, p = 0.01; Fig. 3.5a), as did residency index (x^2 = 26.3046, p = <0.001; Fig. 3.5b) in 2015. In 2016, space use (Fig. 3.5c, d) significantly increased with water temperature (x^2 = 5.4234, p = 0.020, core; x^2 = 9.3907, p = 0.002, extent).

3.4.4. Age -1 Fish

3.4.4.1 Muskellunge

Nineteen (95%) of the age-0 Muskellunge tagged in the fall of 2015 in Rose were detected at some point (31 ± 20 SD, [mean detection of fish detected ± SD]) as age-1 fish in the fall and winter of 2016 in their natal embayment. Of these 19 Muskellunge, four fish were consistently present (Table S.4) throughout the winter period of 2016/2017 (mean residency 0.48 ± 0.12 SE). These four fish exhibited relatively small core use size (0.02 km^2) and extent (0.072 km^2 ± 0.008 SE). The likelihood of an age-1 Muskellunge being present in the array increased with total length

at first capture ($x^2 = 4.7012$, $p = 0.03$; Fig. S.3.14), but RI was low with warmer air temperature ($x^2 = 5.2921$, $p = 0.02$, Fig. S.3.15). Space use was not influenced by covariates.

3.4.4.2 Northern Pike

Eighteen of the 24 Northern Pike originally tagged in 2015 as age-0 fish were detected (75 ± 67 SD) in the 2016/17 array in Flynn Bay as age-1 fish, and seven fish were present throughout the winter months (Table 3.5). Presence peaked in December (63% of fish present) and declined in winter months (44%). Mean residency index was high (>0.55) for these seven fish, mean core space use (<0.2km^2) was concentrated on the western edge of the embayment mouth (Fig. 3.3b). Average extent included all receivers located in the grid pattern within the embayment mouth (0.62 ± 0.005 SE). No parameters were influenced by covariates.

3.4.5 Habitat Features

Flynn was the most diverse bay in terms of habitat including nine different habitat types that were classified. These included: established *Typha,* a mixture of SAV and emergent vegetation, SAV and floating vegetation, combination (50/50) of SAV and exposed substrates, newly developed *Typha* patches, exposed substrate, combination (25/75) SAV and exposed substrates, full (100%) SAV and deep waters (>3-meter; Fig. 3.1). The least diverse system was Buck that included only three habitat categories (i.e., floating vegetation, SAV and emergent vegetation, and exposed substrate); the array overlapped all three categories. Rose and Grass Point shared habitat features (Fig. 3.1.), except for deep littoral waters with SAV and a small sediment plume observed along the shoreline that was unique to Rose (Fig. 3.1.).

Of the habitat features classified in each bay, the receiver array overlapped with four in Rose for the 2016/17 survey (i.e., deep waters, deeper littoral regions with SAV, and small proportions of both SAV intermixed with floating vegetation and exposed-shallow areas). In

Flynn, the 2016/17 receiver array overlapped with seven of the nine habitat features (i.e., deeper waters, SAV, the combined [25/75] SAV and exposed region, exposed substrates, new *Typha* stands and submergent, emergent vegetative regions). The 2016/17 Grass Point fall survey overlapped with four of six features (i.e., deep waters, deeper littoral regions with SAV, regions with 50/50 exposed substrates and SAV amongst varying depths, and proportions of both SAV intermixed with floating vegetation), while the overwinter survey overlapped with all six features, which included shallow regions either exposed or with SAV.

3.4.5.1 Muskellunge Habitat

In fall and early winter of 2015 and 2016/17, age-0 Muskellunge in Rose were found to disproportionally favour one habitat type over others ($x^2 > 1.41$, $p < 0.001$, for both years). Muskellunge frequented deep waters (>90% of habitat use within all core space areas) relative to other available habitats (Tukey's, $z = -103.9$, $p = <0.001$). Despite the availability of floating and SAV habitats, only 40 - 45% of core space use was of this habitat type in October and November of 2015.

Buck Bay Muskellunge more frequently occupied shallow waters characterized by exposed substrates (55 - 85% of habitat use within core space areas) and a mixture of SAV and emergents (30 - 40%; $x^2 = 238.8137$, $p = <0.001$; Fig. 3.6) than floating vegetation. Muskellunge in Grass Point appeared to occupy deeper waters (55-75%) deeper littoral waters with SAV (20-80%) more often relative to habitats characterized by a 50:50 ratio of exposed water/substrate and SAV cover (<20%) and floating vegetation with SAV (<10%) ($x^2 = 52.9370$, $p = <0.001$; Fig. 3.6).

3.4.5.2 Northern Pike Habitat

Eight Northern Pike (TL = 213 to 275-mm) were nearly exclusively found in the vicinity of a receiver associated with 100% SAV cover and adjacent to habitat characterized by a 50:50

ratio of SAV cover and exposed substrates. Similar patterns were noted for all Northern Pike during both survey periods where fish disproportionately used different habitat types ($x^2 > 458.59$, $p < 0.001$; Fig. 3.6). All 17 age-0 Northern Pike monitored preferentially occupied one habitat over others ($x^2 = 252.7292$, $p = <0.001$); shallow nearshore region of Flynn, characterized by 50% SAV cover and exposed substrates, was preferred over exposed, shallow waters (Tukey test, $z = 4.688$, $p = <0.001$; Fig. 3.6). In contrast, overwintering age-0 Northern Pike monitored in 2016/17 used significantly more exposed, shallow habitats (30 - 55%) near the interior and southwest shore of Flynn Bay relative to deep water habitats (20 - 35%) (Tukey test, $z = 14.968$, $p = <0.001$).

3.4.5.3 Age -1 Habitat Use

Age-1 Muskellunge detected in Rose in 2016/17 showed similar habitat use patterns observed during their first seasonal change; a greater proportion (>95%) of all core space areas was comprised of deeper zones (>95%), with little use of deeper littoral zones with SAV (3-4%). Age-1 Northern Pike detected also showed similar patterns as their first year; individuals tended to use exposed zones (35-70%), but also used deeper zones (25-45%) within small patches of SAV. Though habitat features (exposed, shallow waters, partially exposed waters with SAV, and deep zones, in rank order) were used in significantly different proportions ($x^2 = 252.7292$, $p = <0.001$; Fig. 3.7) in 2016/17, the tendency for core use areas to include low proportions of available SAV within arrays either year may suggest core juvenile Northern Pike habitat is quantified by particular habitat use ratios beyond their first summer.

3.5 Discussion

This study is the first to use acoustic telemetry to examine spatial ecology of age-0 Muskellunge and Northern Pike. Results showed complex (and underestimated) space and habitat uses for both species, and influence of environmental covariates were dependent on embayment

and the spatial variable examined. Muskellunge residency was positively related with warmer water and air temperatures, and core space use fluctuated pending water levels, while Northern Pike residency was positively related to warmer water temperatures and higher water levels, though these increases were dependent on the year fish were monitored. Fish used the entirety of their respective natal embayments as fall progressed to winter, contrasting Farrell et al. (2014), where age-1 Muskellunge and Northern Pike exhibited segregated space use of Flynn Bay based on radio-tracked movements. Overwinter, neither species nor age-class monitored were often present within embayment entrances, suggesting either continuous use of coastal wetlands and shallow shorelines, or deeper habitats at the edge of the embayment mouths over winter. As analytic tools may influence ecological interpretation, future exploration will evaluate age-0 Rose Muskellunge using network analysis to provide a more comprehensive picture of young Muskellunge movements (i.e., bidirectional movement through corridors; Lédée et al. 2015).

Segregation was noted in the habitat types most often used between age-0 Muskellunge (i.e., deep waters and deeper littoral zones) and Northern Pike (i.e., shallow, exposed zones around littoral patches) in early and late winter periods. This tendency towards segregation was observed by Farrell et al. (2014) between sympatric age-1 Muskellunge (stocked and wild) and Northern Pike (wild), radio-tracked in Flynn Bay in late fall. The contrasts noted in habitat use between age-0 fish (present study) and age-1 fish (i.e., use of shallow, perimeter habitats by Muskellunge and deeper, offshore regions by Northern Pike; Farrell et al. 2014) may have been associated with how habitat uses were documented based on the telemetry tools employed or the monitoring year, but may have reflected habitat use in allopatric (present study) vs. sympatric (e.g., Farrell et al. 2014) scenarios.

Both species tended to use regions that supported growth of submergent aquatic vegetation (SAV) in the fall and winter. This tendency was noted based on visual assessments of core space use, and documented use of different depth ranges (present study) and fine-scale water column depths in shared habitats (Farrell et al. 2014) may indicate that these congeneric predators occupy distinct realized environmental niches, similarly to *Pterocles* spp. (Benitez-Lopez et al. 2014). Juvenile Muskellunge and Northern Pike have a shared affinity for similar habitats (Murry and Farrell 2007), and as segregation was noted within nursery bays (site-specific), coexistence of juvenile Muskellunge and Northern Pike in any given embayment in the upper St. Lawrence River may result from a combination of macro- and micro-scale variables, rather than interspecific interactions. Monitoring both species within an embayment and manipulative habitat-use experiments are required to test this hypothesis.

Variation in residency based on water-levels may suggest that seasonal fluctuations (macro-habitat) in water levels and distributions of sensed SAV (micro-habitat). The upper St Lawrence River experienced drought-like conditions in 2016 and extreme flooding in 2017. As varying water levels may serve an important role in spatial overlap between species (Rosenfeld and Hatfield, 2006), future spatiotemporal analyses focused on the influence of variable water level cycles authorized by new IJC water level management in the upper St. Lawrence River (International Joint Commission 2014) may be worthwhile. Mimicking natural variation in water levels may accentuate segregation observed during spawning periods (Cooper et al. 2008) and juvenile space and habitat use (Farrell et al. 2014). Additionally, use of moderate- cover, fine-and broad-leafed SAV (e.g., *Vallisineria;* Rybicki and Carter 1986) is well-documented (Farrell et al. 1996, Farrell 1998, 2001, Kapuscinski and Farrell 2014), and use of different yet specific depths (one for each species) over a small depth gradient (i.e., one to three meters), as observed in

sympatric juvenile skates (*Raja* spp.; Humphries et al. 2014) and age-1 Muskellunge and Northern Pike (Farrell et al. 2014), may play a key role in micro-habitat segregation the first winter so Muskellunge can effectively forage on preferred prey sources in these habitats (i.e., fusiform-cyrpinds; Woodside 2009, Kapunscinski et al. 2012), and to avoid predation by the competitively superior Northern Pike. Understanding how macro-habitat (fluctuating water levels) and micro-habitat use (regions that support growth of SAV) differs in their inaugural winter, and their use of vertical habitat in association with canopy-forming SAV may support the hypothesis of macro- and micro-habitat use but also predict fine-scale core space use by each species to inform restorative actions (i.e., plantings) to improve nursery habitat for juvenile Muskellunge.

The lone age-0 Muskellunge transported to Buck from Flynn Bay in 2015 was briefly detected in the mouth of its natal embayment (i.e., Flynn) the winter of 2016. Spawning adults are known to exhibit strong site fidelity (e.g. LaPan et al. 1996); however, limited information on site fidelity for this earlier life stage is available. A complex corridor, made up of several islands, shoals, and deep channels exists between Buck and Flynn Bay; however, a continuous band of deeper growing SAV around this corridor may have been used by this Muskellunge to return to its natal embayment. Future spatiotemporal ecology studies which transplant juvenile Muskellunge to increase sample sizes may test the hypothesis that esocids establish their overwintering range near their natal embayment in their juvenile years. Supporting this hypothesis may elucidate an important ontogenetic change in space and habitat use by juvenile, sub-adult and adult esocids.

The importance of elevated water levels and temperatures for juvenile Northern Pike was found to extend beyond initial recruitment post-spawning (i.e., Hudon et al. 2010) in this study. Water temperature decreases with increasing depths, and this relationship is known to exert profound effects on early life survival and recruitment for fish, including Northern Pike (Hudon et

al. 2010). Smith et al. (2007) noted year-class strength for Northern Pike in the upper St. Lawrence River was positively associated with high water levels and water temperatures in spawning and nursery areas in fall months, while Hudon et al. (2010) found ideal recruitment years for Northern Pike in the lower St. Lawrence River were characterized by high water levels and high (>18.6ºC) air temperature in June. Indeed, presence, residency and space use by age-0 Northern Pike in the first two autumn seasons in the present study corresponded with higher water levels and air temperatures, suggesting these conditions may act two-fold: good recruitment and good nursery habitat conditions in fall months. In addition, residency of age-0 fish was strongly associated with a deeper littoral region in early fall known to contain dense pondweed (*Potamogeton* spp.) patches, as well as nearshore regions with high SAV cover. Farrell et al. (2014) documented frequent use of this deeper littoral region by free-ranging, radio tracked age-1 Northern Pike (391± 8.7-mm), suggesting similar embayment-level habitat use throughout their juvenile stage.

Stocked and wild counterparts monitored in Rose and Buck Bays implied similar spatiotemporal behaviours between sources - a fundamental assumption (similar behaviours) of stocking - indicating restoration efforts targeting wild fish will likely benefit stocked conspecifics. Fifty percent more Muskellunge were caught and tagged at Rose in 2015 than 2016, likely due to stocking advanced fry prior to seine surveys in 2015. Success of stocked fingerlings within the upper St. Lawrence River must consider whether similar spatiotemporal patterns exist between stocked and wild fish (Farrell and Werner 1999). Farrell et al. (2014) postulated that the consistent habitat use by stocked age-1 Muskellunge in Flynn Bay resulted from their captive rearing environment; however, results showed overwhelmingly consistent habitat use between stocked and wild fish within Rose (>90%). Though stocked fish could not be differentiated from wild ones, detections from 95% of age-0 fish as age-1 fish in Rose Bay suggests high survival rates.

The acoustic tags used in the initial season lasted substantially longer than anticipated, and permitted an evaluation of presence, residency, space and habitat uses of each Muskellunge and Northern Pike as age-1 individuals within two embayments. Specifications indicated a calculated lifespan of 87-days (L-AMT-1.416) and 131-days (L-AMT-1.421) with transmissions emitting at 20-second pings (Lotek, 2018); however, detections up to March 2017 suggest a lifespan of more than 570-days. More research is required into the lifespan of mini acoustic transmitters, to determine their validity in multi-year studies and the performance of an array with JSATS in various aquatic environments. For instance, juvenile esocids share an affinity for shallow, vegetated habitats, which create challenges for passive acoustic monitoring as transmitter signals are attenuated by dense vegetation (Cooke et al. 2013) and shallow water receivers can become exposed when water levels drop (i.e., <1 m nursery bays). To this end, biased detections rates (i.e., diel period) due to the environment in the present study may have influenced residency patterns, and thus my interpretation of how macro-scale variables (i.e., water levels) influence the length of time juveniles remain in their embayment and motives to stay rather than move out.

Future studies should focus efforts in deeper littoral waters and adjacent river shorelines, to better elucidate macro-habitat use and avoid fluctuating environmental conditions that restrict receiver placement, and test attenuation issues in shallow, heavily vegetated regions compared to deeper littoral zones. Further, studies may desire to explore the spatial ecology of age-0 Muskellunge and Northern Pike in the lower St. Lawrence River to determine model extrapolation and transferability within Lake St. Lawrence. Results of the present study identified a spatial process that correlates with water level and temperature; however, fine-scale, manipulative studies within the upper and lower river system may identify a causal process in space and habitat use between these juvenile esocids.

Echoing Crane et al. (2015), protection and re-establishing moderate densities of SAV to maximize edge habitats may aid juveniles in meeting basic biological needs overwinter, though manipulative studies are required to test predictions associated with micro-habitat use relative to Northern Pike. Ontogeny is known to play a crucial role in habitat segregation and existence of sympatry between juveniles and adults (e.g. *Rhnogobius spp*; Sone et al. 2001, Guo et al. 2014), as subadult fish are rarely observed despite significant sampling effort (Farrell, *pers. comm*); this area of research is a critical, yet understudied link to elucidate movement patterns and critical habitat uses which may promote survivorship of esocids to adulthood.

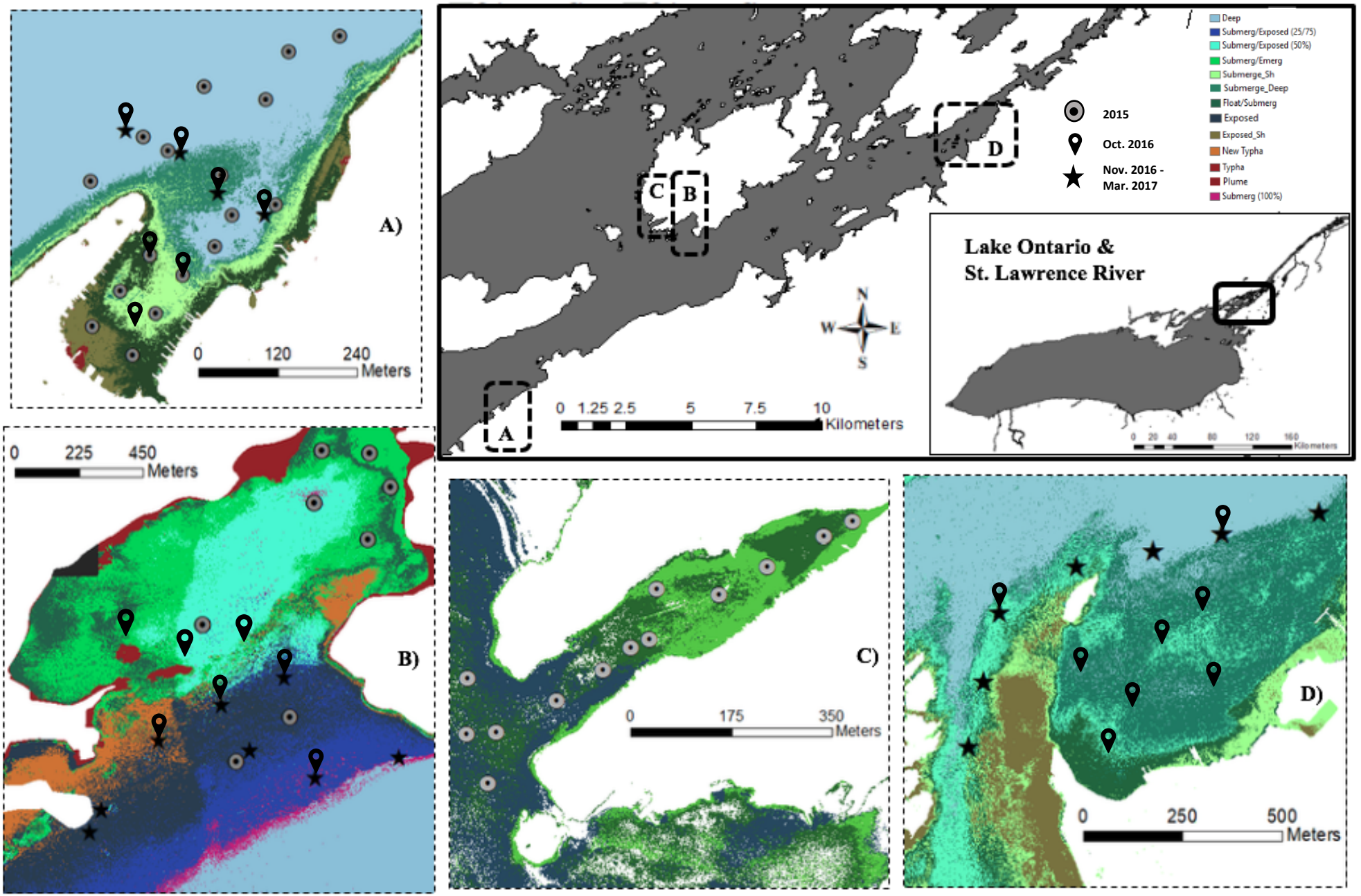

A)
0 120 240
Meters
Deep
Submerg/Exposed (25/75)
Submerg/Exposed (50%)
Submerg/Emerg
Submerge_Sh
Submerge_Deep
Float/Submerg
Exposed
Exposed_Sh
New Typha
Typha
Plume
Submerg (100%)
2015
Oct. 2016
Nov. 2016 - Mar. 2017
A
B
C
D
N
W
E
S
0 1.25 2.5 5 7.5 10
Kilometers
Lake Ontario &
St. Lawrence River
0 225 450
Meters
B)
C)
0 175 350
Meters
D)
0 250 500
Meters

Figure 3.4. Map of the upper St. Lawrence River, and the study site, relative to Lake Ontario and the St. Lawrence River, where age-0 Muskellunge and Northern pike were captured, tagged, and tracked between 2015 and 2017. Embayment locations in which age-0 Muskellunge and Northern Pike were tagged and tracked are denoted by a dotted line indicating its location in the upper St. Lawrence River, with the associated letter. Embayments include **A)** Rose, **B)** Flynn, **C)** Buck and **D)** Grass Point Bays. The receivers deployed in 2015 are denoted by a grey circle with a black dot; October 2016 are denoted by a locator icon, from November 2016 to March 2017 by black stars. Colours denote the habitat features selected through the Iso unsupervised clustering analysis in ArcGIS. Deep zones are those >3 meters. Submerg/Exposed zones indicate regions with 25% or 50% exposed substrate. Submerge/Emerge zones include both SAV and emergent species in shallow waters, similarly to zones with both Floating and SAV. Exposed zones are exposed substrates in >3 meters of water, and Exposed_Sh are similar zones in shallow waters. Note that Typha is only present in Flynn, while the Plume is only observed in the nearshore of Rose.

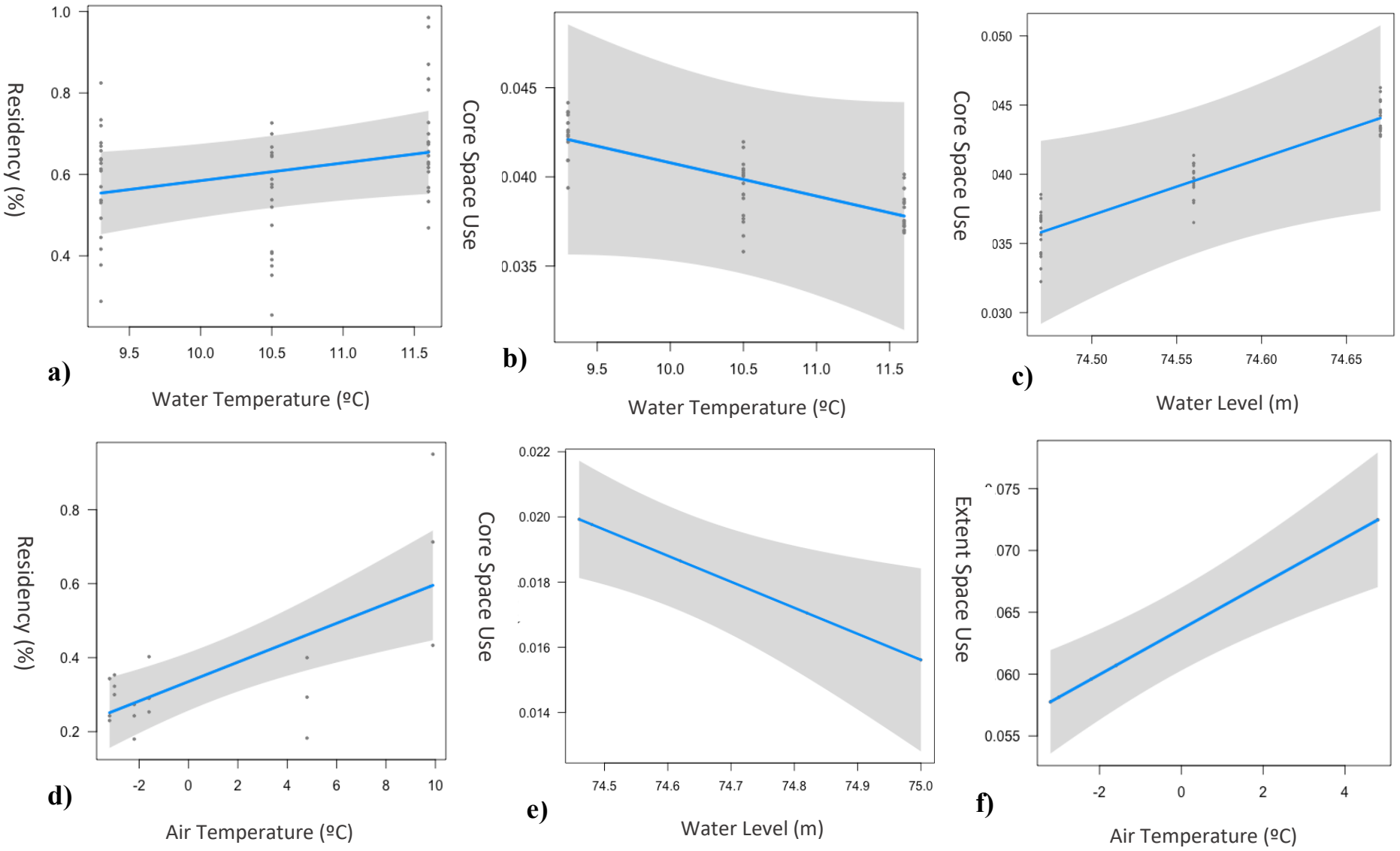
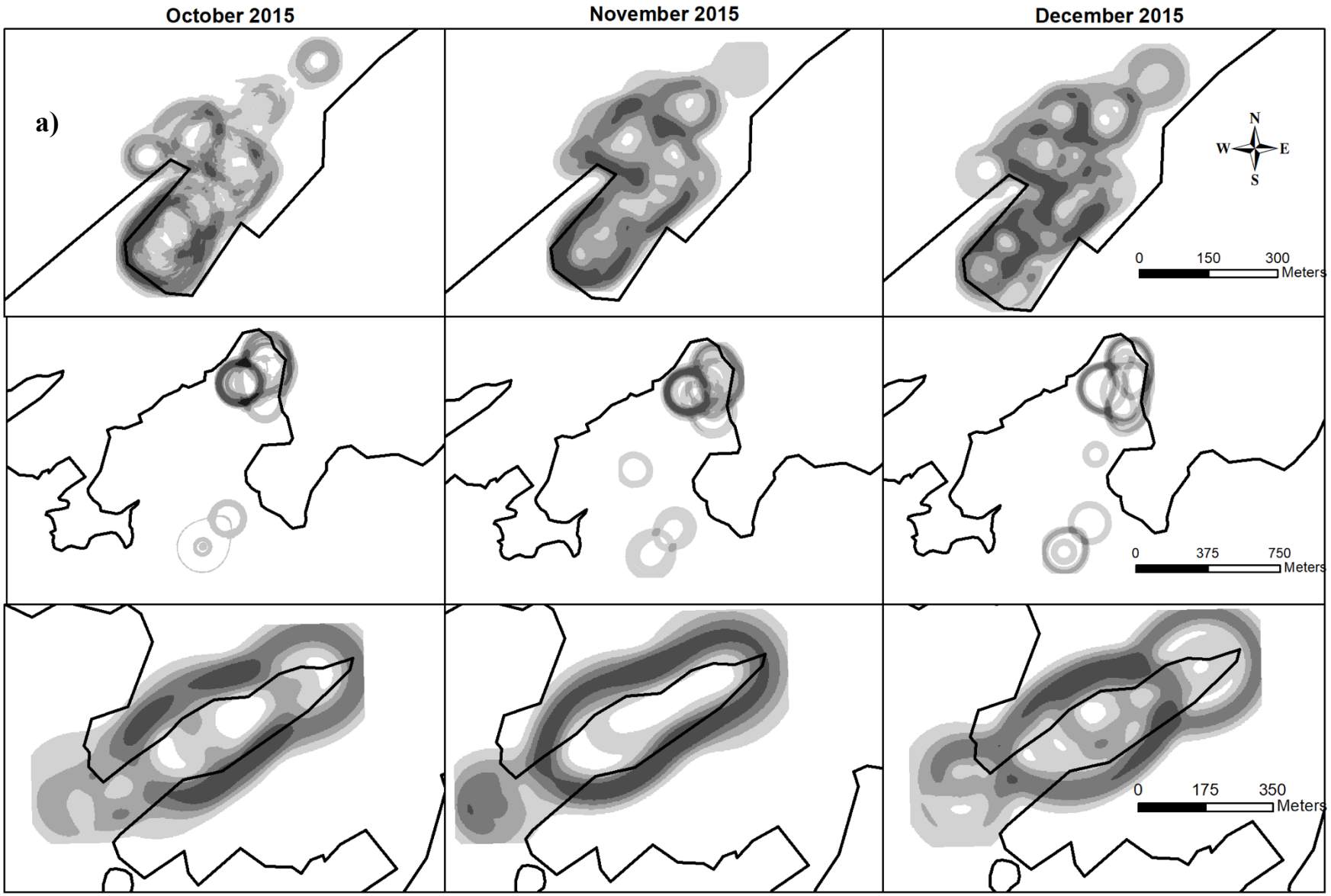


Figure 3.2. Significant relationships in residency (RI) and space use were observed for age-0 Muskellunge in Rose Bay in 2015 and 2016/17 on a monthly basis. Each graph represents a separate statistical model. Dots represent individual RI and space use values at monthly water temperature and water levels; a) residency increased with warmer water temperatures in fall months, while b) core space use decreased with increased water temperatures and c) higher water levels. In 2016/17, d) residency increased with water temperatures, e) core space use became variable with high water levels, and f) extent increased with higher water temperatures.


October 2015
November 2015
December 2015
a)
N
W
E
S
0 150 300
Meters
0 375 750
Meters
0 175 350
Meters

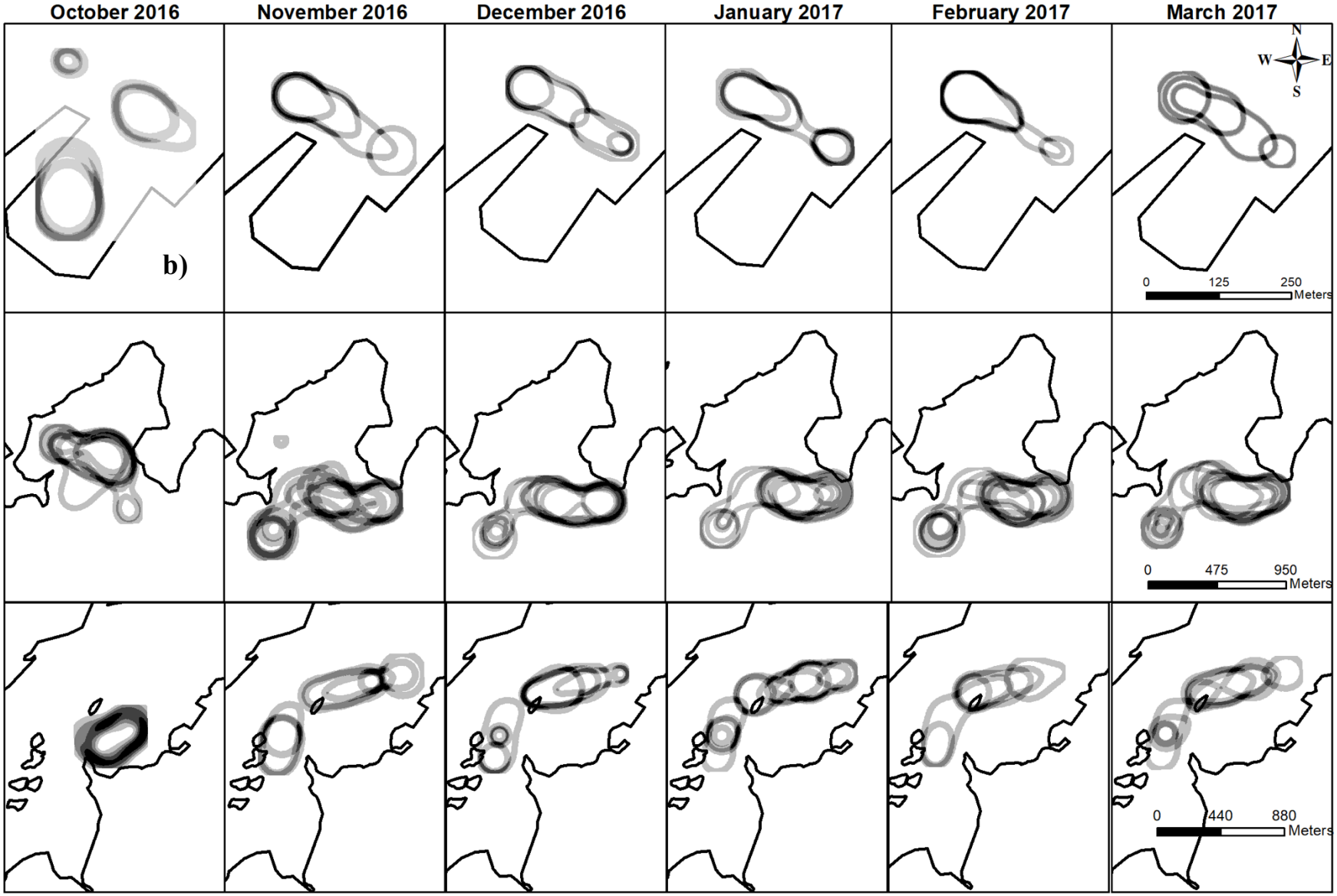


Figure 3.3. Core space use (km^2 - 50% KUD) by age-0 Muskellunge and Northern Pike in the upper St. Lawrence River in a) 2015 and b) 2016 and 2017. Darker circles denote areas heavily used by fish based on a monthly analysis for a) Rose (top), Flynn (middle) and Buck (bottom) and b) Rose (top), Flynn (middle) and Grass Point (bottom).

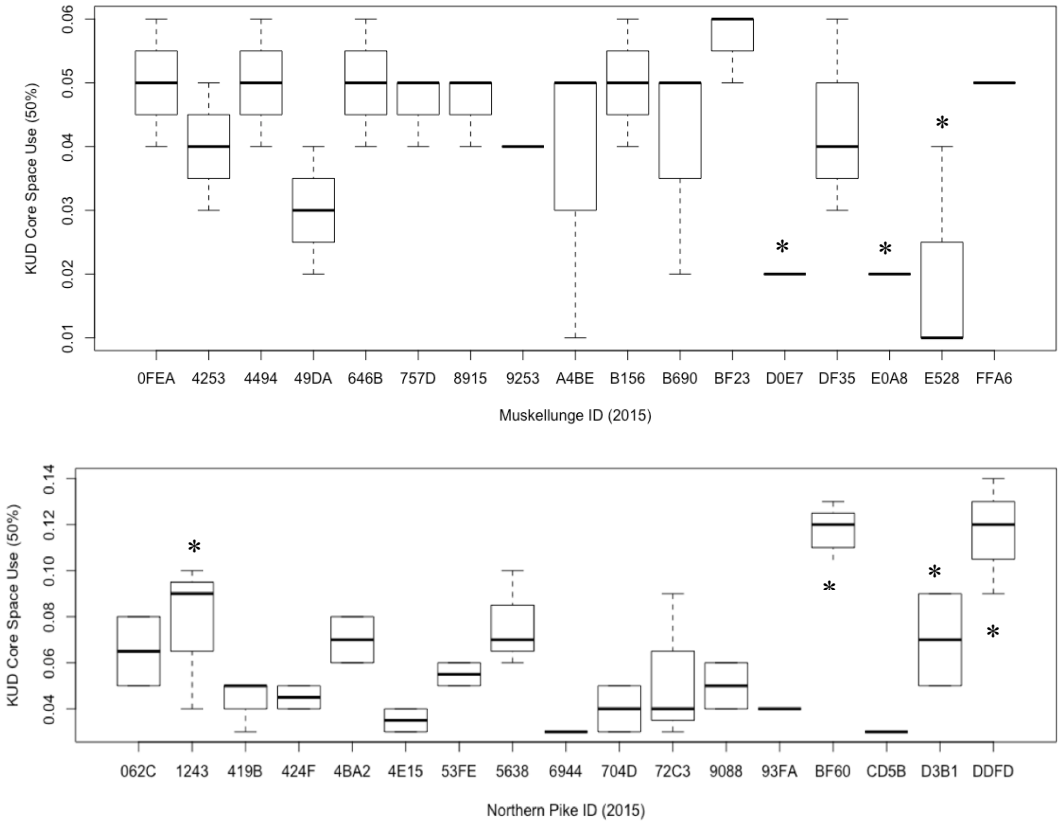


Figure 3.4. Significant differences in core use (km^2 - 50% KUD) between muskellunge in Rose Bay, 2015 (top) and Northern pike in Flynn Bay, 2015 (bottom). Three muskellunge (BF60, D3B1 and DDF) had significantly larger core use areas, relative to conspecifics. Four Northern pike (49DA, D0E7, E0A8, and E528) had significantly smaller core use areas, relative to conspecifics. Total length did not influence core use size between fish. Fish with significant differences are denoted by a star, above or below their boxplot.

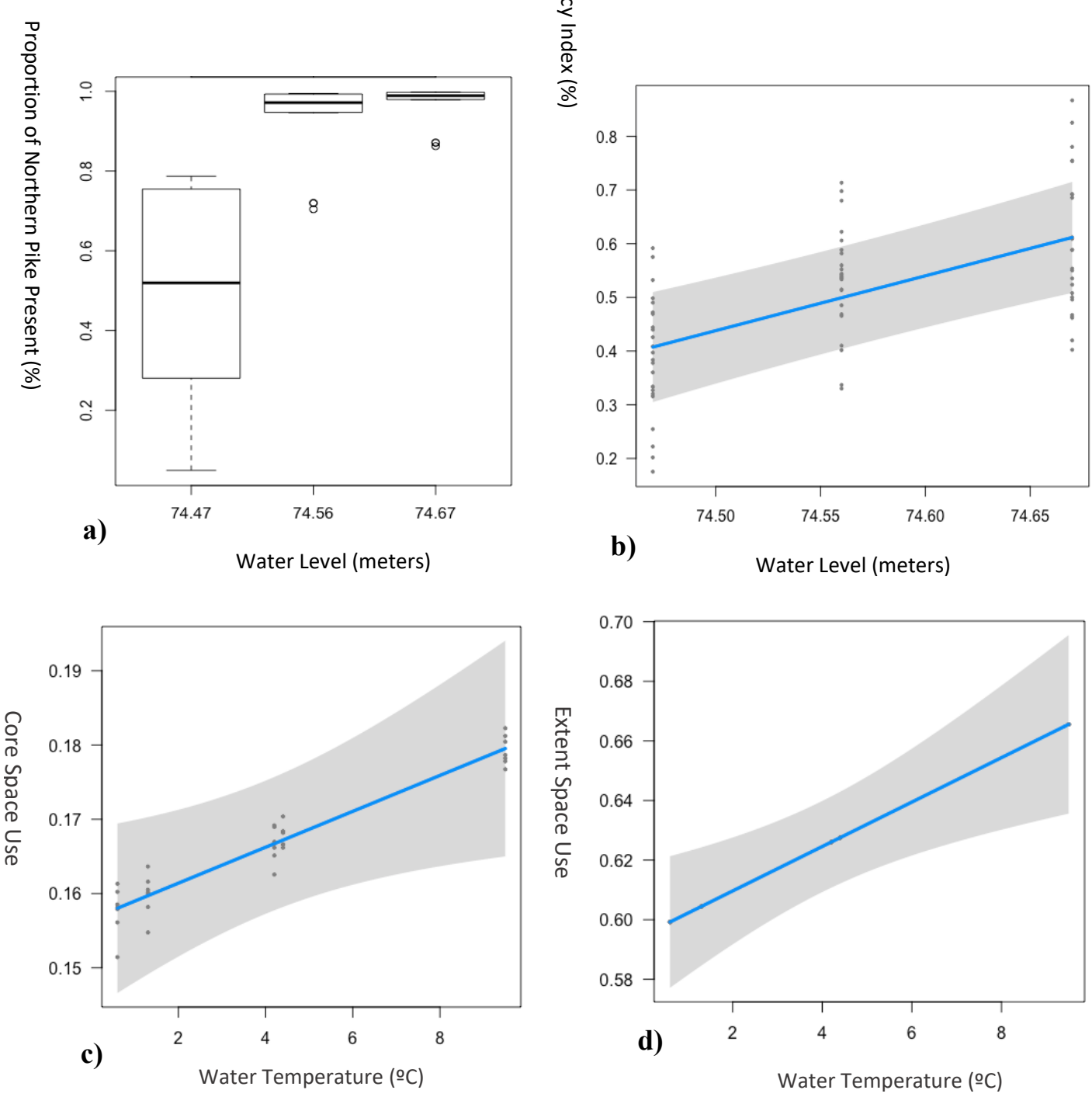


Figure 3.5. The significant effects of water levels and temperature on spatial ecology of age-0 Northern Pike in 2015; a) the proportion of age-0 Northern Pike relative to water levels managed by the IJC was significantly more variable below 74.5 meters, while b) the residency index of age-0 Northern Pike in Flynn Bay in 2015 significantly increased as water levels increased above 74.5 meters**.** **C**ore space use (c) and extent (d) Northern significantly increased with higher air temperatures in fall months (core space, $x^2 = 5.4234$, $p = 0.020$; extent $x^2 = 9.3907$, $p = 0.002$).

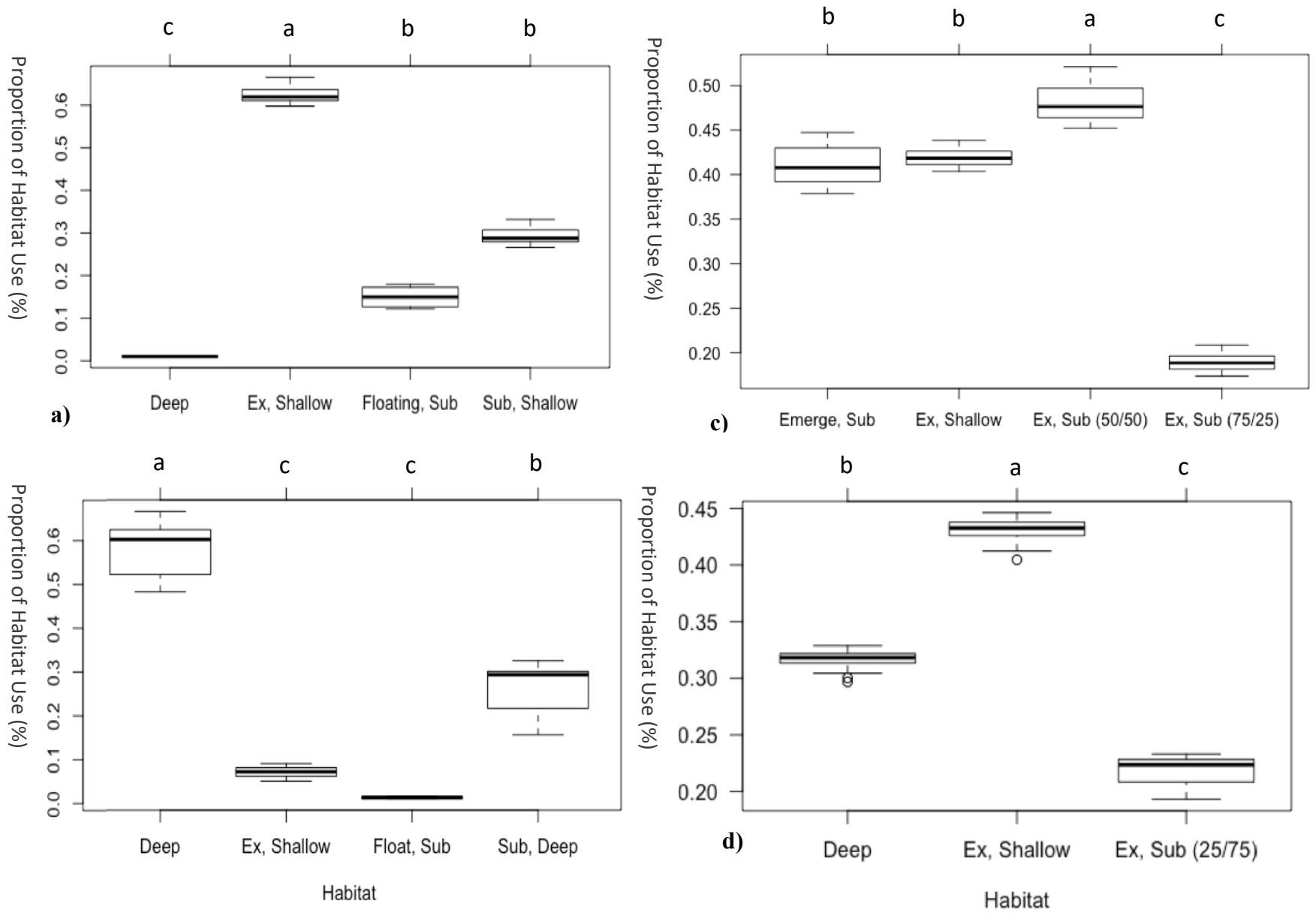


Figure 3.6. Boxplots indicating significant differences in proportional habitat use by age-0 Muskellunge in (a) Buck Bay in 2015 and (b) Grass Point Bay from 2016 to 2017), and for age-0 Northern Pike within (c) Flynn Bay in 2015 and (d) Flynn Bay from 2016 to 2017. Letters indicate how habitats are grouped with respect to their level of significance. Deeper regions were most used by Rose Muskellunge (>90%) compared to Float, Sub.

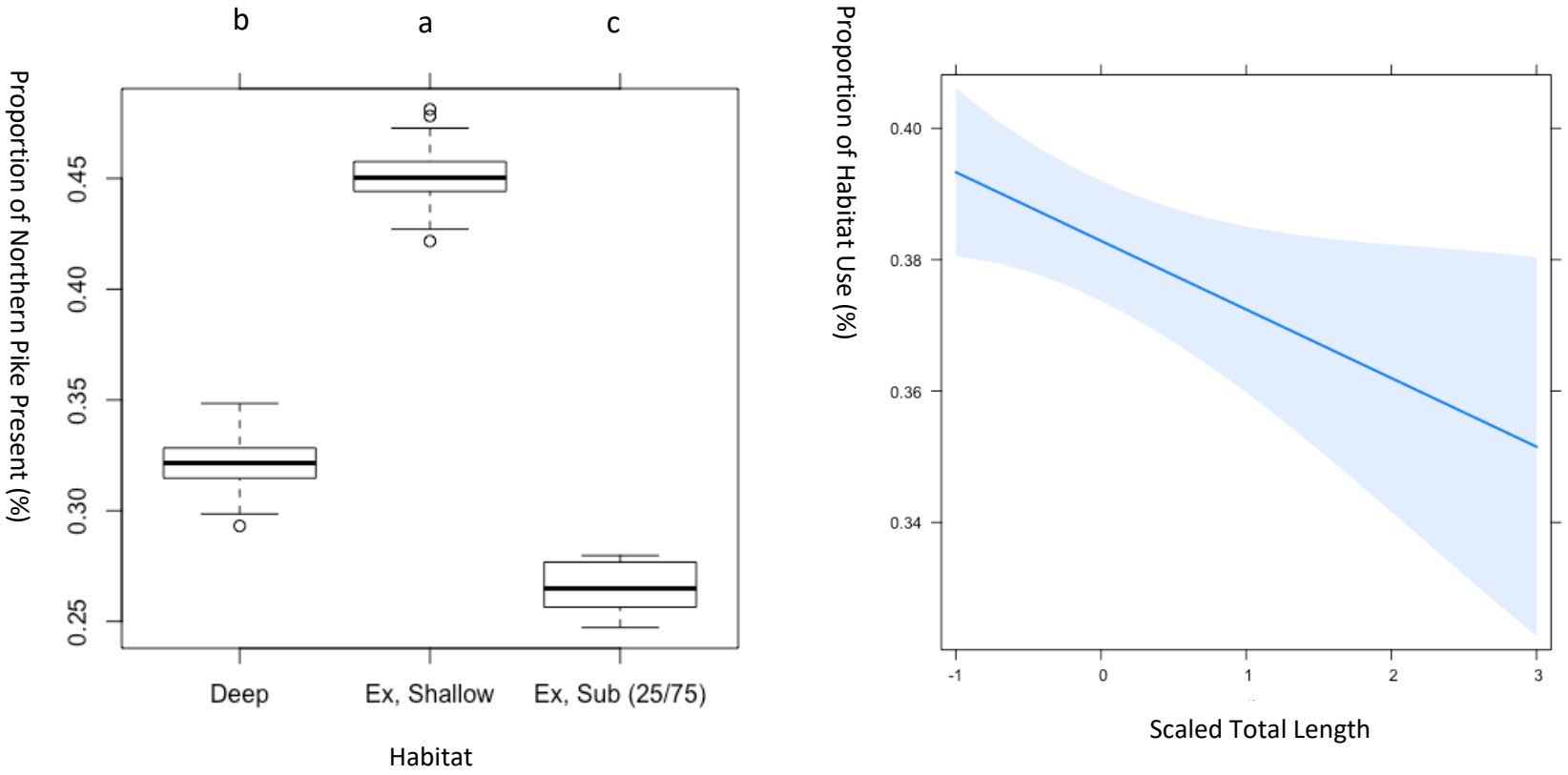


Figure 3.7. A) Boxplot indicating significant differences in proportional habitat use by age-1 Northern Pike from 2016 to 2017. Letters indicate how habitats are grouped with respect to their level of significance; B) Total length was found a significant predictor of proportional habitat use by age-1 Northern Pike; the lower the habitat use (e.g. deep zone, exposed with SAV), the larger the fish.

Table 3.7. Detection and space use information for age-0 Muskellunge monitored in the upper St. Lawrence River over two different years. Fish captured in 2015 were tracked between October and December, and those in September 2016 from October 2016 to March 2017. Core use (± SE) and Extent (± SE) represent the mean 50% and 95% KUDs for each bay. Monthly residency Index was calculated using the consecutive number of days fish were detected by the number of days the array was active. The bracketed residency index values for fish monitored in 2016/17 were divided by the number of receivers deployed each month, to ensure a reduction in detections was not due to the reduction in number of receivers from October to November through March, and to confirm a natural pattern rather than an artefact of the array.

Year	Bay	Size (ha)	No. Fish	Total Length ± SD (mm)	Weight ± SD (g)	Number of Detections	Number of Detections ± SD	Core Use (km^2) ± SE	Extent (km^2) ± SE	Number of Days Array Active	Consecutive Days Present	Residency Index ± SD
2015	Flynn	74	15	234 ± 55.2	83 ± 64.2	18 691	788 ± 812	0.06 ± 0.005	0.32 ± 0.02	71	0 - 70	0.53 ± 5.6
	Rose	9	20	151 ± 19.4	18 ± 6.5	45 760	577 ± 1 125	0.04 ± 0.002	0.16 ± 0.004	71	2 - 45	0.64 ± 5.4
	Buck	18	7	164 ± 23.5	19 ± 7.8	566	81 ± 42	0.13 ± 0.005	0.50 ± 0.01	70	2 - 18	0.54 ± 0.2
2016	Flynn	74	16	227 ± 38.3	85 ± 47.2	1 074	80 ± 102	0.18 ± 0.01	0.62 ± 0.008	178	9 - 165	0.49 ± 0.21 [0.06 ± 0.03]
	Rose	9	4	182 ± 45.5	35 ± 28.5	761	143 ± 127	0.02 ± 0.008	0.06 ± 0.002	180	31 - 86	0.40 ± 0.21 [0.09 ± 0.03]
	Grass	47	5	174 ± 33.5	32 ± 11.9	661	98 ± 102	0.11 ± 0.004	0.49 ± 0.01	170	0 - 12	0.38 ± 0.27 [0.05 ± 0.04]

Table 3.8. Detection and biological data for individual age-0 Muskellunge monitored in the upper St. Lawrence River from October to December 2015. The total number of detections are those of individual fish after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other. Residency Index (%) was the number of days detected by array days. Fish greyed out were not used in residency, space or habitat use analyses, as they were detected <7 days in October or November (or <2 days in December), or less than two consecutive months. Muskellunge 875E was captured in Flynn and released in Buck Bay.

JSAT TAG ID	Total Length ± SD (mm)	Weight ± SD(g)	Capture Date	Capture Bay	Total Number of Detections	Total Days Detected	Cumulative Days Detected	Residency Index (%)
F50E	177	23.2	2015-09-11	BUCK	37	26	2	37
AEF1	158	17.1	2015-09-11	BUCK	102	40	18	57
C687	181	26.1	2015-09-12	BUCK	95	42	6	60
5859	167	19.4	2015-09-12	BUCK	39	29	5	41
DF35	125	10.6	2015-09-16	ROSE	62	36	5	51
BD92	150	19.6	2015-09-16	ROSE	96	35	3	49
646B	145	17.0	2015-09-16	ROSE	95	41	4	58
0FEA	140	17.1	2015-09-16	ROSE	375	70	25	99
49DA	122	8.6	2015-09-16	ROSE	711	49	27	69
A4BE	160	25.4	2015-09-16	ROSE	3 989	45	17	63
BF23	148	19.6	2015-09-16	ROSE	314	66	28	93
DA2A	149	16.2	2015-09-16	ROSE	30	26	2	37
B690	126	12.0	2015-09-16	ROSE	503	42	9	59
4494	134	13.9	2015-09-16	ROSE	71	42	6	59
757D	125	7.5	2015-09-16	ROSE	100	50	10	70
F3B8	195	27.8	2015-09-17	BUCK	104	45	6	64
E6CC	127	7.27	2015-09-17	BUCK	43	30	2	43
730C	143	10.4	2015-09-17	BUCK	146	63	14	90
875E	**223**	**45.8**	**2015-09-18**	***FLYNN**	**123**	**44**	**8**	**63**

64E7	156	18.0	2015-09-19	ROSE	111	34	4	48
3915	158	17.9	2015-09-19	ROSE	0	0	0	0
D0E7	171	27.2	2015-09-19	ROSE	16 385	61	35	86
FFA6	156	19.4	2015-09-19	ROSE	155	64	32	90
4253	185	31.1	2015-09-19	ROSE	75	39	3	55
B156	174	25.5	2015-09-19	ROSE	42	33	4	46
E0A8	170	21.7	2015-09-19	ROSE	8 339	69	43	97
9253	179	26.7	2015-09-19	ROSE	31	24	2	34
E528	162	21.0	2015-09-19	ROSE	12 575	47	37	66

Table 9.3. Detection and biological data for individual age-0 Northern pike monitored in the upper St. Lawrence River from October to December 2015. Total number of detections is the total number of detections collected from an individual fish, after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other. Residency Index (%) was the number of days detected by array days. Fish grey out were not used in analyses (residency, space or habitat use) as they either died prior to tracking due to surgery or were detected <7 days in October or November (or <2 days in December), or less than two consecutive months. Fish 6944 and CD5B were detected solely in November.

JSAT TAG ID	Total Length ± SD (mm)	Weight ± SD(g)	Capture Date	Capture Bay	Total Number of Detections	Total Days Detected	Cumulative Days Detected	Residency Index (%)
4BA2	298	155	2015-09-26	FLYNN	20	16	0	23
6BA2	301	145	2015-09-26	FLYNN	336	22	3	31
BF60	380	290	2015-09-26	FLYNN	120	62	15	87
99EB	146	18.5	2015-09-26	FLYNN	14	13	0	18
DDFD	171	26.8	2015-09-26	FLYNN	295	71	70	100
419B	255	87	2015-09-26	FLYNN	2 982	63	17	89
AA29	247	85.0	2015-09-26	FLYNN	23	11	29	15
704D	241	80.0	2015-09-26	FLYNN	2 005	55	24	77
*6944	356	235	2015-09-26	FLYNN	300	28	4	39
93FA	222	59.3	2015-09-26	FLYNN	2 314	59	18	83
1243	210	49.7	2015-09-28	FLYNN	831	40	8	56
424F	215	57.0	2015-09-28	FLYNN	417	27	7	38
9088	235	78.7	2015-09-28	FLYNN	801	43	12	61
53FE	205	51.6	2015-09-28	FLYNN	1 271	46	8	65
062C	200	43.5	2015-09-28	FLYNN	83	29	12	41

5638	172	27.0	2015-09-28	FLYNN	857	58	18	82
72C3	216	57.0	2015-09-28	FLYNN	1 451	58	24	82
A6AE	240	76.3	2015-09-28	FLYNN	311	21	9	30
CF7F	247	93.4	2015-09-28	FLYNN	521	53	8	75
4E15	250	105	2015-09-28	FLYNN	630	0	0	0
D3B1	252	95.0	2015-09-28	FLYNN	51	23	2	32
*CD5B	213	56.0	2015-09-28	FLYNN	1 286	43	26	61
C57F	275	120	2015-09-28	FLYNN	1 744	33	19	46

Table 3.10. Detection and biological data for individual age-0 Muskellunge tracked in their natal embayment from November 2016 to March 2017. Total number of detections is the total number of detections collected from an individual fish, after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other. Residency Index (%) was the number of days detected by array days. Fish grey out were not used in analyses (residency, space or habitat use) as they were detected <7 days per month, or less than two consecutive months. Muskellunge A76D was first tagged as 933D on September 9, 2016.

Species	JSAT TAG ID	Total Length ± SD (mm)	Weight ± SD(g)	Capture Date	Capture Bay	Total Number of Detections Nov to Mar	Total Days Detected	Cumulative Days Detected	Residency Index (%)
Musky	**933D	156	18.0	2016-09-06	ROSE	70	6	0	4
Musky	3605	168	25.5	2016-09-06	ROSE	59	46	2	31
Musky	0274	118	11.9	2016-09-07	GRASS	78	55	3	12
Musky	07DE	196	41.5	2016-09-07	GRASS	374	144	21	96
Musky	33F4	176	32.1	2016-09-07	GRASS	73	45	4	30
Musky	30EC	155	18.0	2016-09-12	ROSE	59	45	3	30
Musky	790D	154	18.0	2016-09-21	FLYNN	19	20	1	13
Musky	AAD4	178	32.8	2016-09-29	GRASS	25	23	1	15
Musky	D14F	203	40.4	2016-10-06	GRASS	61	48	3	32
Musky	810C	250	78.5	2016-10-07	ROSE	84	67	5	45
Musky	**A76D	234	67.5	2016-10-07	ROSE	46	11	0	7

Table 3.5. Detection and biological data for individual age-0 Northern Pike tracked in their natal embayment, November 2016 to March 2017. Number of detections is the total number of detections collected from an individual fish, after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other. Residency Index (%) was the number of days detected by array days. Fish grey out were not used in analyses (residency, space or habitat use) as they were detected <7 days per month, or less than two consecutive months.

Species	JSAT TAG ID	Total Length ± SD (mm)	Weight ± SD(g)	Capture Date	Capture Bay	Number of Detections Nov to Mar	Total Days Detected	Cumulative Days Detected	Residency Index (%)
N. Pike	413E	263	118.0	2016-09-21	FLYNN	77	64	7	43
N. Pike	38C3	250	110.5	2016-09-21	FLYNN	79	52	3	34
N. Pike	4D88	310	202.8	2016-09-21	FLYNN	61	50	3	33
N. Pike	†EC39	259	115.5	2016-09-21	FLYNN	38	35	4	23
N. Pike	†F603	254	105.6	2016-09-21	FLYNN	140	92	7	61
N. Pike	91FA	205	58.4	2016-09-21	FLYNN	22	21	0	14
N. Pike	36B8	179	40.1	2016-09-21	FLYNN	31	25	1	17
N. Pike	5A49	235	89.8	2016-09-21	FLYNN	11	8	0	5
N. Pike	69B5	216	67.5	2016-09-21	FLYNN	7	7	0	5
N. Pike	1A2B	219	66.8	2016-09-21	FLYNN	29	27	1	18
N. Pike	0351	183	38.0	2016-09-21	FLYNN	95	68	6	45
N. Pike	92F2	222	78.0	2016-09-21	FLYNN	18	16	1	11
N. Pike	4317	195	43.8	2016-09-21	FLYNN	77	57	3	38
N. Pike	0219	215	70.8	2016-09-21	FLYNN	358	139	31	93
N. Pike	196A	197	47.8	2016-09-21	FLYNN	19	19	1	9

Table 3.6. Detection and biological data for individual age-1 Muskellunge monitored in Rose Bay from November 2016 to March 2017. Number of detections is the total number after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other. Residency Index (%) was the number of days detected by array days. Fish grey out were not used in analyses (residency, space or habitat use) as they were detected <7 days per month, or less than two consecutive months.

JSAT TAG ID	Total Length ± SD (mm)	Weight ± SD(g)	Capture Date	Capture Bay	Number of Detections	Days Detected	Cumulative Days Detected	Residency Index (%)
DF35	125	10.6	2015-09-16	ROSE	27	16	2	11
BD92	150	19.6	2015-09-16	ROSE	14	11	0	7
646B	145	17.0	2015-09-16	ROSE	29	17	2	11
0FEA	140	17.1	2015-09-16	ROSE	232	113	13	75
49DA	122	8.6	2015-09-16	ROSE	18	12	2	8
A4BE	160	25.4	2015-09-16	ROSE	12	9	0	6
BF23	148	19.6	2015-09-16	ROSE	77	49	3	33
DA2A	149	16.2	2015-09-16	ROSE	14	11	2	7
B690	126	12.0	2015-09-16	ROSE	26	5	2	3
4494	134	13.9	2015-09-16	ROSE	41	26	2	17
757D	125	7.5	2015-09-16	ROSE	44	35	3	23
64E7	156	18.0	2015-09-19	ROSE	63	38	2	25
3915	158	17.9	2015-09-19	ROSE	0	0	0	0
D0E7	171	27.2	2015-09-19	ROSE	26	22	1	15
FFA6	156	19.4	2015-09-19	ROSE	74	46	6	31
4253	185	31.1	2015-09-19	ROSE	22	17	2	11
B156	174	25.5	2015-09-19	ROSE	26	19	2	13
E0A8	170	21.7	2015-09-19	ROSE	29	23	2	15
9253	179	26.7	2015-09-19	ROSE	15	14	1	9
E528	162	21.0	2015-09-19	ROSE	6	5	0	3

Table 3.7. Detection and biological data for individual age-1 Northern Pike monitored in Flynn Bay. Number of detections is the total number after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other. Residency Index (%) was the number of days detected by array days. Fish grey out were not used in analyses (residency, space or habitat use) as they were detected <7 days per month, or less than two consecutive months.

JSAT TAG ID	Total Length ± SD (mm)	Weight ± SD(g)	Capture Date	Capture Bay	Number of Detections	Days Detected	Cumulative Days Detected	Residency Index (%)
4BA2	298	155	2015-09-26	FLYNN	43	39	1	26
6BA2	301	145	2015-09-26	FLYNN	13	13	1	9
BF60	380	290	2015-09-26	FLYNN	275	143	13	95
99EB	146	18.5	2015-09-26	FLYNN	38	33	2	22
DDFD	171	26.8	2015-09-26	FLYNN	663	180	59	100
419B	255	87	2015-09-26	FLYNN	92	70	6	47
AA29	247	85	2015-09-26	FLYNN	6	6	0	4
704D	241	80	2015-09-26	FLYNN	25	25	2	17
6944	356	235	2015-09-26	FLYNN	40	37	2	25
93FA	222	59.3	2015-09-26	FLYNN	122	88	6	59
1243	210	49.7	2015-09-28	FLYNN	56	46	2	31
424F	215	57	2015-09-28	FLYNN	32	30	3	20
9088	235	78.7	2015-09-28	FLYNN	47	43	2	29
53FE	205	51.6	2015-09-28	FLYNN	94	74	8	49
062C	200	43.5	2015-09-28	FLYNN	54	47	6	31
5638	172	27	2015-09-28	FLYNN	198	117	10	78
72C3	216	57	2015-09-28	FLYNN	75	64	4	43
A6AE	240	76.3	2015-09-28	FLYNN	12	12	0	8
CF7F	247	93.4	2015-09-28	FLYNN	151	99	4	66
4E15	250	105	2015-09-28	FLYNN	13	13	1	9
D3B1	252	95	2015-09-28	FLYNN	67	55	3	37
CD5B	213	56	2015-09-28	FLYNN	17	16	2	11
C57F	275	120	2015-09-28	FLYNN	34	30	1	20
*875E	223	45.8	2015-09-18	*FLYNN	43	38	3	25

3.6 Supplementary

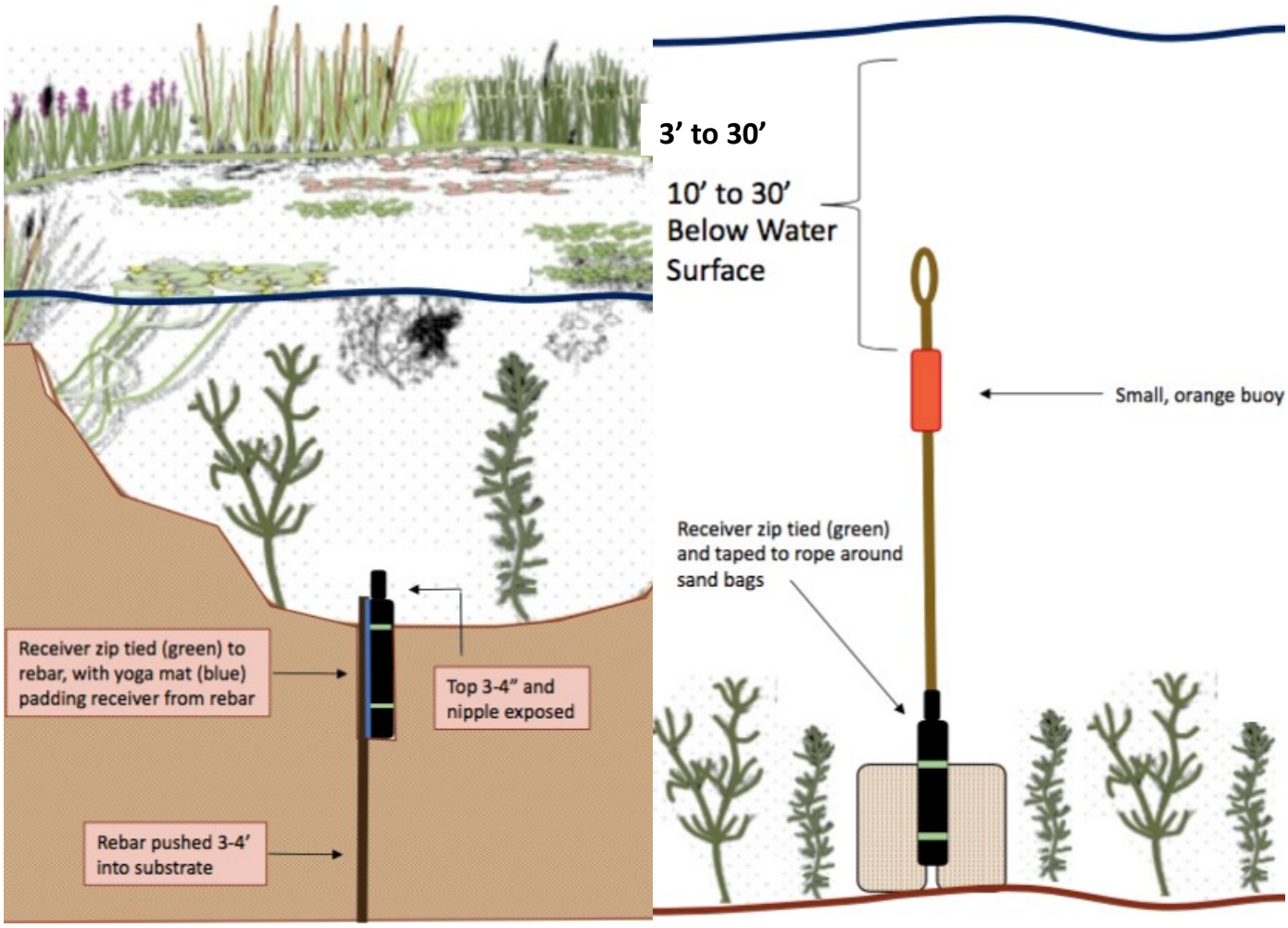


Figure S.3.1. Deployment methods for Lotek WSH4250 receivers in upper St. Lawrence River wetland nursery embayments for passive acoustic monitoring of juvenile Muskellunge and Northern Pike. Shallow (<2 meters) deployment (left) involved attaching the receiver to rebar and placing the unit into the substrate. Deeper deployment (right) involved attaching the receiver to a cobble-filled bag and buoy system. Buoys were submerged underwater by a minimum of 3 feet (1-meter).

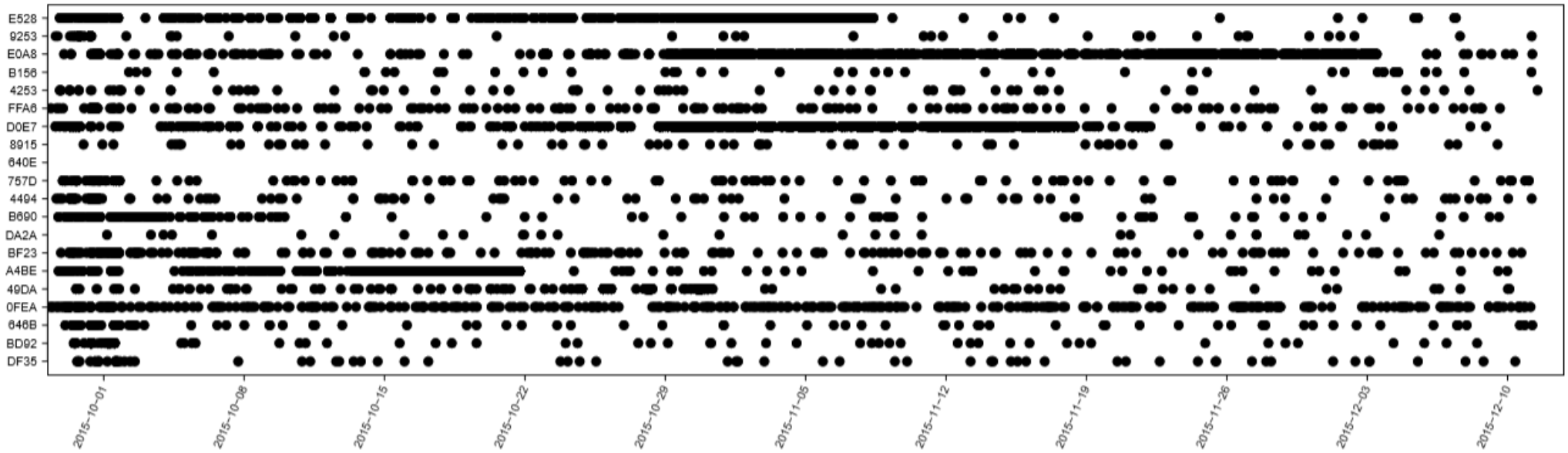


Figure S.3.2. Detections of individual age-0 Muskellunge (n = 24) in Rose Bay from October 1 to December 10, 2015. This array covered the entirety of the natal Muskellunge embayment. The X axis indicates an individual week starting on October 1, 2015.

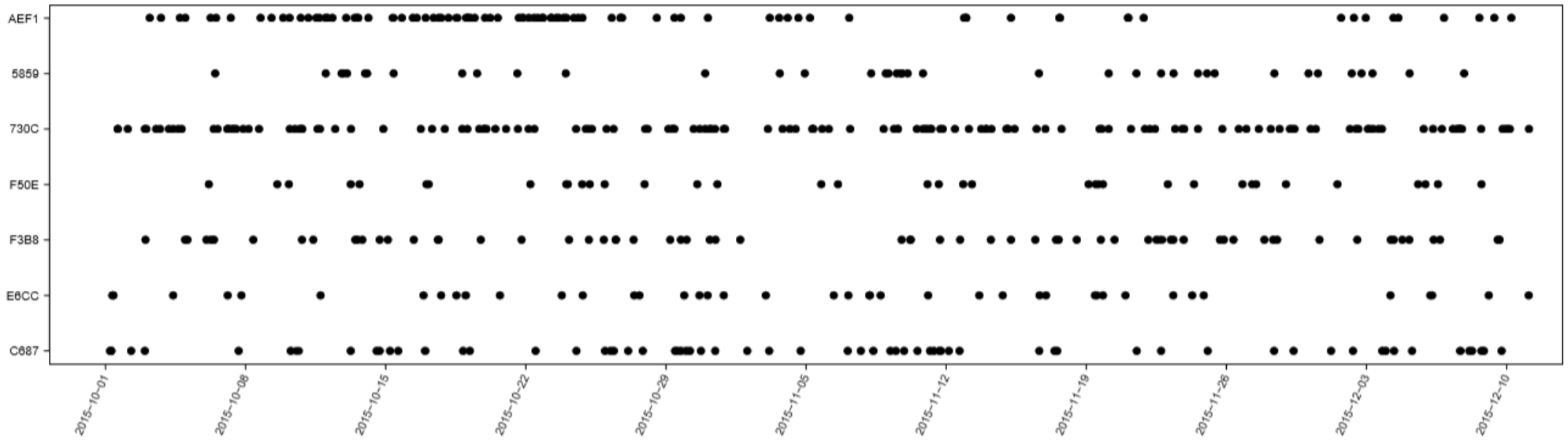


Figure S.3.3. Detections of individual age-0 Muskellunge (n = 7) in Buck Bay from October 1 to December 10, 2015. This array covered the entirety of the natal Muskellunge embayment. The X axis indicates an individual week starting on October 1, 2015.

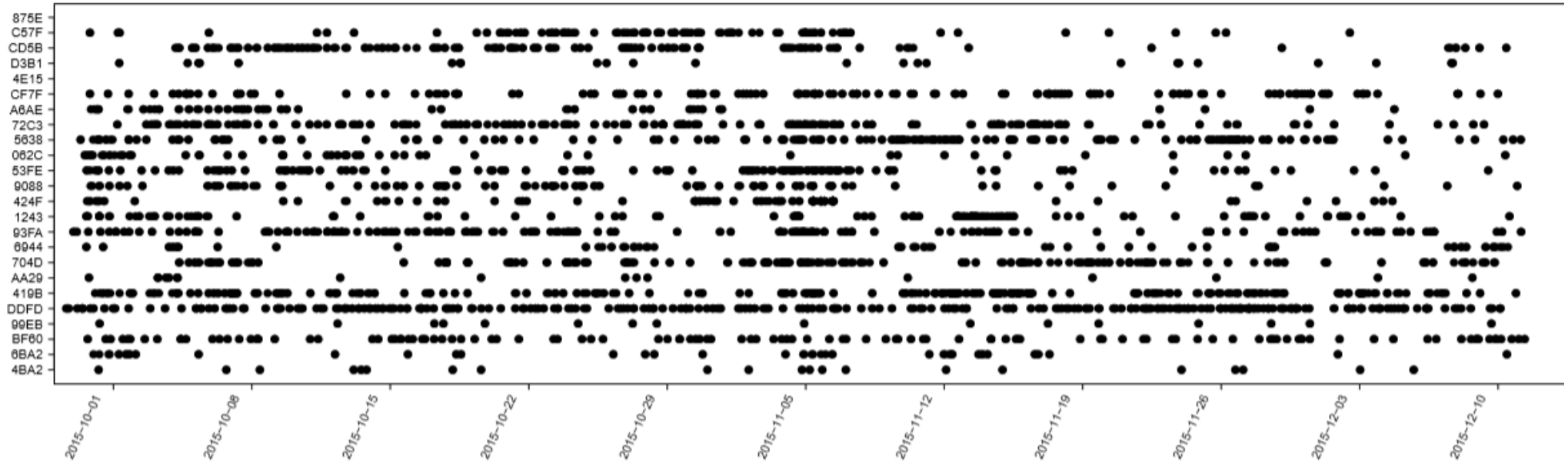


Figure S.3.4. Detections of individual age-0 Northern Pike (n = 24) in Buck Bay from October 1 to December 10, 2015. Arrays were deployed within the nearshore interior and the embayment mouth; therefore, detections could have occurred at either location. The X axis indicates an individual week starting on October 1, 2015.

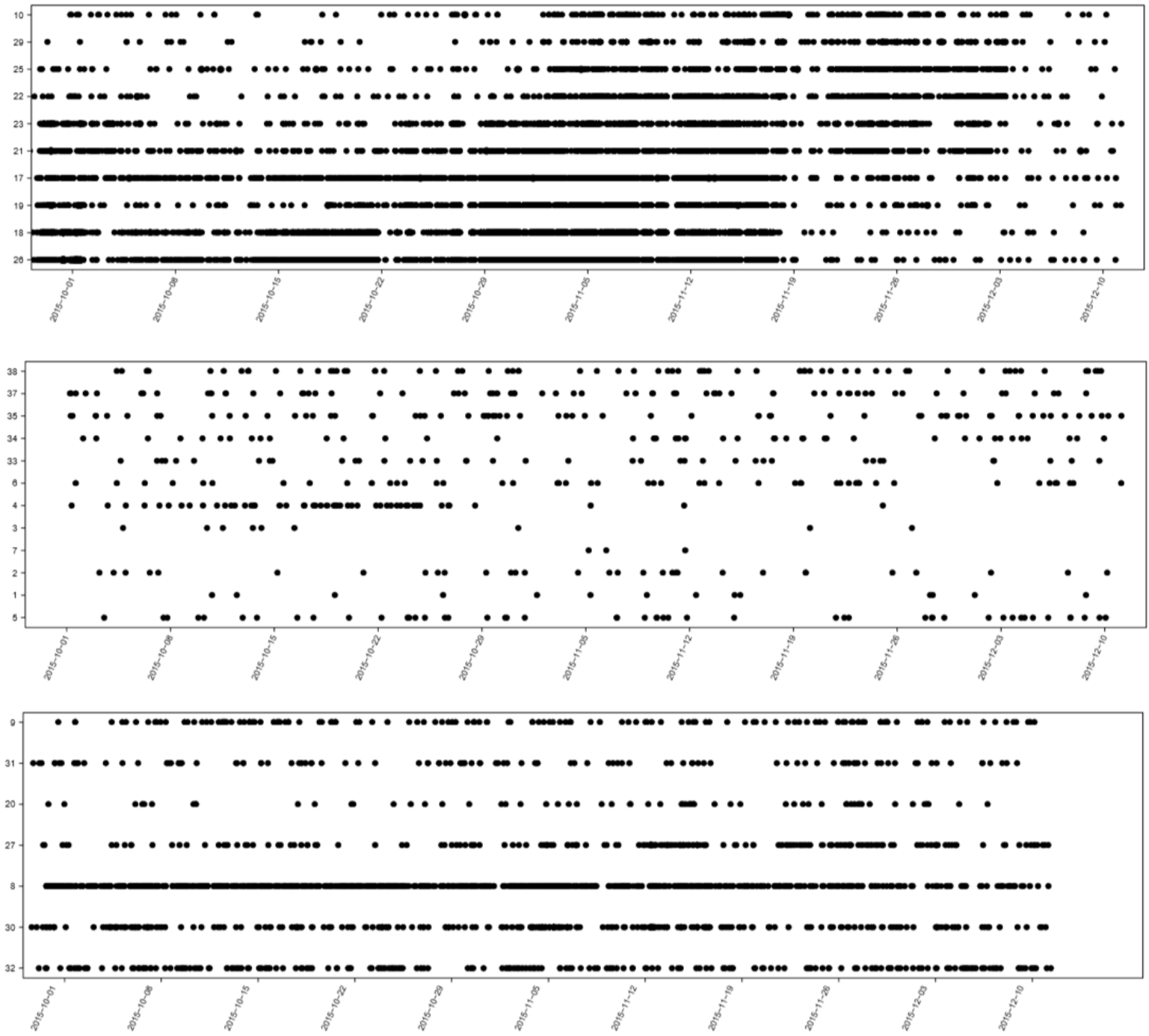


Figure S.3.5. Abacus plots indicating detections by all age-0 Muskellunge (n = 20, Rose, top; n = 7, Buck, middle) and age-0 Northern Pike (n = 15, Flynn, bottom) from October 1 to December 10, 2015. Y axis indicates fish moving out of their embayment; receiver numbers start in the nearshore (bottom) and move to deeper waters (top). The X axis indicates an individual week starting on October 1, 2015.

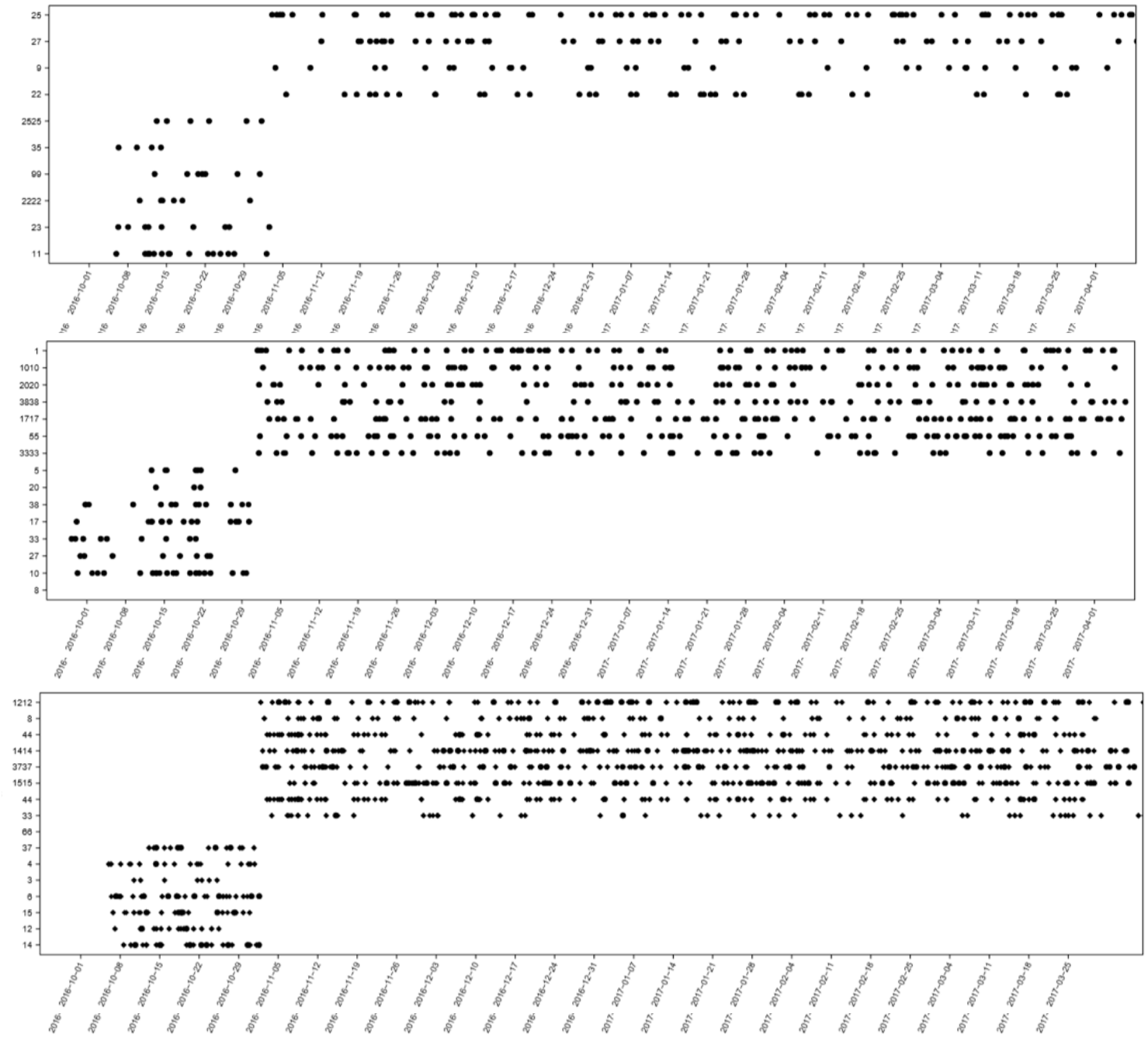
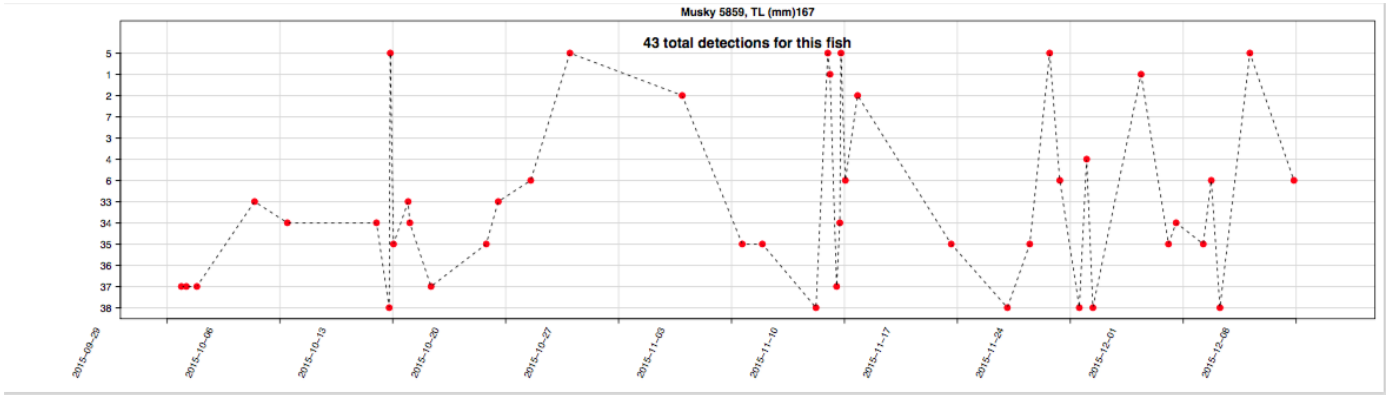
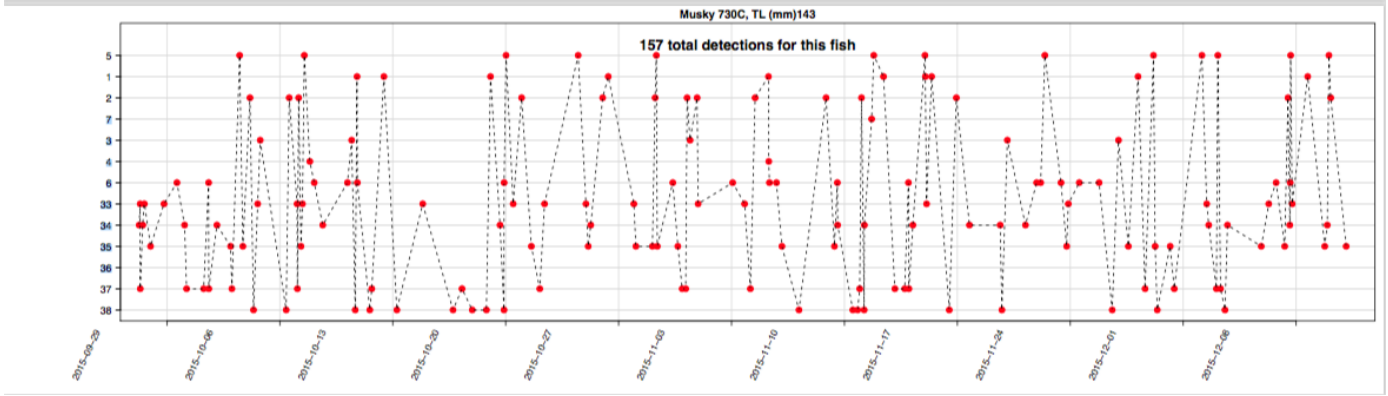
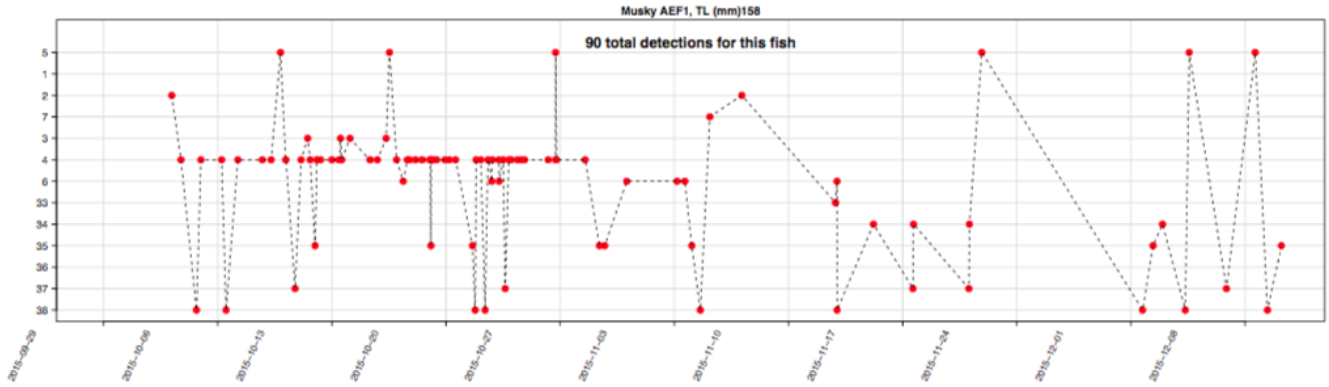
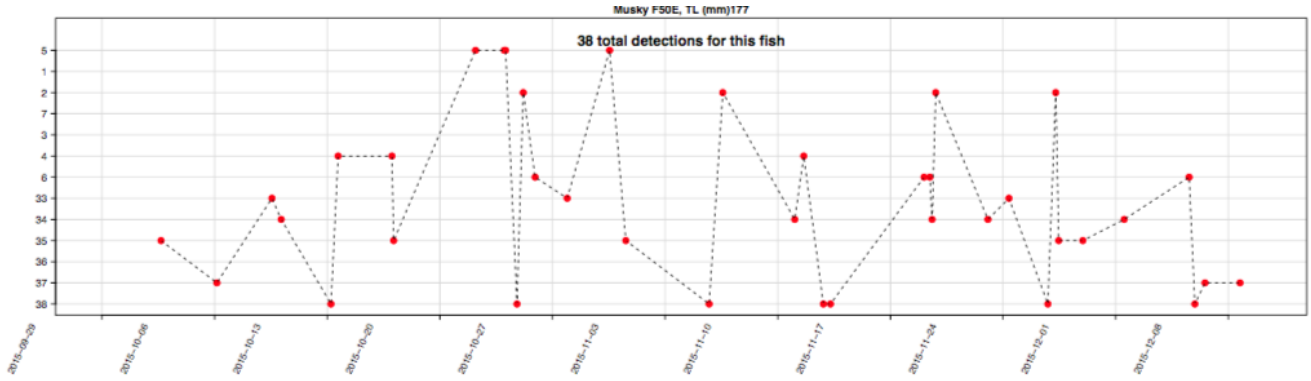


Figure S.3.6. Abacus plots indicating detections by all age-0 Muskellunge (n = 4, Rose, top; n = 5, Grass, middle) and age-0 Northern Pike (n = 15, Flynn, bottom) from October 1, 2016 to March 30, 2017. Y axis indicates fish moving out of their embayment; receiver numbers start in the nearshore (bottom) and move to deeper waters (top). The X axis indicates an individual week starting on October 1, 2015. The X axis indicates an individual week starting on October 1, 2016. Note the lack of detections in nearshore regions due to receiver deployment in deeper locations overwinter (starting November 1, 2016).


Musky 5859, TL (mm)167
43 total detections for this fish


Musky 730C, TL (mm)143
157 total detections for this fish


Musky AEF1, TL (mm)158
90 total detections for this fish


Musky F50E, TL (mm)177
38 total detections for this fish

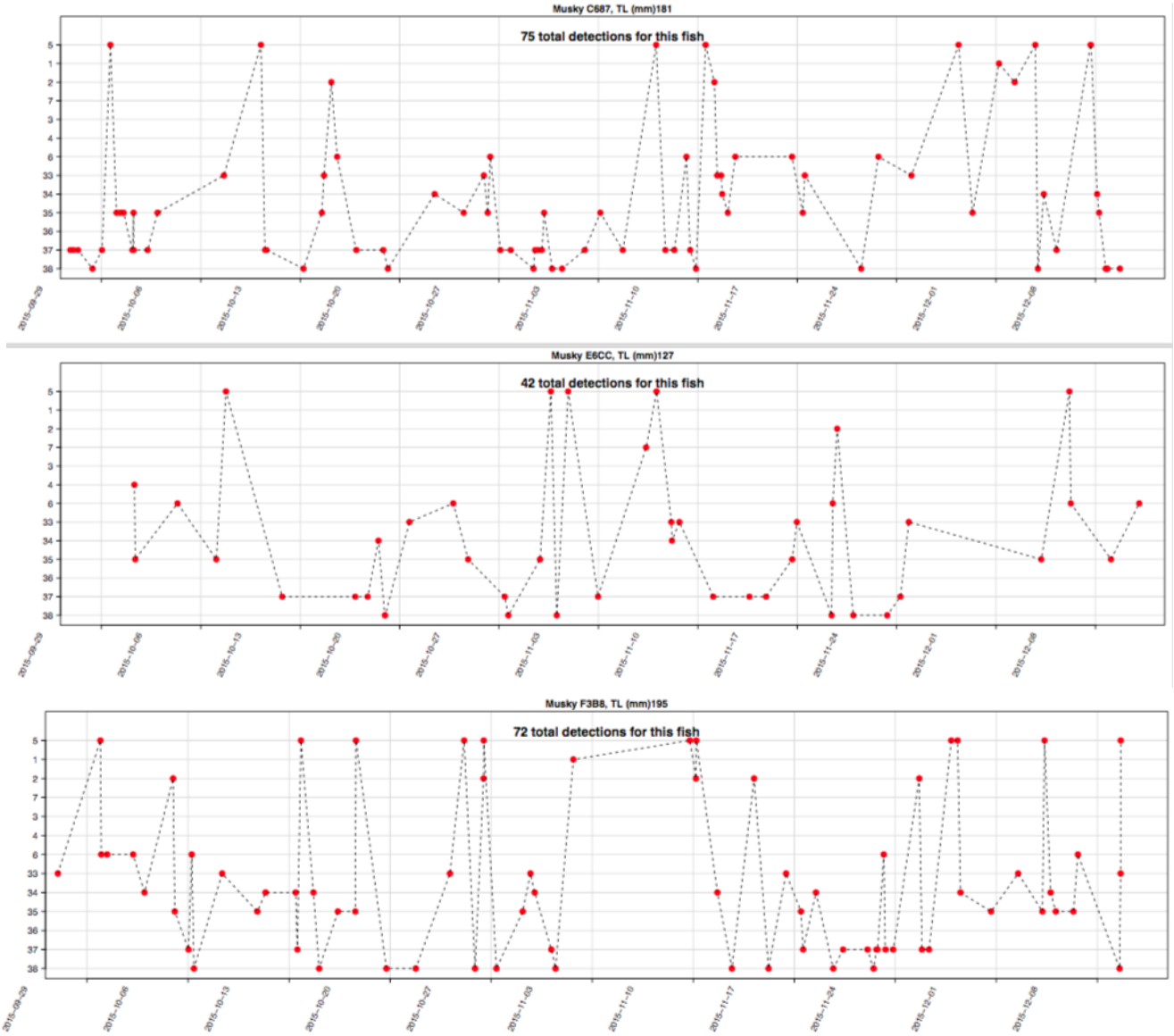
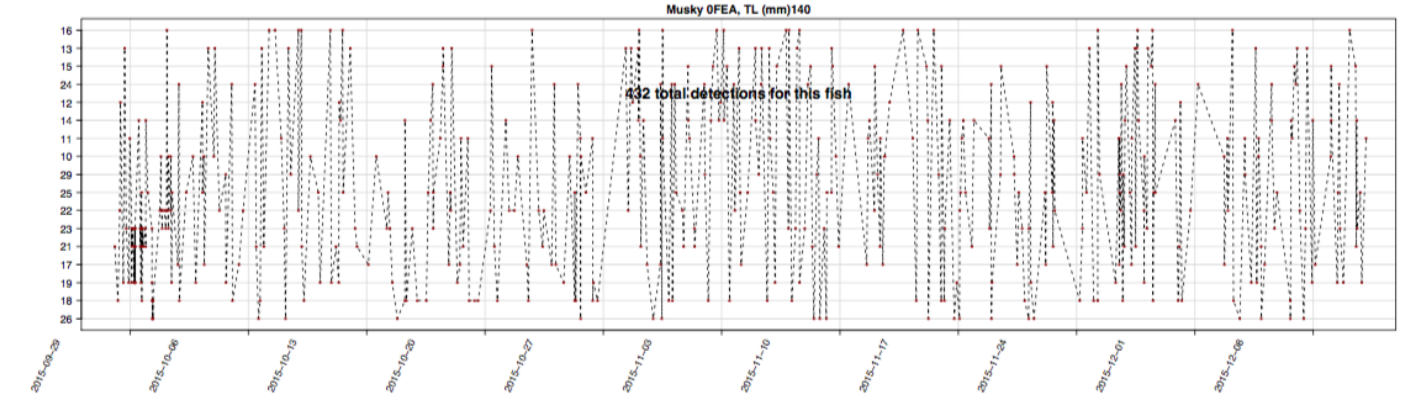
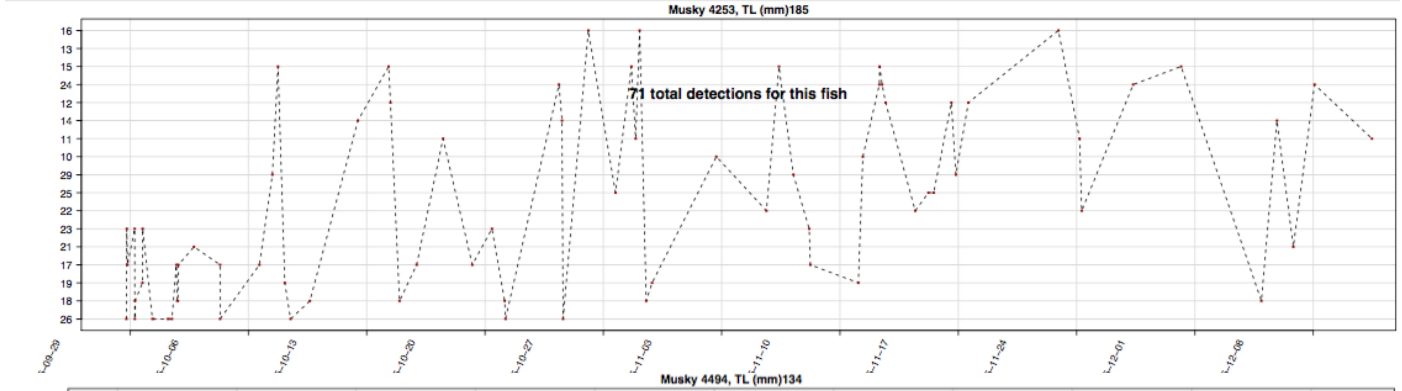
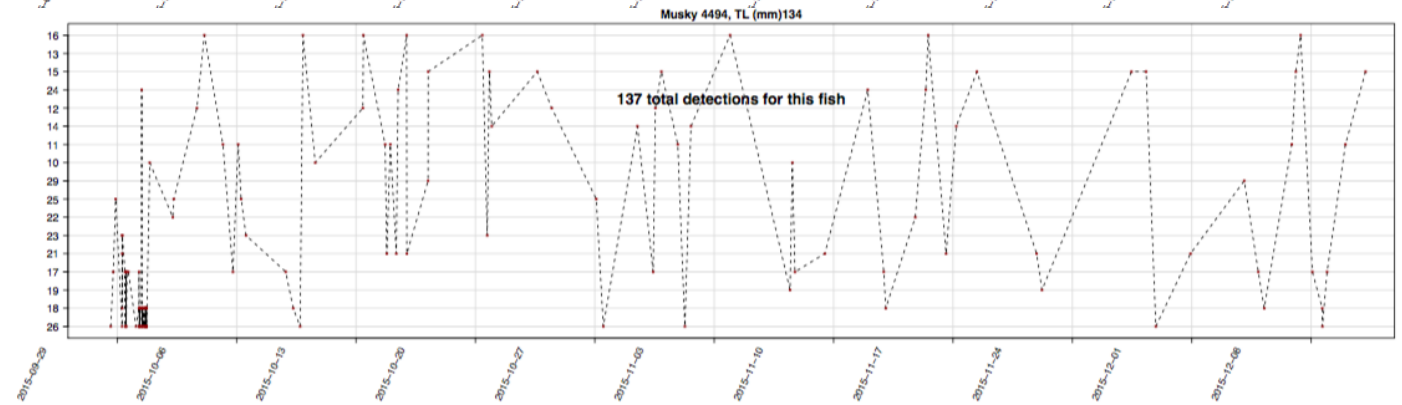
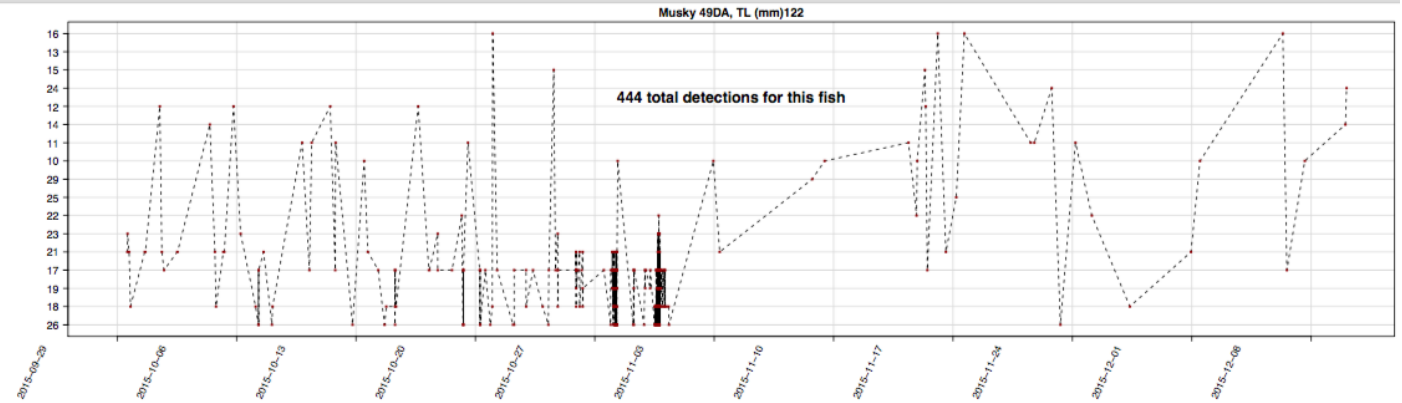


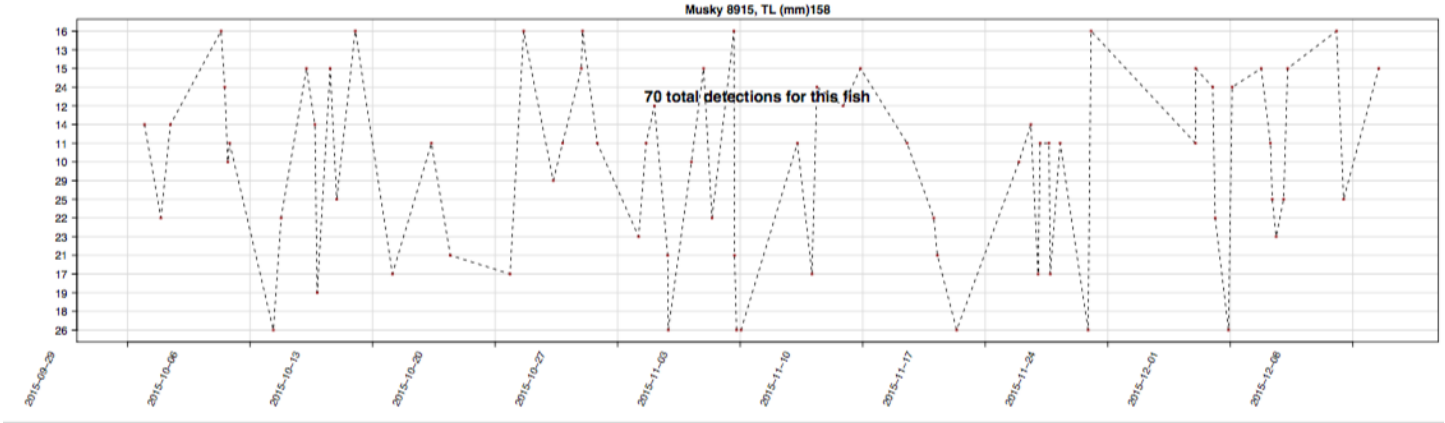
Figure S.3.7. Abacus plots for individual age-0 Muskellunge in Buck Bay (n = 7) from October 1 to December 10, 2015. Points indicate when fish were detected, and lines movement patterns between receivers from nearshore (Y axis bottom) and deeper waters (Y axis top) in the fall and early winter. Time is depicted by weeks starting with October 1, 2015 (X axis).

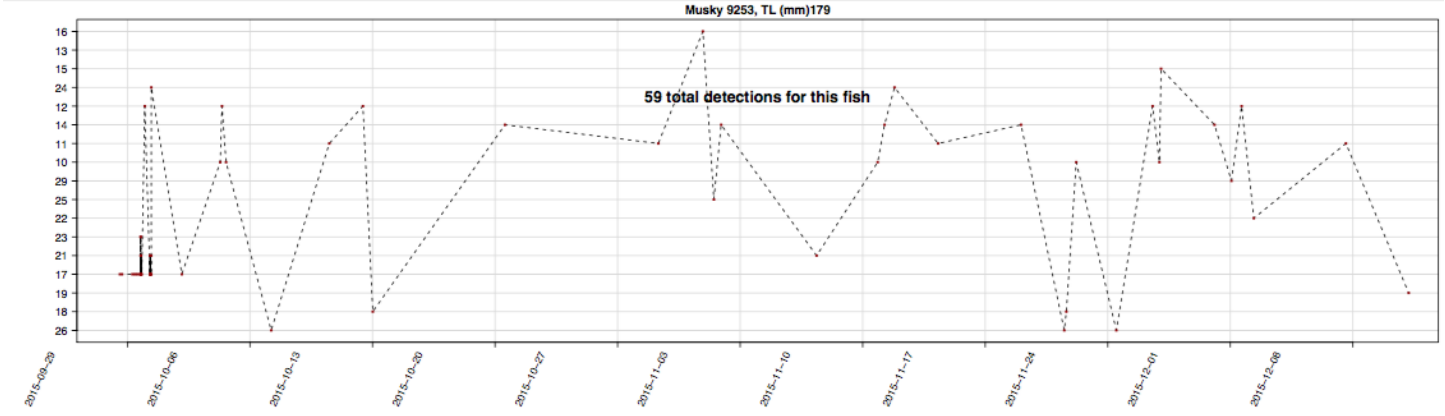

Musky 0FEA, TL (mm)140
432 total detections for this fish

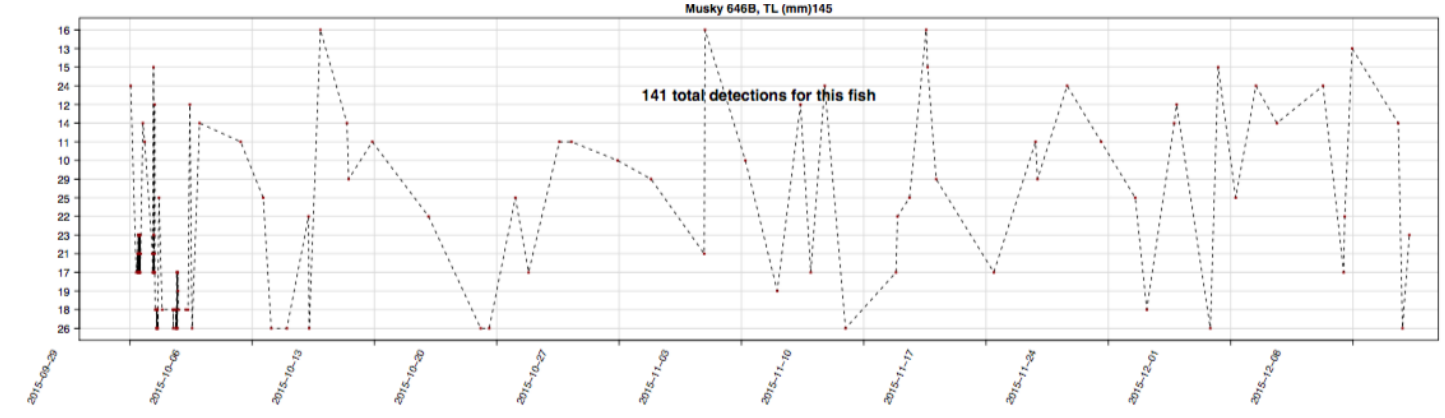

Musky 4253, TL (mm)185
71 total detections for this fish

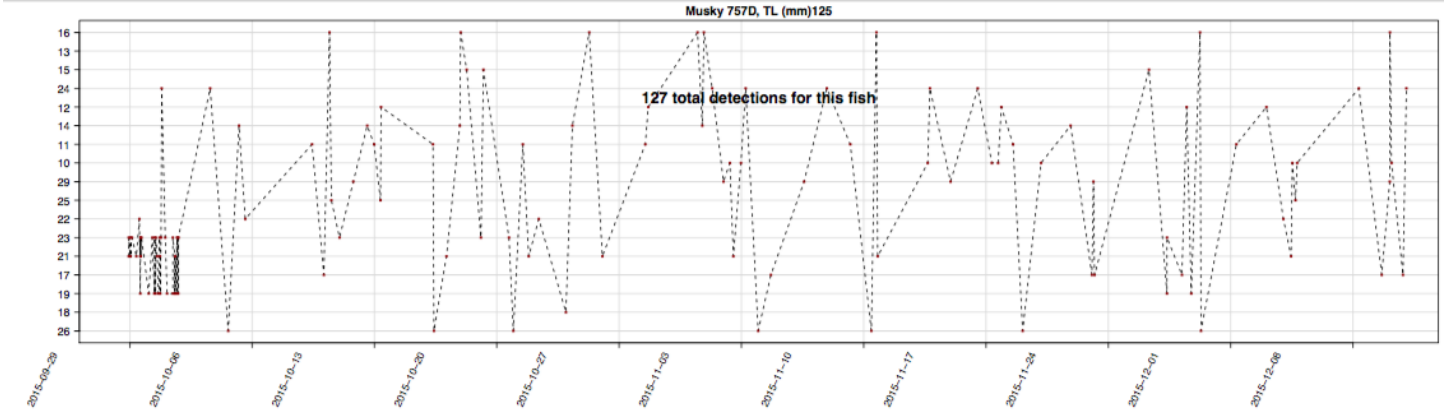

Musky 4494, TL (mm)134
137 total detections for this fish

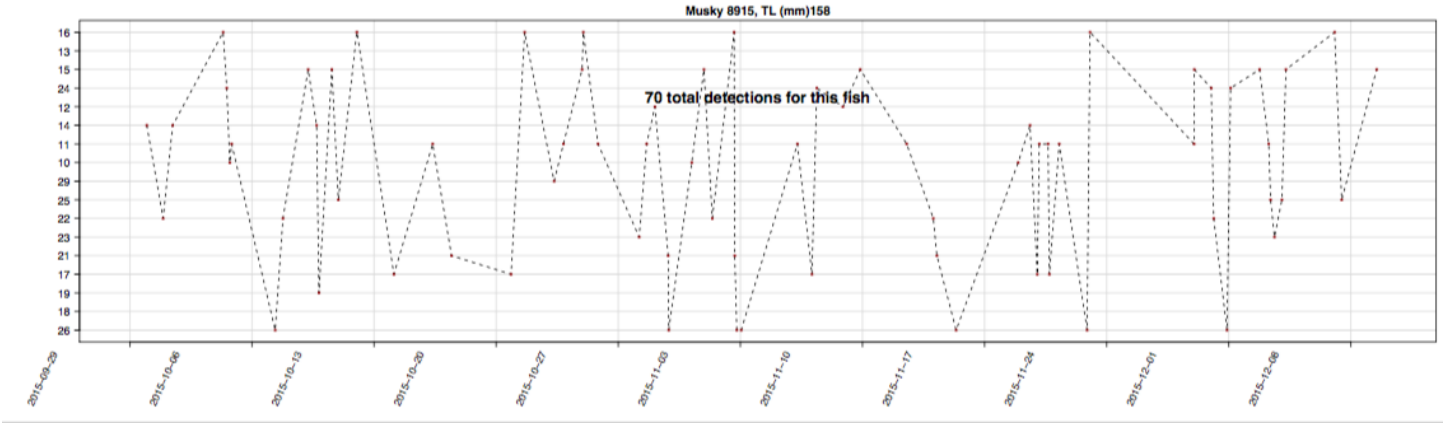

Musky 49DA, TL (mm)122
444 total detections for this fish

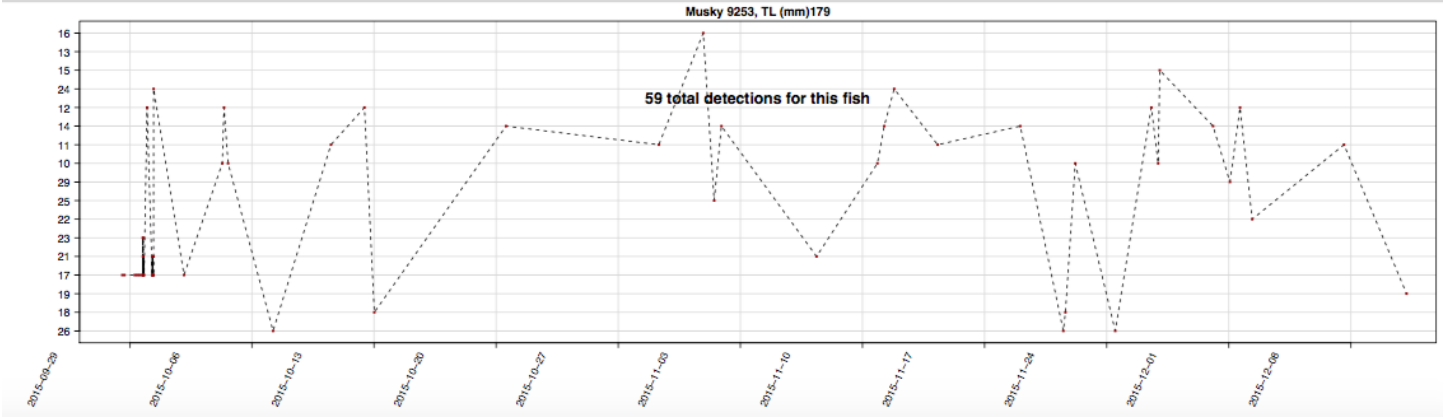

Musky 8915, TL (mm)158
70 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

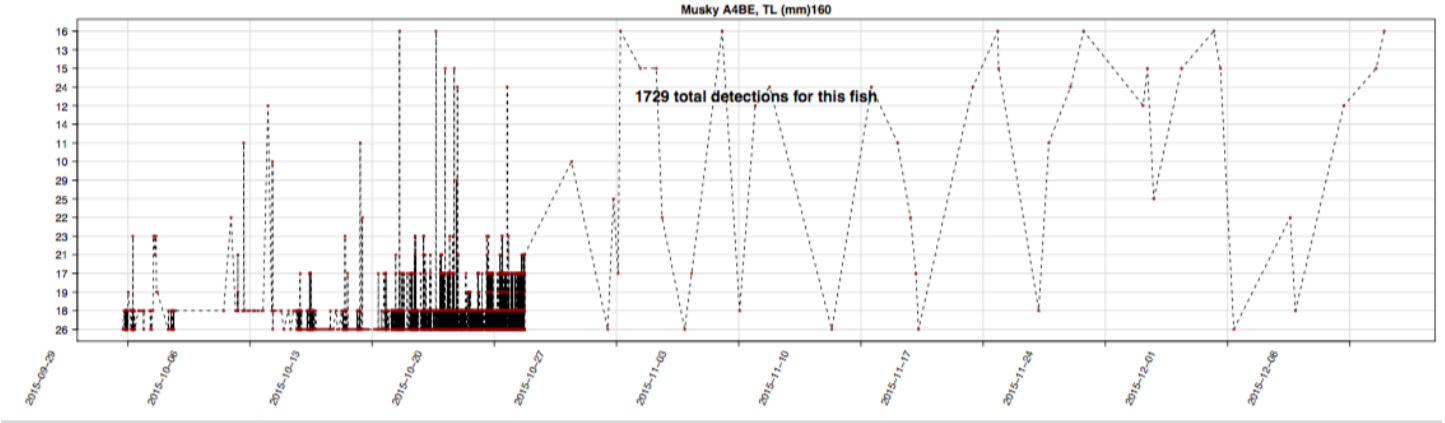

Musky 9253, TL (mm)179
59 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

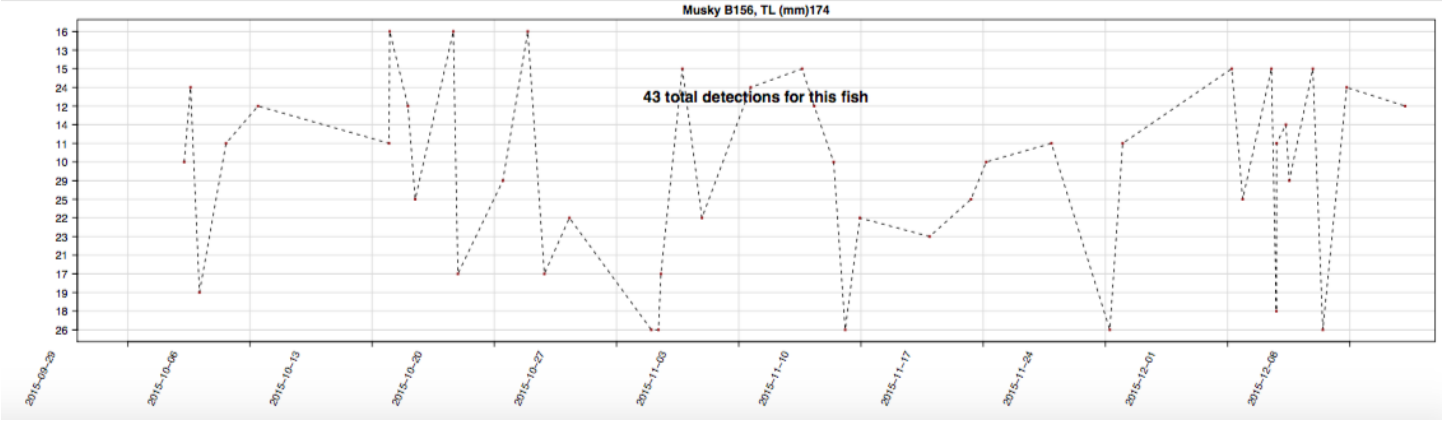

Musky 646B, TL (mm)145
141 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

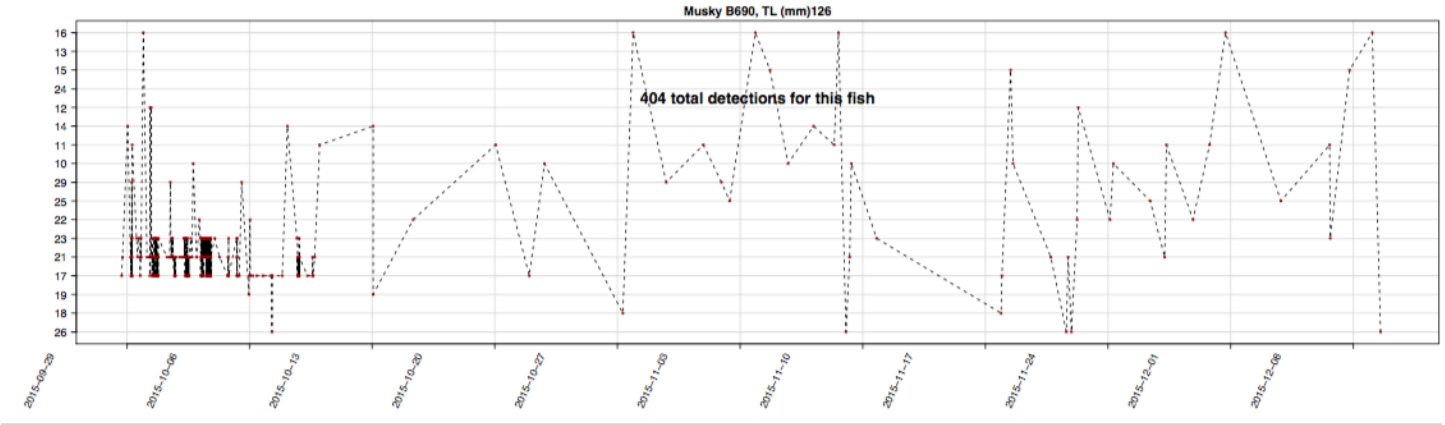

Musky 757D, TL (mm)125
127 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

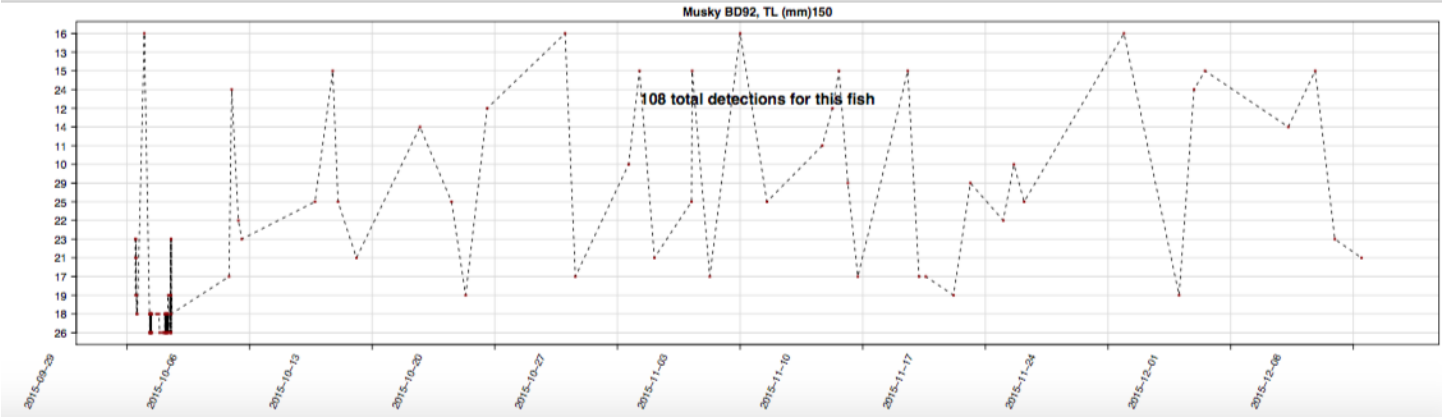

Musky 8915, TL (mm)158
70 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

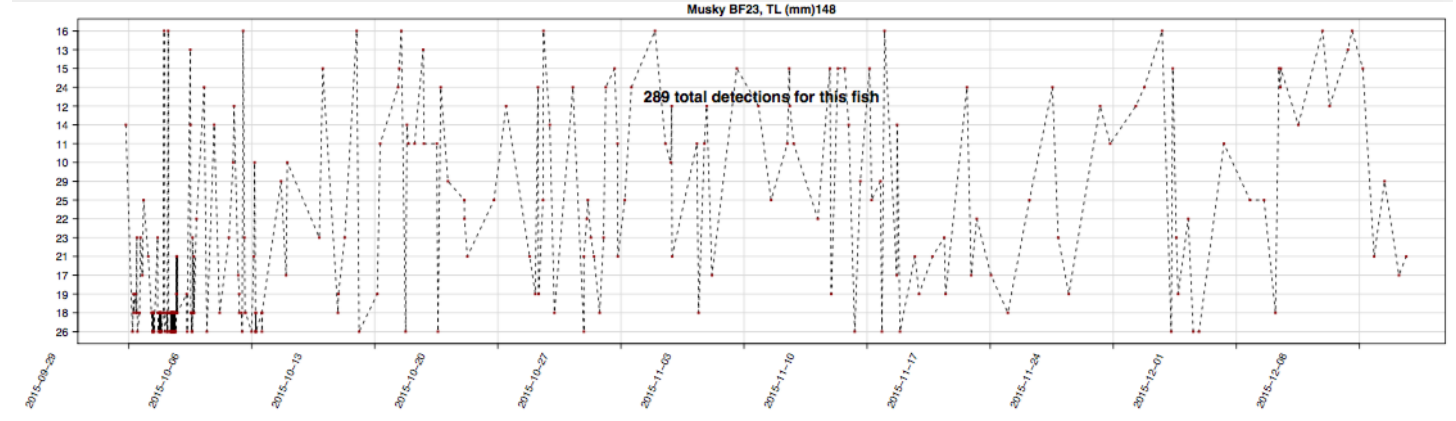

Musky 9253, TL (mm)179
59 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

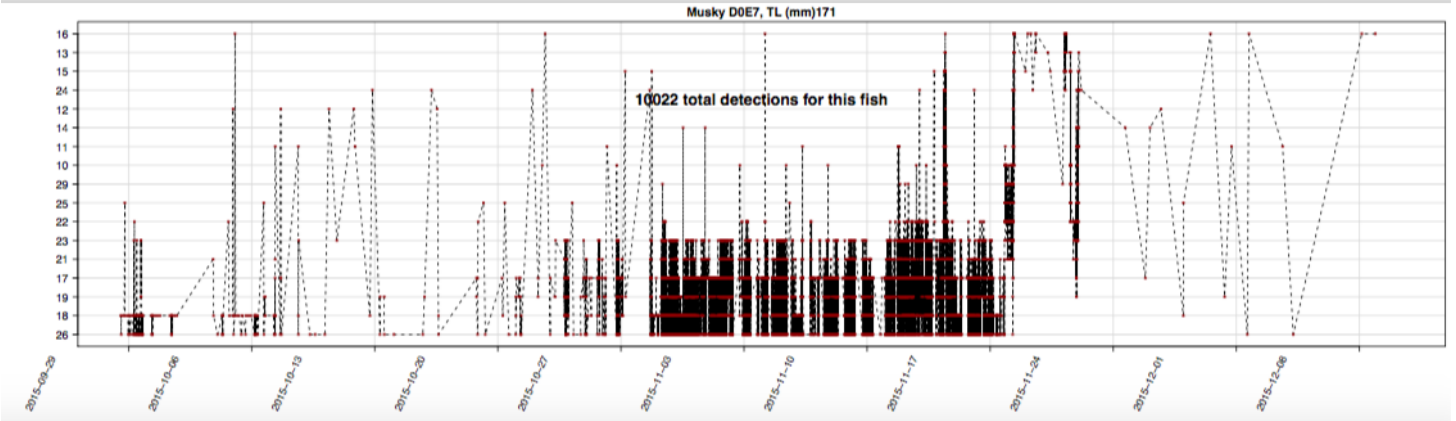

Musky A4BE, TL (mm)160
1729 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

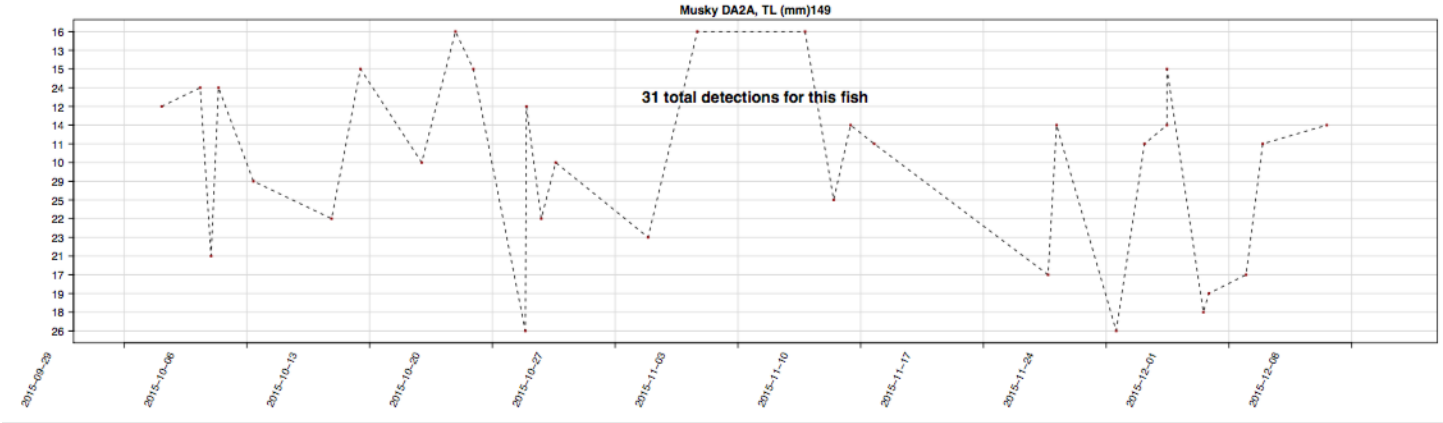

Musky B156, TL (mm)174
43 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

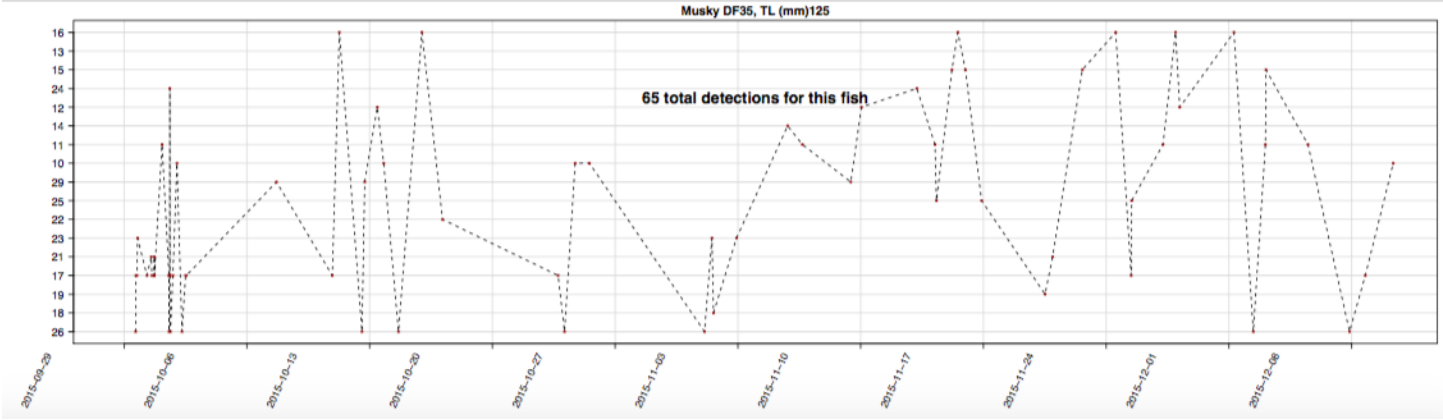

Musky B690, TL (mm)126
404 total detections for this fish


Musky BD92, TL (mm)150
108 total detections for this fish


Musky BF23, TL (mm)148
289 total detections for this fish


Musky D0E7, TL (mm)171
10022 total detections for this fish


Musky DA2A, TL (mm)149
31 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08


Musky DF35, TL (mm)125
65 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
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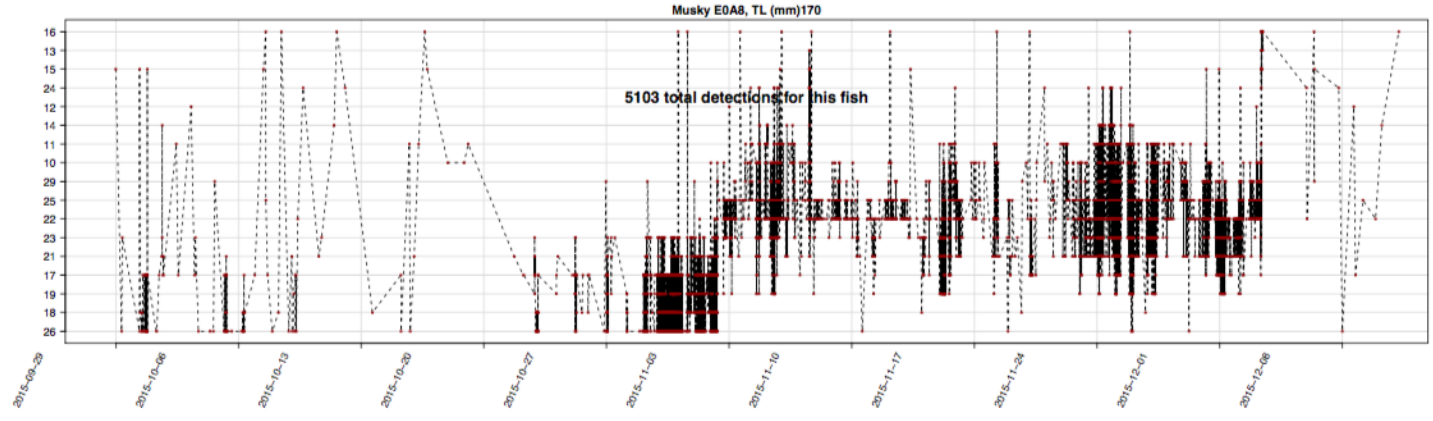
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08


Musky E0A8, TL (mm)170
5103 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

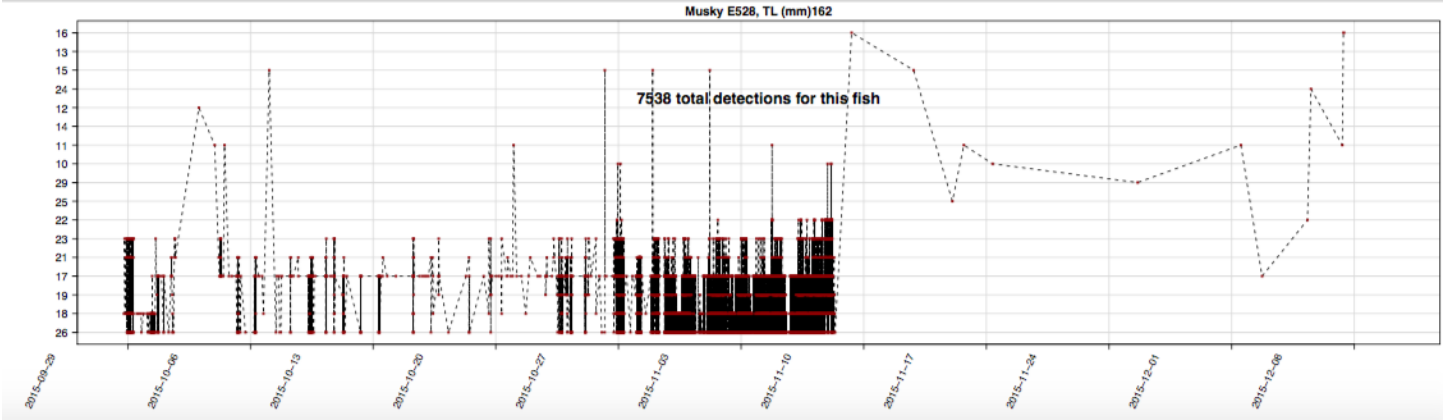
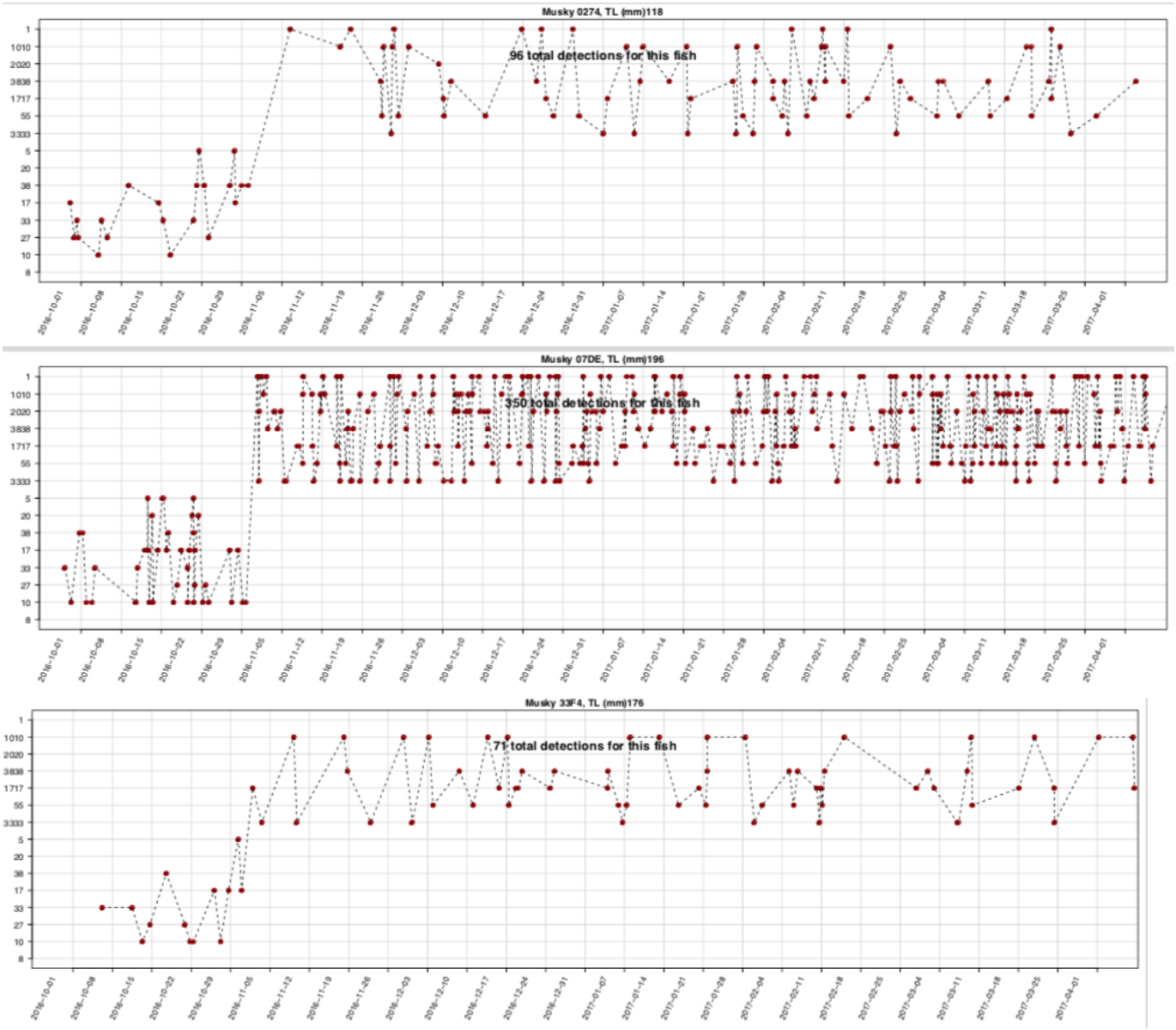

Musky E528, TL (mm)162
7538 total detections for this fish
2015-09-29
2015-10-06
2015-10-13
2015-10-20
2015-10-27
2015-11-03
2015-11-10
2015-11-17
2015-11-24
2015-12-01
2015-12-08

Figure S.3.8. Abacus plots for individual age-0 Muskellunge in Rose Bay (n = 20) from October 1 to December 10, 2015. Points indicate when fish were detected, and lines movement patterns between receivers from nearshore (Y axis bottom) and deeper waters (Y axis top) in the fall and early winter. Time is depicted by weeks starting with October 1, 2015 (X axis).



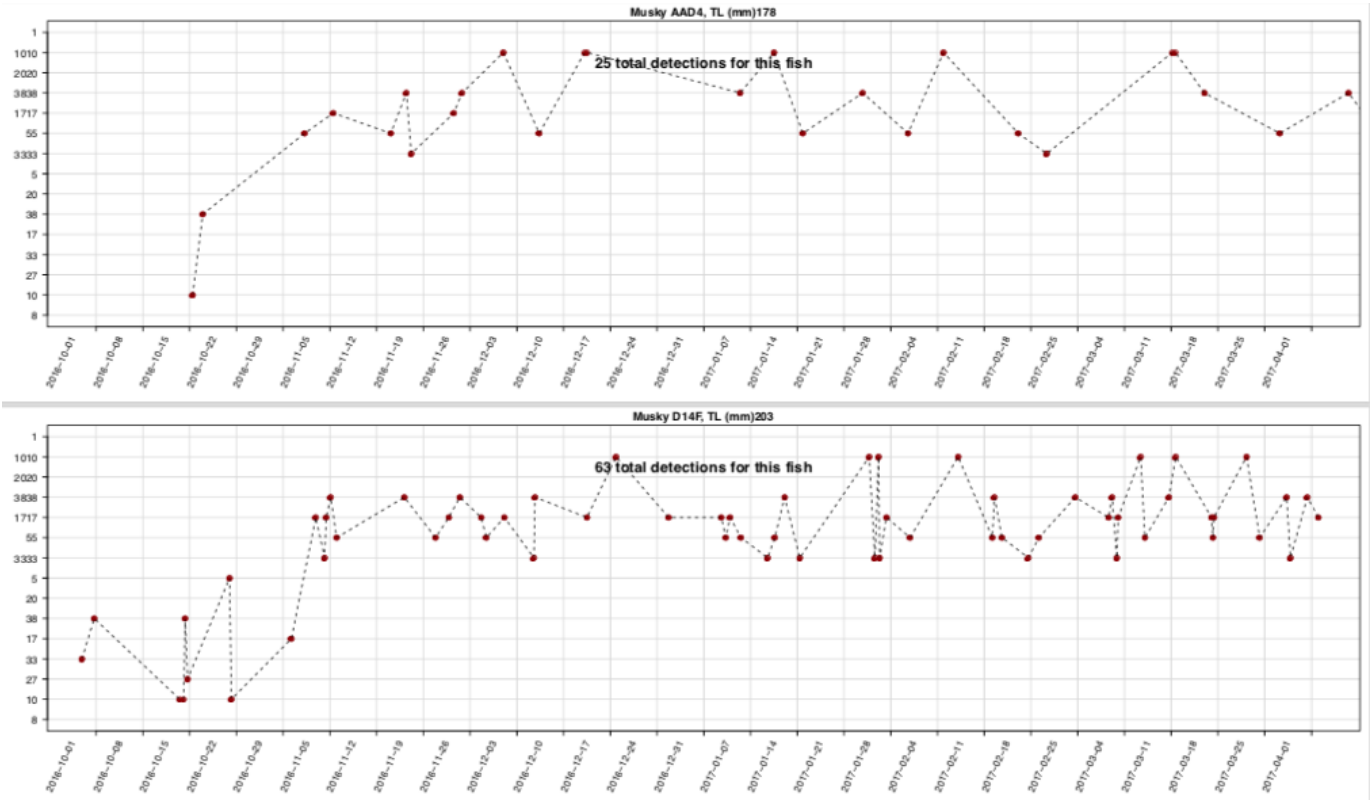
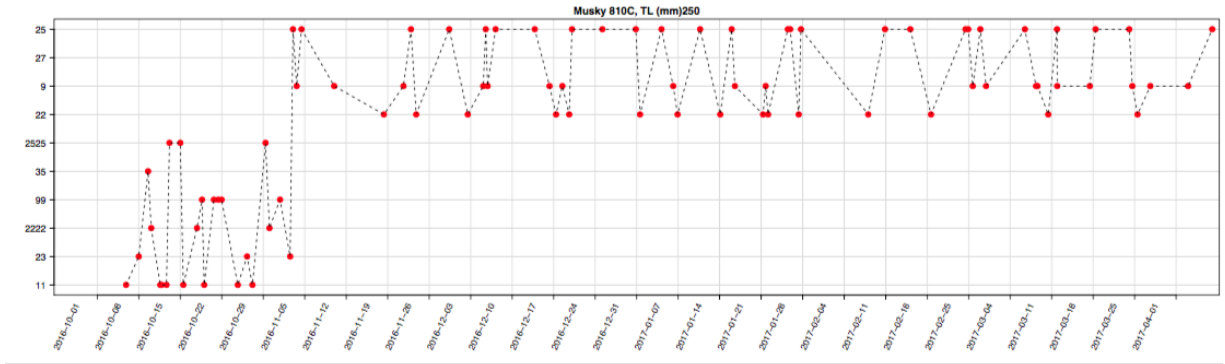
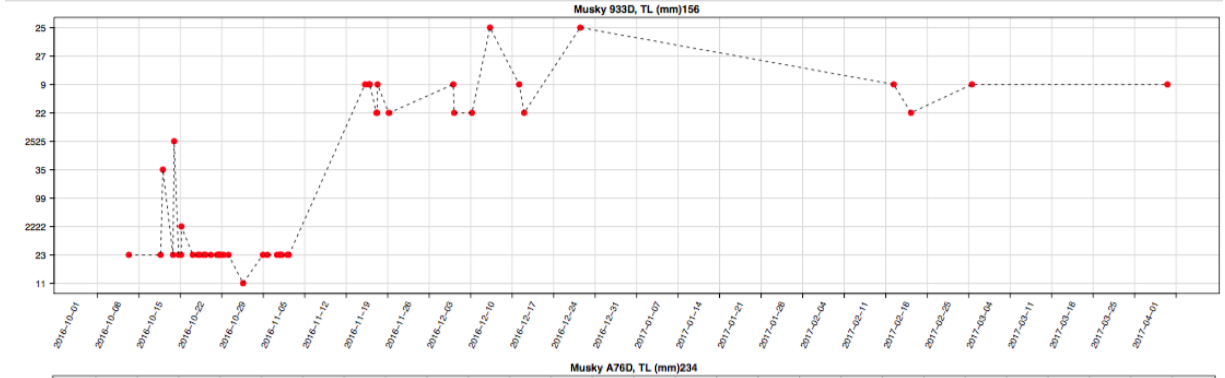
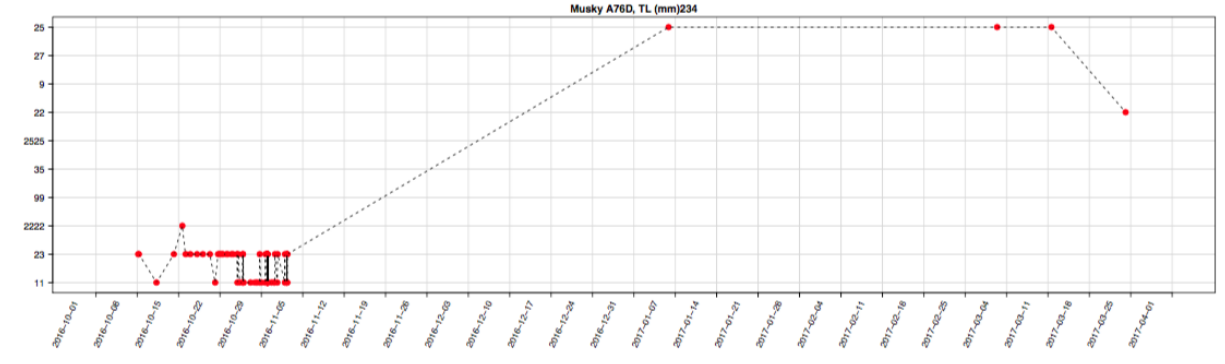


Figure S.3.9. Abacus plots for individual age-0 Muskellunge in Grass Point Bay (n = 5) from October 1 2016 to March 31, 2017. Points indicate when fish were detected, and lines movement patterns between receivers from nearshore (Y axis bottom) and deeper waters (Y axis top) in the fall and winter. Time is depicted by weeks starting with October 1, 2016 (X axis).


Musky 810C, TL (mm)250
25
27
9
22
2525
35
99
2222
23
11
2016-10-01
2016-10-08
2016-10-15
2016-10-22
2016-10-29
2016-11-05
2016-11-12
2016-11-19
2016-11-26
2016-12-03
2016-12-10
2016-12-17
2016-12-24
2016-12-31
2017-01-07
2017-01-14
2017-01-21
2017-01-28
2017-02-04
2017-02-11
2017-02-18
2017-02-25
2017-03-04
2017-03-11
2017-03-18
2017-03-25
2017-04-01


Musky 933D, TL (mm)156
25
27
9
22
2525
35
99
2222
23
11
2016-10-01
2016-10-08
2016-10-15
2016-10-22
2016-10-29
2016-11-05
2016-11-12
2016-11-19
2016-11-26
2016-12-03
2016-12-10
2016-12-17
2016-12-24
2016-12-31
2017-01-07
2017-01-14
2017-01-21
2017-01-28
2017-02-04
2017-02-11
2017-02-18
2017-02-25
2017-03-04
2017-03-11
2017-03-18
2017-03-25
2017-04-01


Musky A76D, TL (mm)234
25
27
9
22
2525
35
99
2222
23
11
2016-10-01
2016-10-08
2016-10-15
2016-10-22
2016-10-29
2016-11-05
2016-11-12
2016-11-19
2016-11-26
2016-12-03
2016-12-10
2016-12-17
2016-12-24
2016-12-31
2017-01-07
2017-01-14
2017-01-21
2017-01-28
2017-02-04
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2017-03-04
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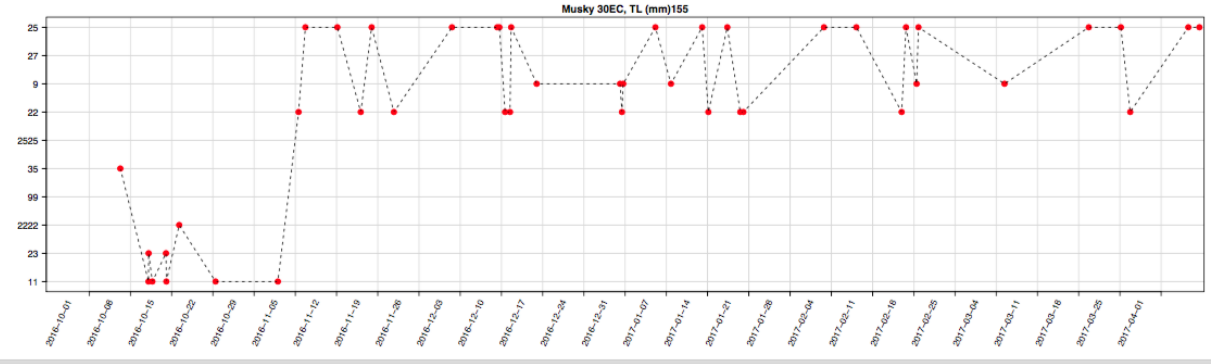
2017-03-18
2017-03-25
2017-04-01


Musky 30EC, TL (mm)155
25
27
9
22
2525
35
99
2222
23
11
2016-10-01
2016-10-08
2016-10-15
2016-10-22
2016-10-29
2016-11-05
2016-11-12
2016-11-19
2016-11-26
2016-12-03
2016-12-10
2016-12-17
2016-12-24
2016-12-31
2017-01-07
2017-01-14
2017-01-21
2017-01-28
2017-02-04
2017-02-11
2017-02-18
2017-02-25
2017-03-04
2017-03-11
2017-03-18
2017-03-25
2017-04-01

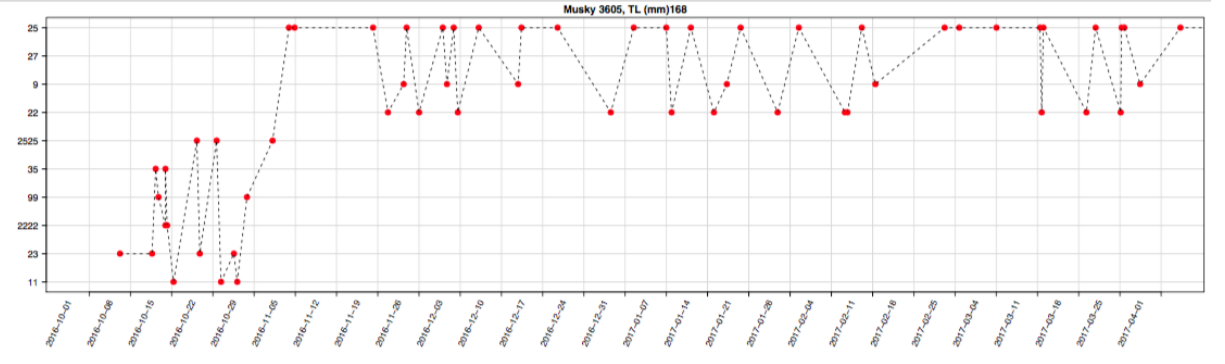
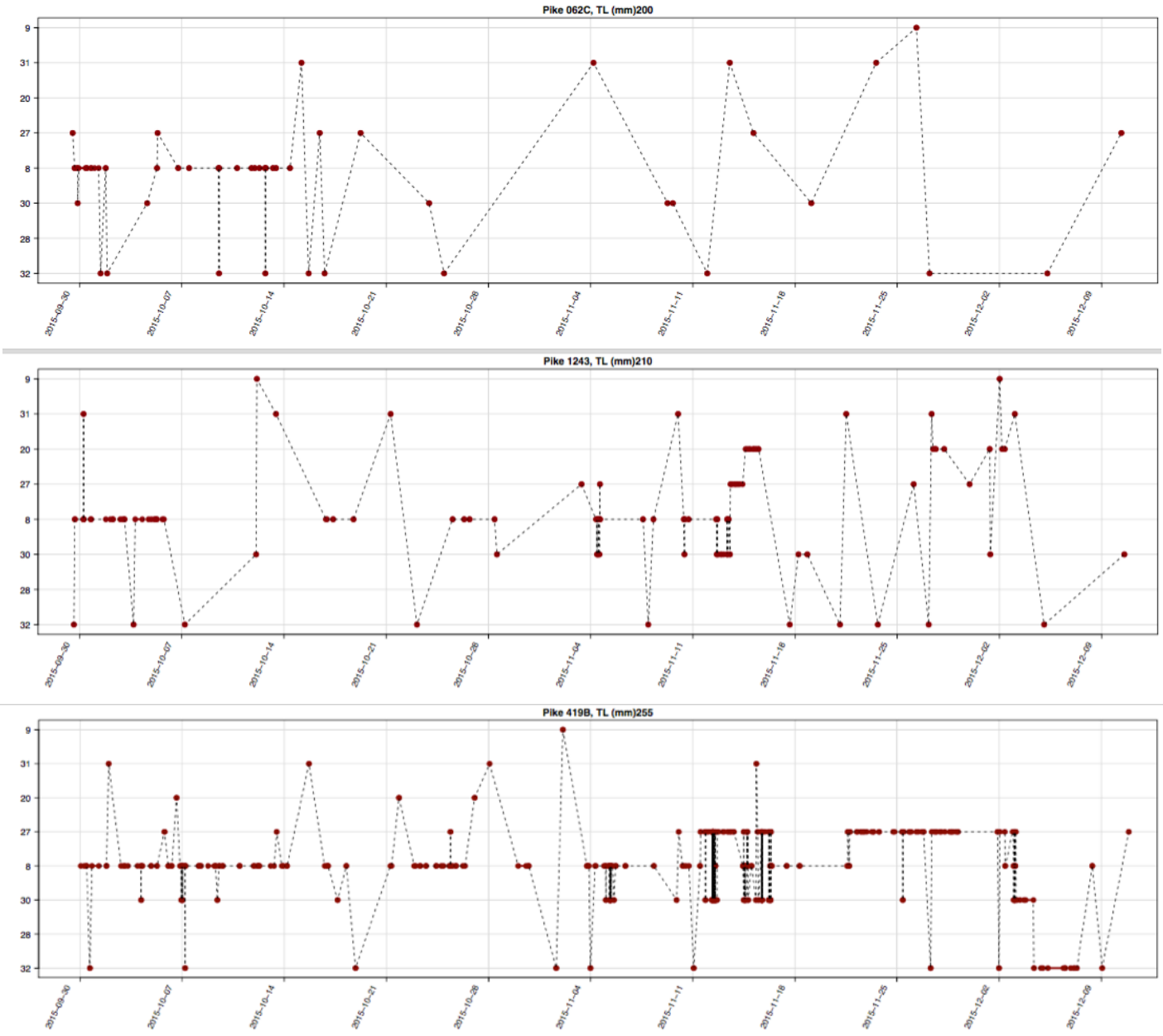
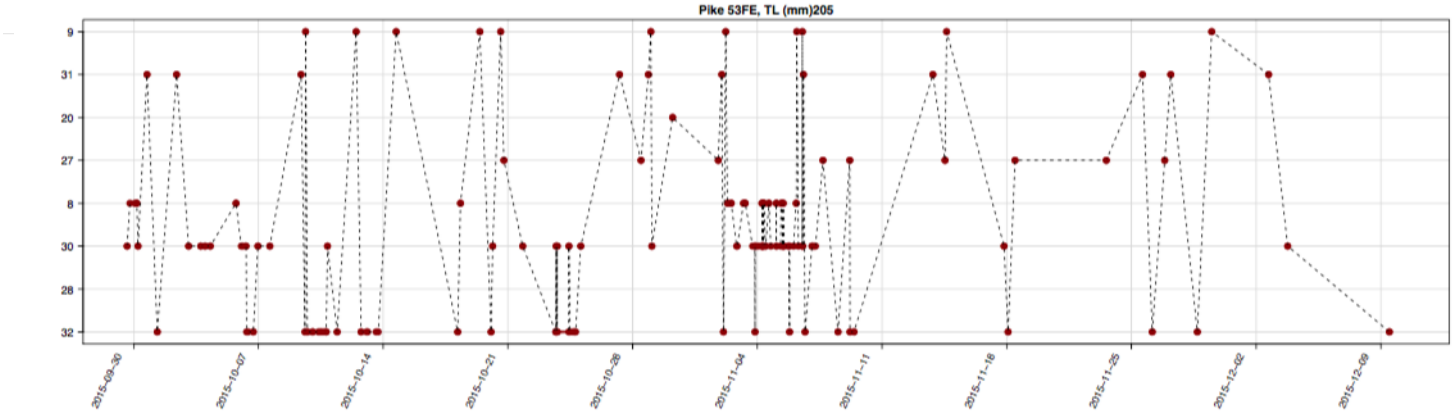

Musky 3605, TL (mm)168
25
27
9
22
2525
35
99
2222
23
11
2016-10-01
2016-10-08
2016-10-15
2016-10-22
2016-10-29
2016-11-05
2016-11-12
2016-11-19
2016-11-26
2016-12-03
2016-12-10
2016-12-17
2016-12-24
2016-12-31
2017-01-07
2017-01-14
2017-01-21
2017-01-28
2017-02-04
2017-02-11
2017-02-18
2017-02-25
2017-03-04
2017-03-11
2017-03-18
2017-03-25
2017-04-01

Figure S.3.10. Abacus plots for individual age-0 Muskellunge in Rose Bay (n = 5) from October 1, 2016 to March 31, 2017. Points indicate when fish were detected, and lines movement patterns between receivers from nearshore (Y axis bottom) and deeper waters (Y axis top) in the fall and winter. Time is depicted by weeks starting with October 1, 2016 (X axis).




Pike 53FE, TL (mm)205
9
31
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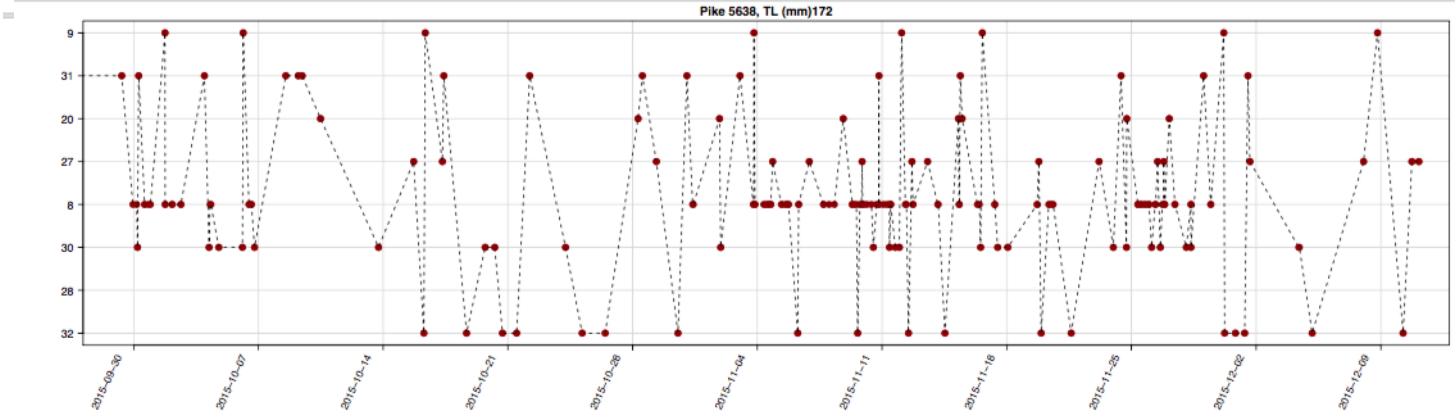
2015-09-30
2015-10-07
2015-10-14
2015-10-21
2015-10-28
2015-11-04
2015-11-11
2015-11-18
2015-11-25
2015-12-02
2015-12-09


Pike 5638, TL (mm)172
9
31
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32
2015-09-30
2015-10-07
2015-10-14
2015-10-21
2015-10-28
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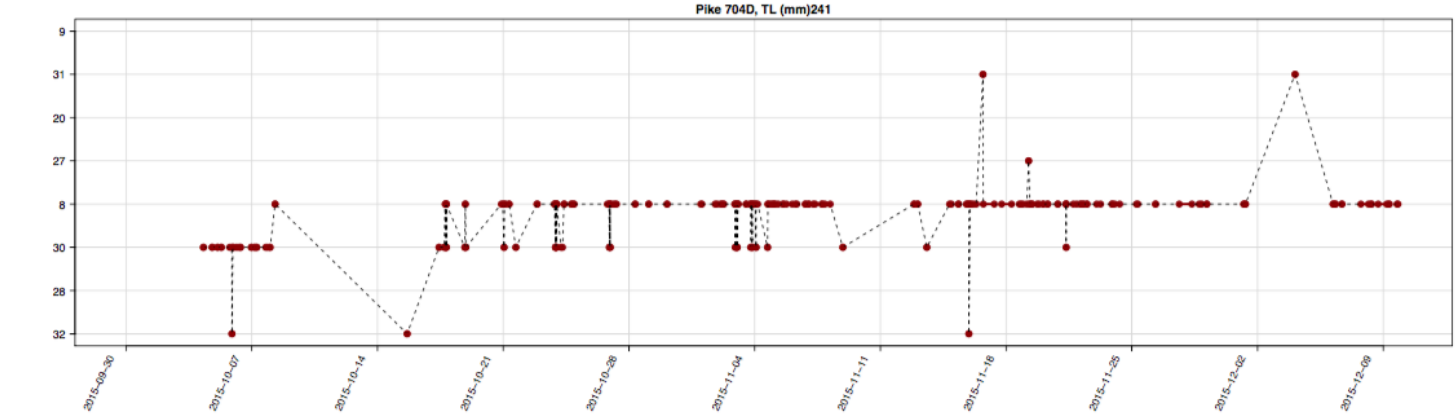
2015-11-25
2015-12-02
2015-12-09


Pike 704D, TL (mm)241
9
31
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2015-09-30
2015-10-07
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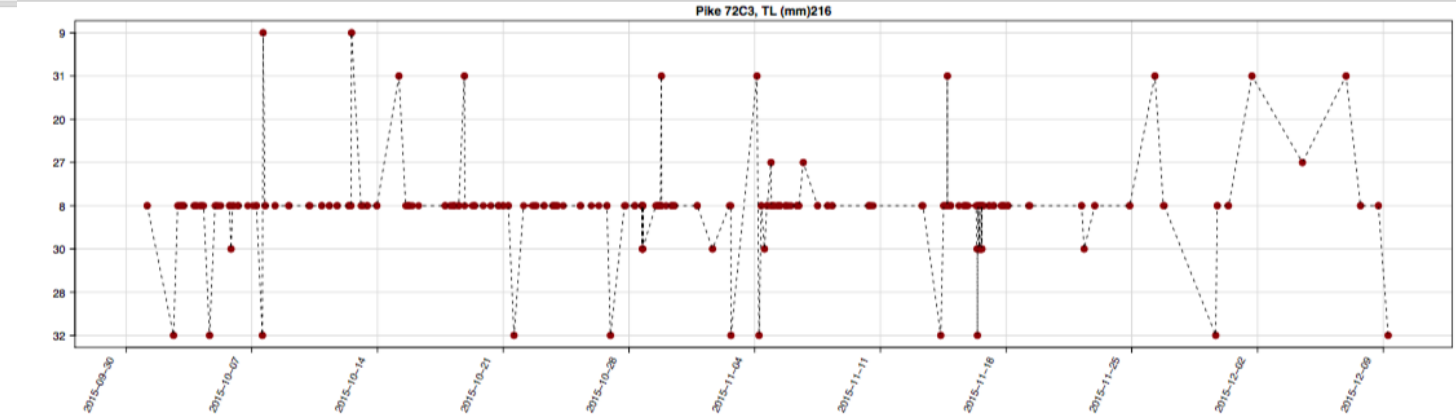
2015-11-25
2015-12-02
2015-12-09


Pike 72C3, TL (mm)216
9
31
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2015-09-30
2015-10-07
2015-10-14
2015-10-21
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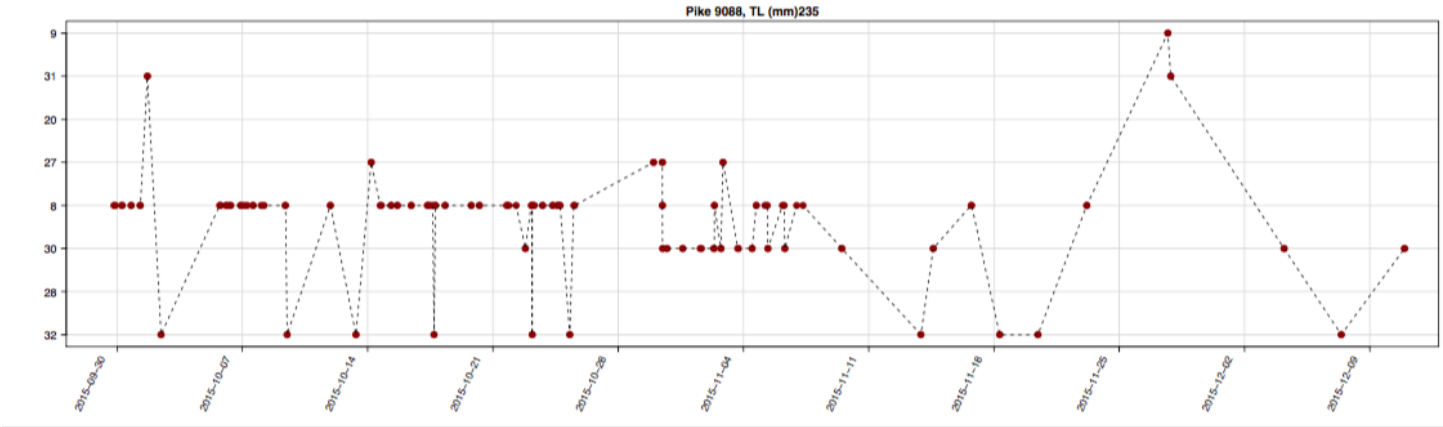
2015-11-04
2015-11-11
2015-11-18
2015-11-25
2015-12-02
2015-12-09


Pike 9088, TL (mm)235
9
31
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32
2015-09-30
2015-10-07
2015-10-14
2015-10-21
2015-10-28
2015-11-04
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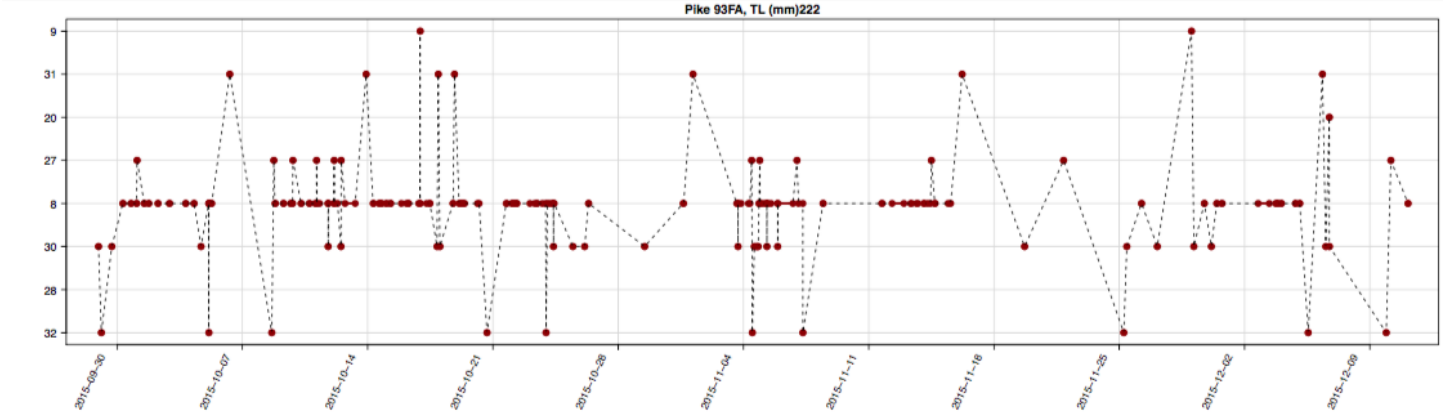
2015-12-09


Pike 93FA, TL (mm)222
9
31
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2015-09-30
2015-10-07
2015-10-14
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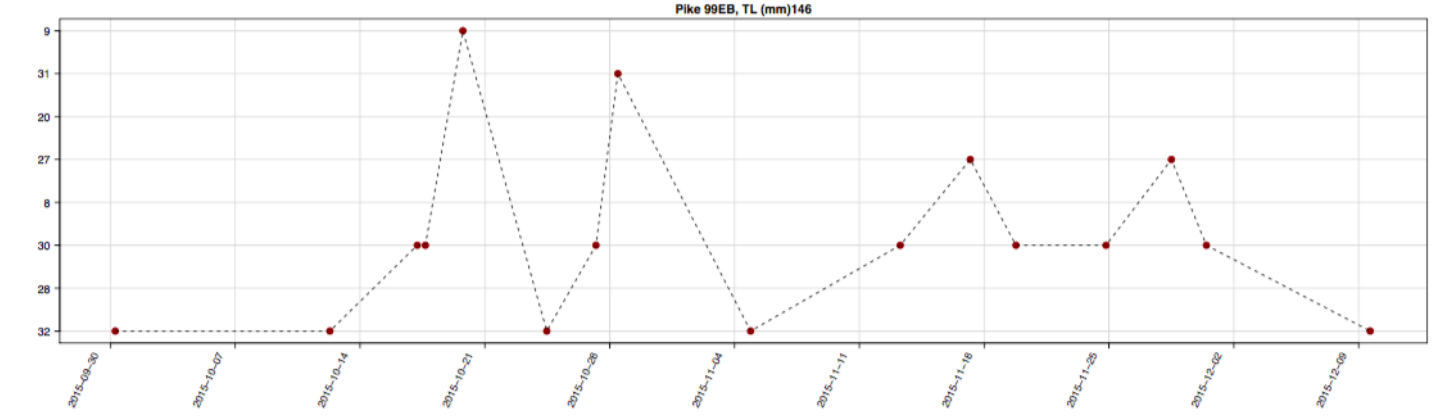
2015-12-02
2015-12-09


Pike 99EB, TL (mm)146
9
31
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27
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2015-09-30
2015-10-07
2015-10-14
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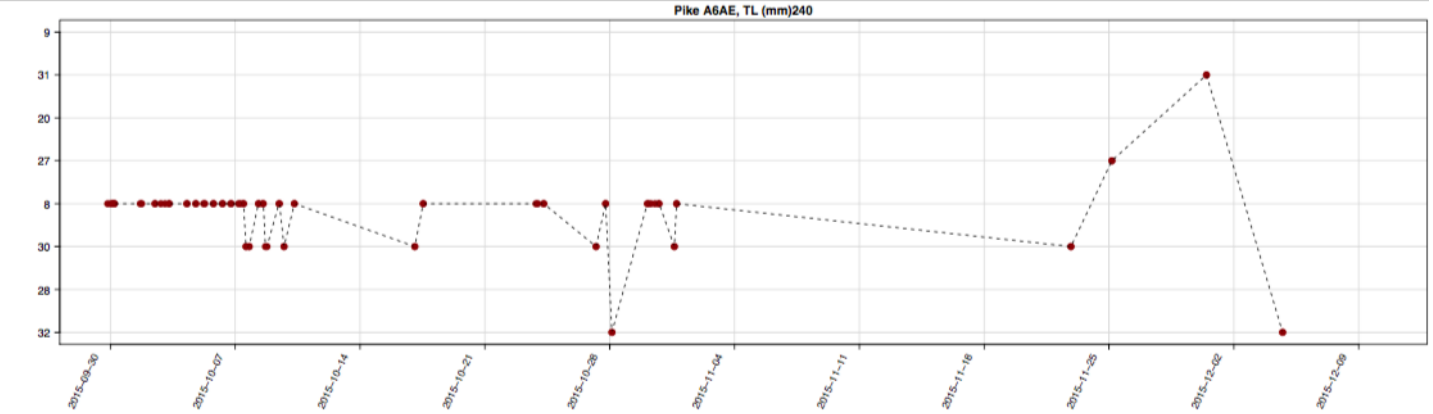
2015-12-09


Pike A6AE, TL (mm)240
9
31
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2015-09-30
2015-10-07
2015-10-14
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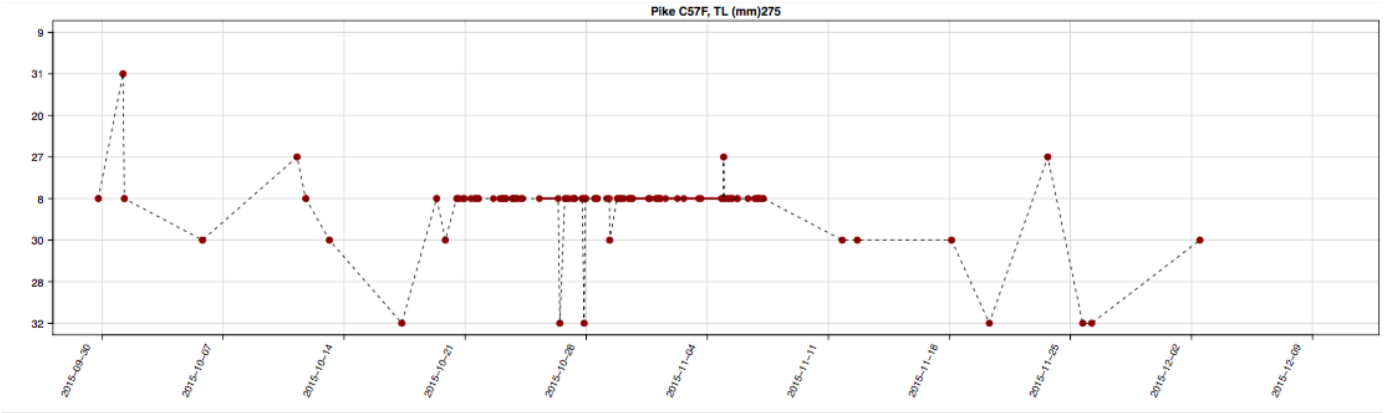
2015-11-25
2015-12-02
2015-12-09


Pike C57F, TL (mm)275
9
31
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2015-09-30
2015-10-07
2015-10-14
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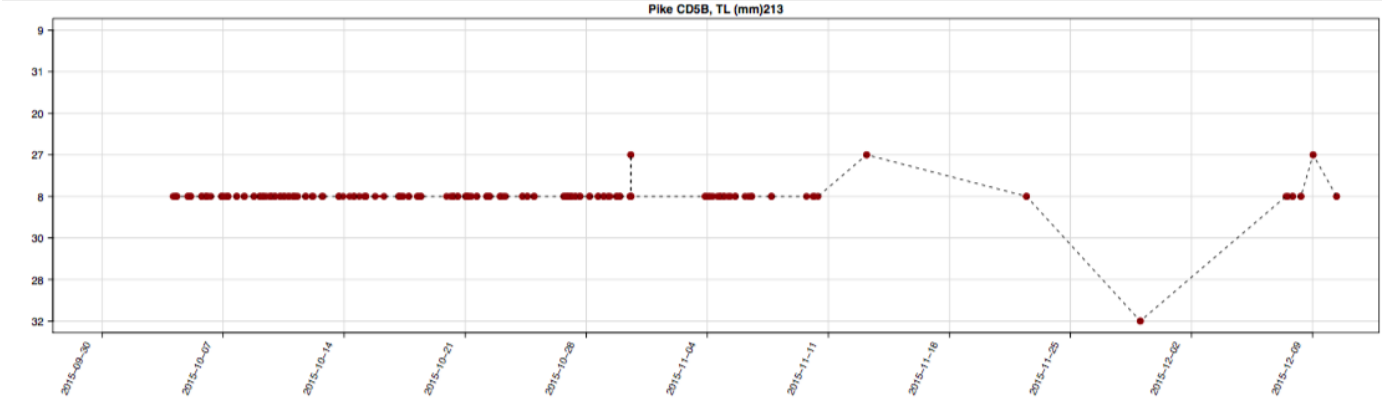
2015-12-02
2015-12-09


Pike CD5B, TL (mm)213
9
31
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27
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32
2015-09-30
2015-10-07
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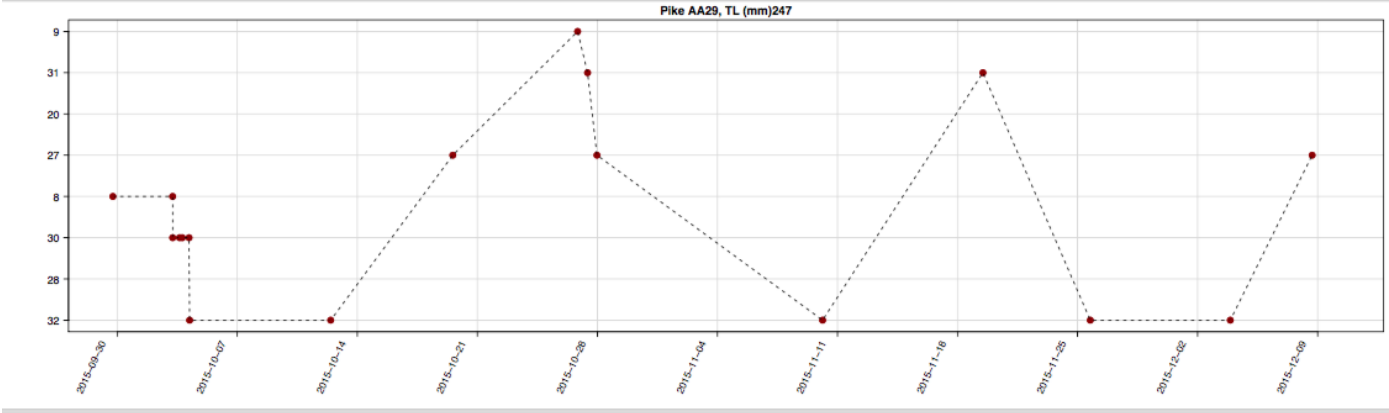
2015-11-04
2015-11-11
2015-11-18
2015-11-25
2015-12-02
2015-12-09


Pike AA29, TL (mm)247
9
31
20
27
8
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32
2015-09-30
2015-10-07
2015-10-14
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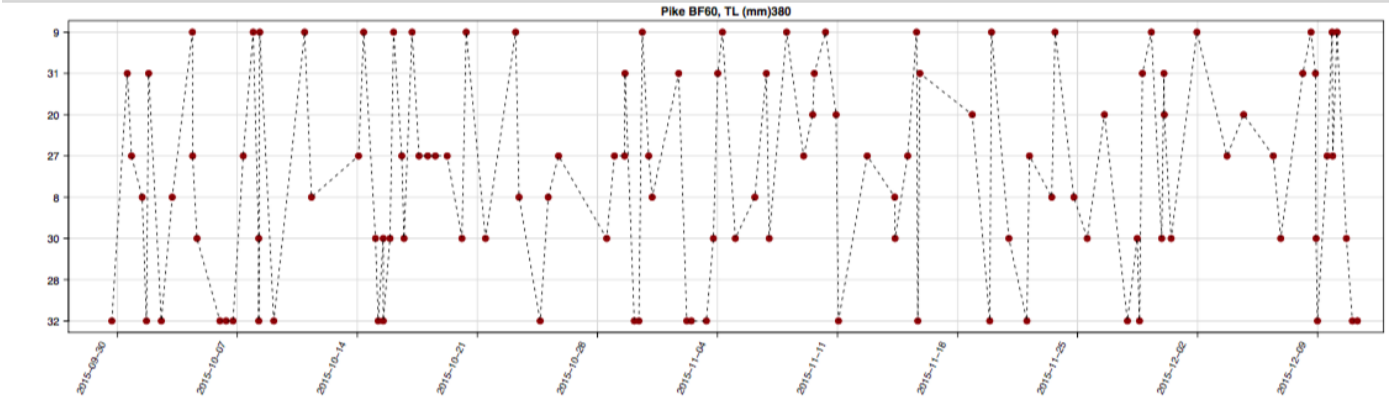
2015-12-02
2015-12-09


Pike BF60, TL (mm)380
9
31
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27
8
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28
32
2015-09-30
2015-10-07
2015-10-14
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2015-10-28
2015-11-04
2015-11-11
2015-11-18
2015-11-25
2015-12-02
2015-12-09

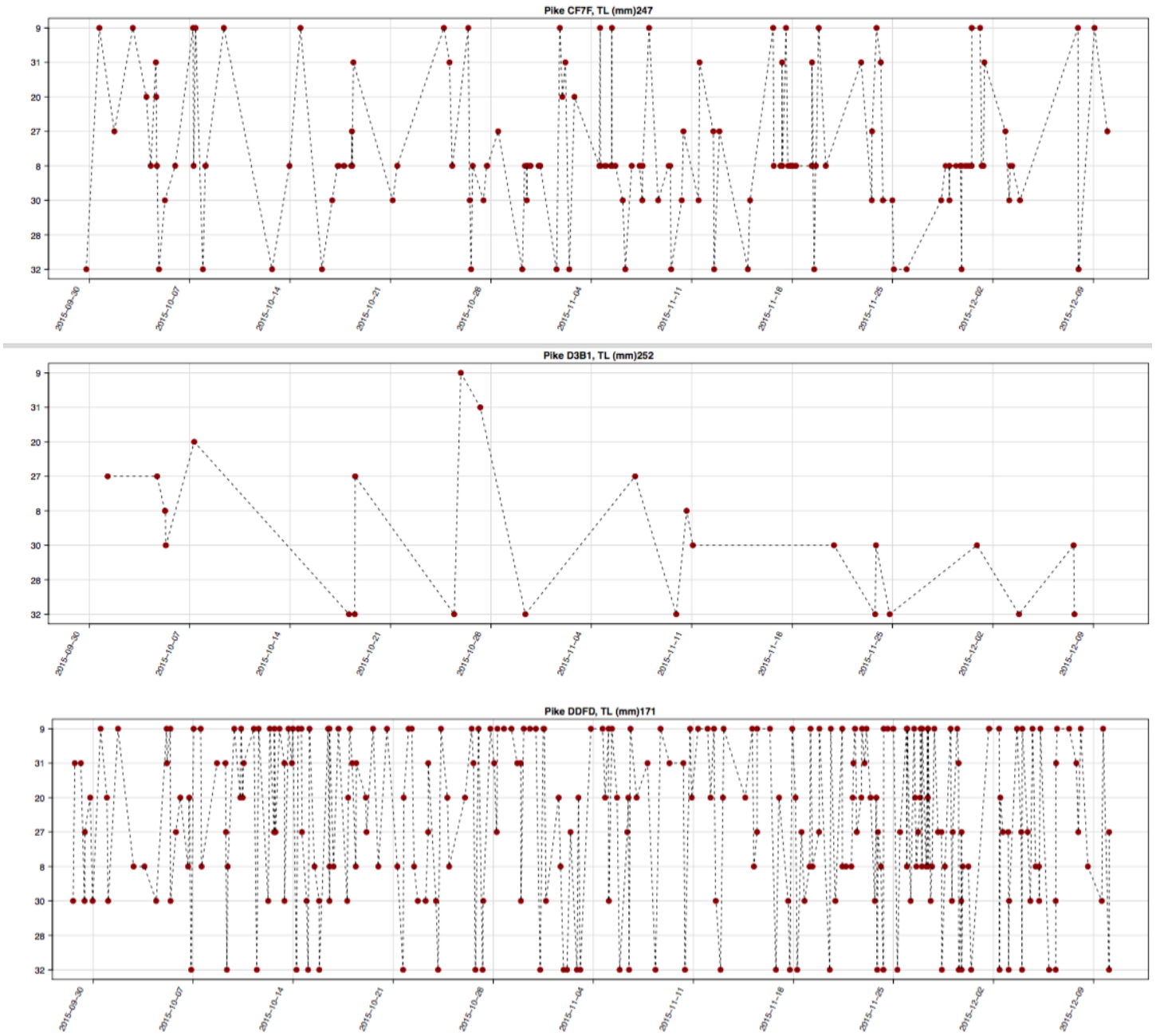
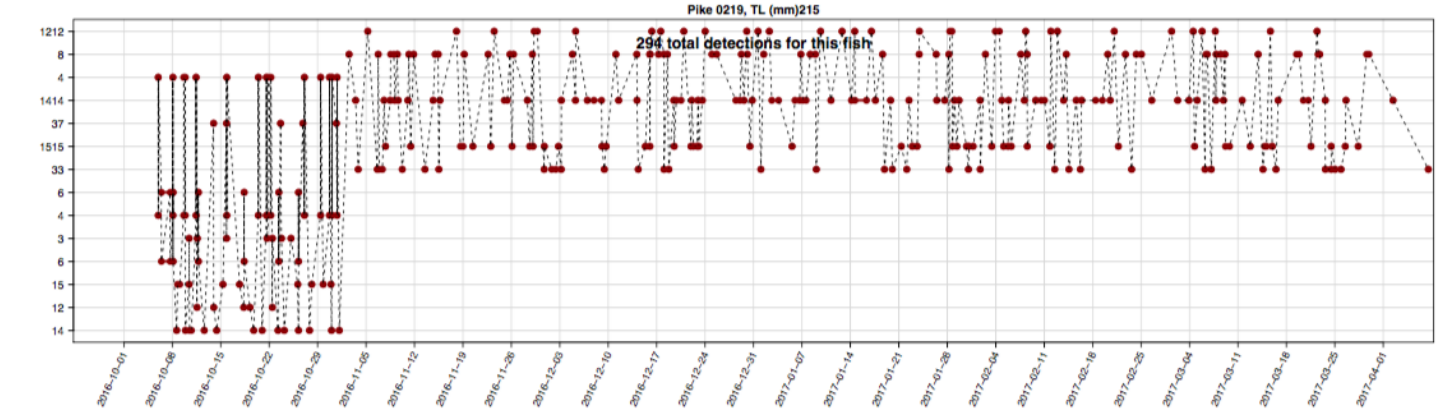
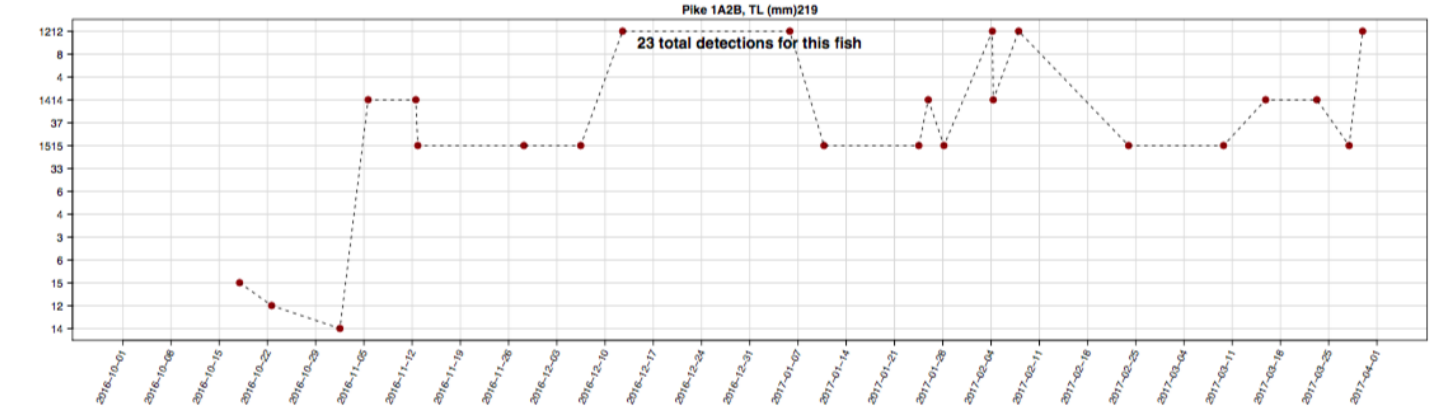
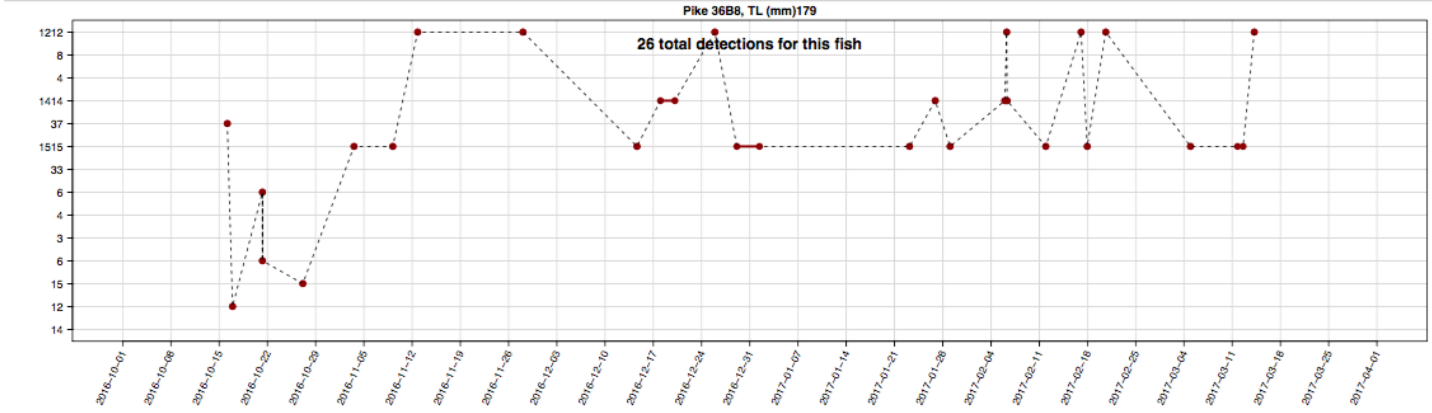
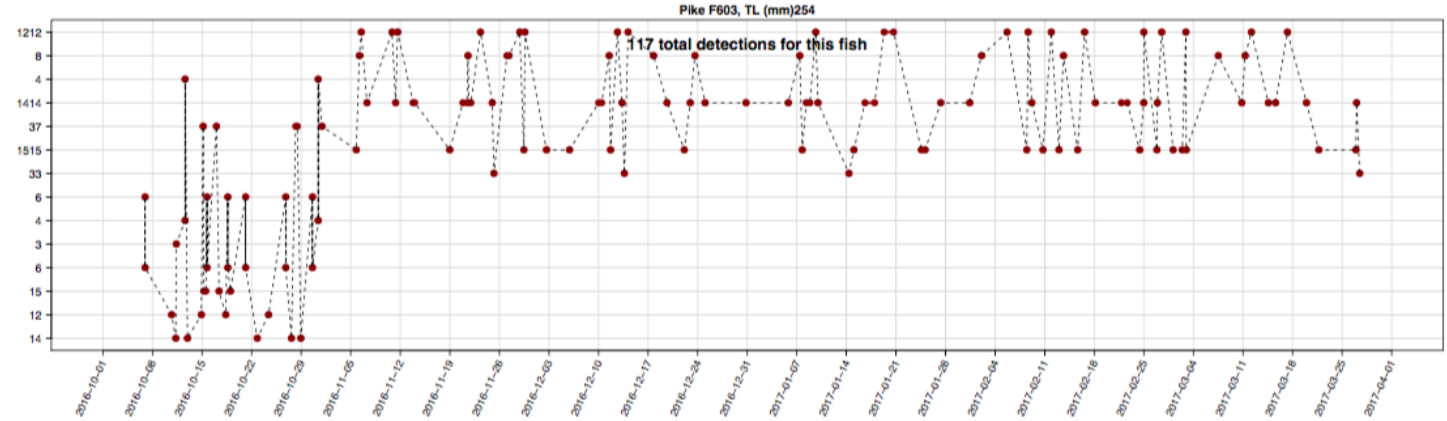


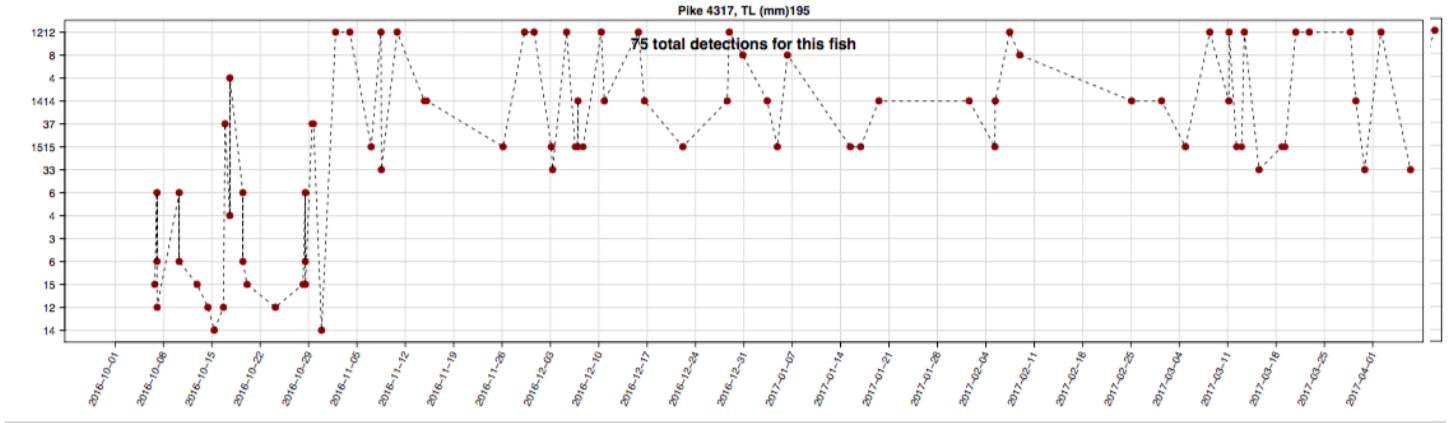
Figure S.3.11. Abacus plots for individual age-0 Northern Pike in Flynn Bay (n = 22) from October 1 to December 10, 2016. Points indicate when fish were detected, and lines movement patterns between receivers from nearshore (Y axis bottom) and deeper waters (Y axis top) in the fall and early winter. Time is depicted by weeks starting with October 1, 2015 (X axis).

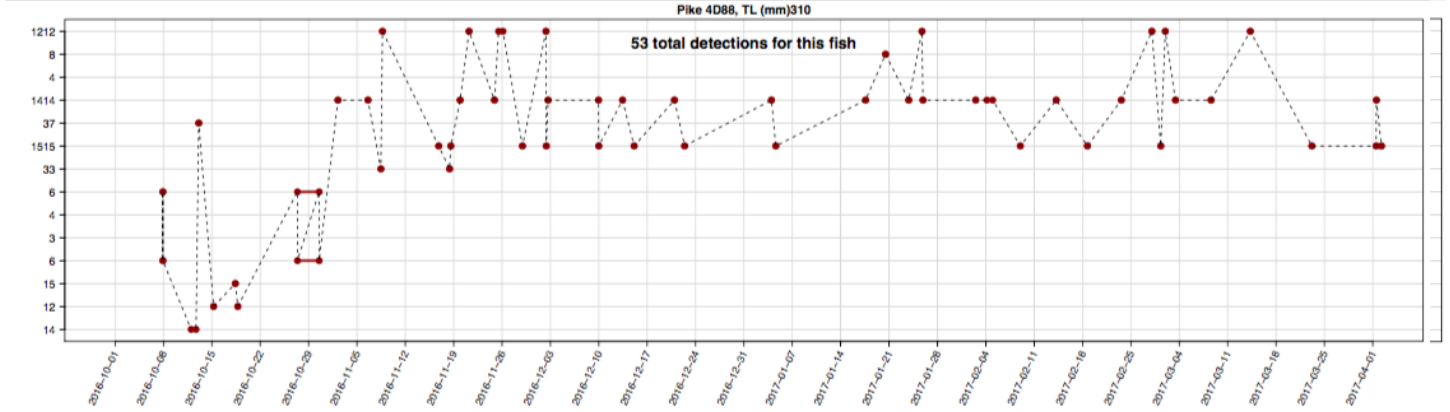

Pike 0219, TL (mm)215
294 total detections for this fish

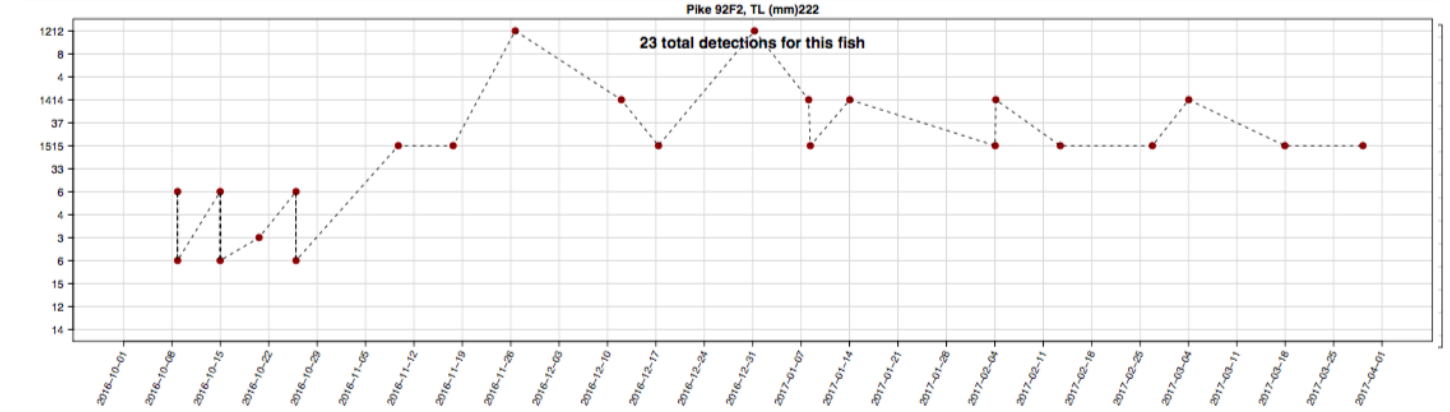

Pike 1A2B, TL (mm)219
23 total detections for this fish

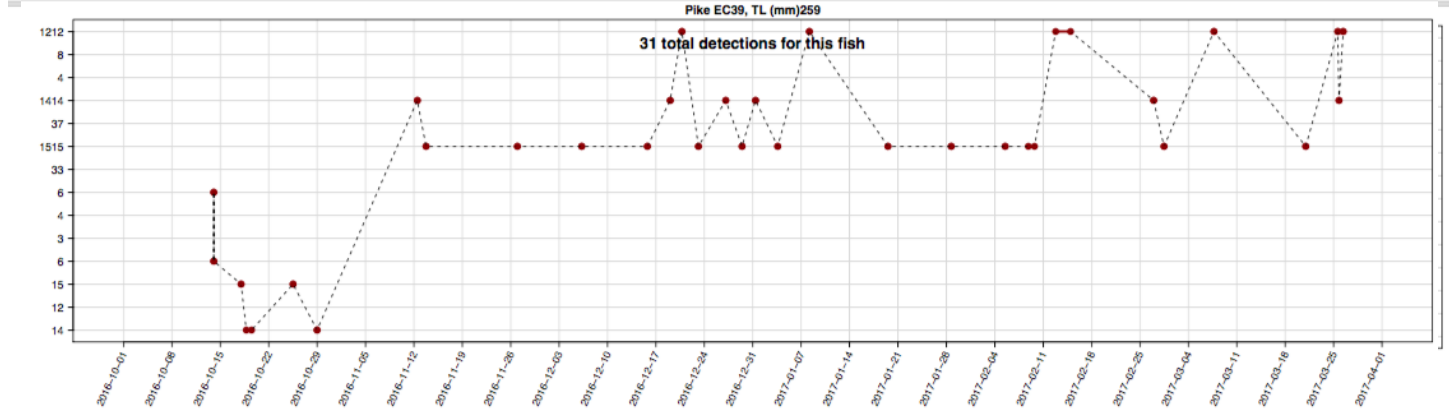

Pike 36B8, TL (mm)179
26 total detections for this fish

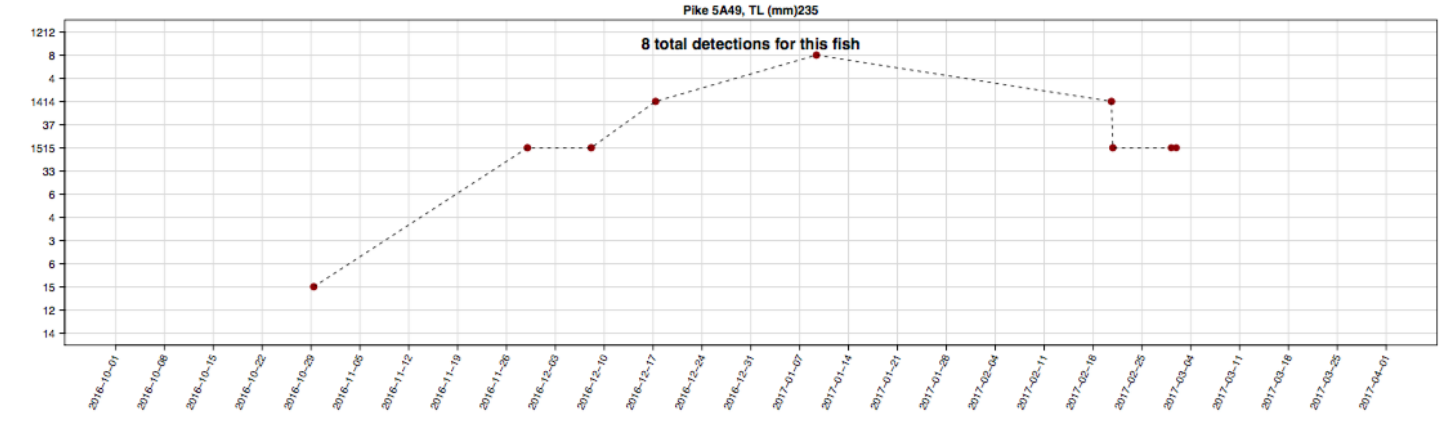

Pike F603, TL (mm)254
117 total detections for this fish

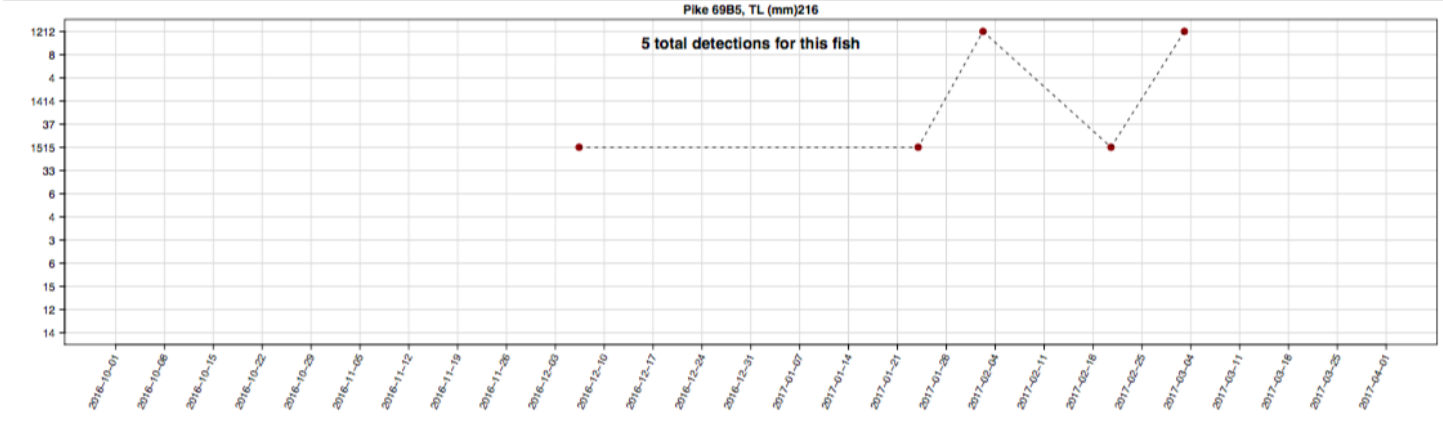

Pike 4317, TL (mm)195
75 total detections for this fish

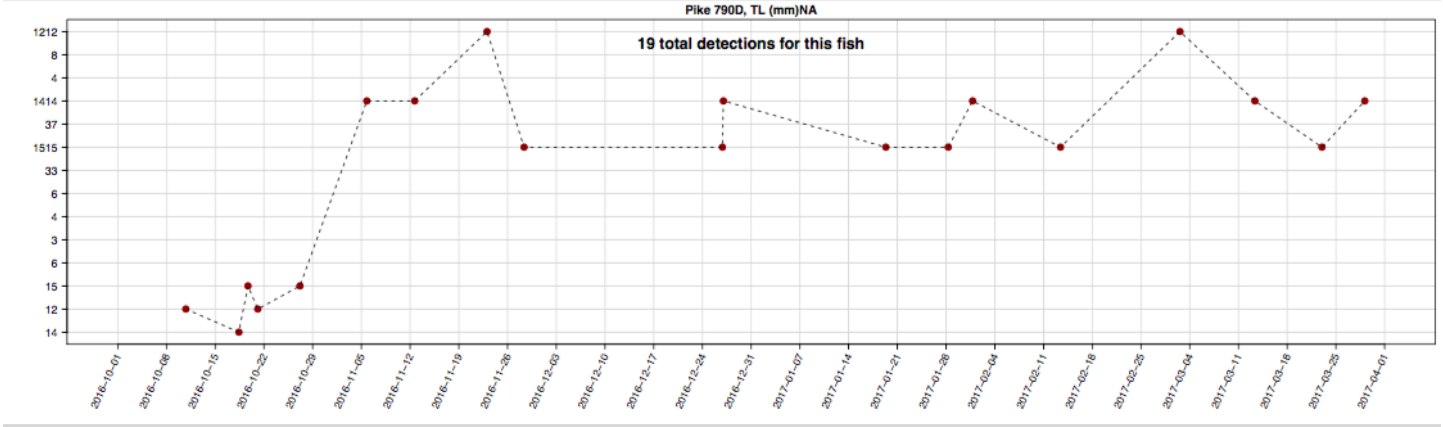

Pike 4D88, TL (mm)310
53 total detections for this fish


Pike 92F2, TL (mm)222
23 total detections for this fish


Pike EC39, TL (mm)259
31 total detections for this fish


Pike 5A49, TL (mm)235
8 total detections for this fish


Pike 69B5, TL (mm)216
5 total detections for this fish


Pike 790D, TL (mm)NA
19 total detections for this fish

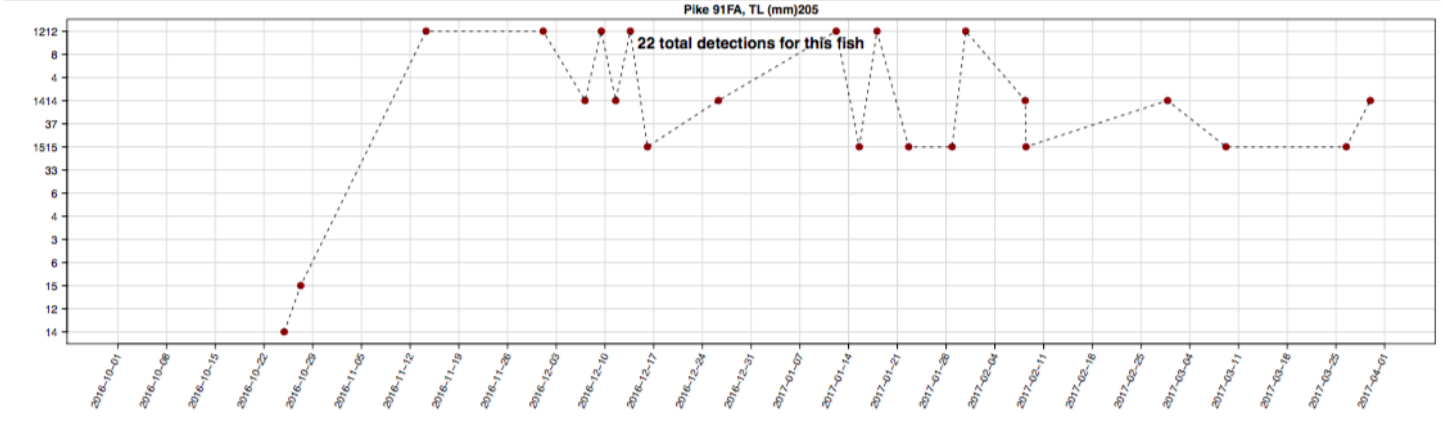

Pike 91FA, TL (mm)205
22 total detections for this fish

Figure S.3.12. Abacus plots for individual age-0 Northern Pike in Flynn Bay (n = 20) from October 1, 2016 to March 31, 2017. Points indicate when fish were detected, and lines movement patterns between receivers from nearshore (Y axis bottom) and deeper waters (Y axis top) in the fall and winter. Time is depicted by weeks starting with October 1, 2016 (X axis).

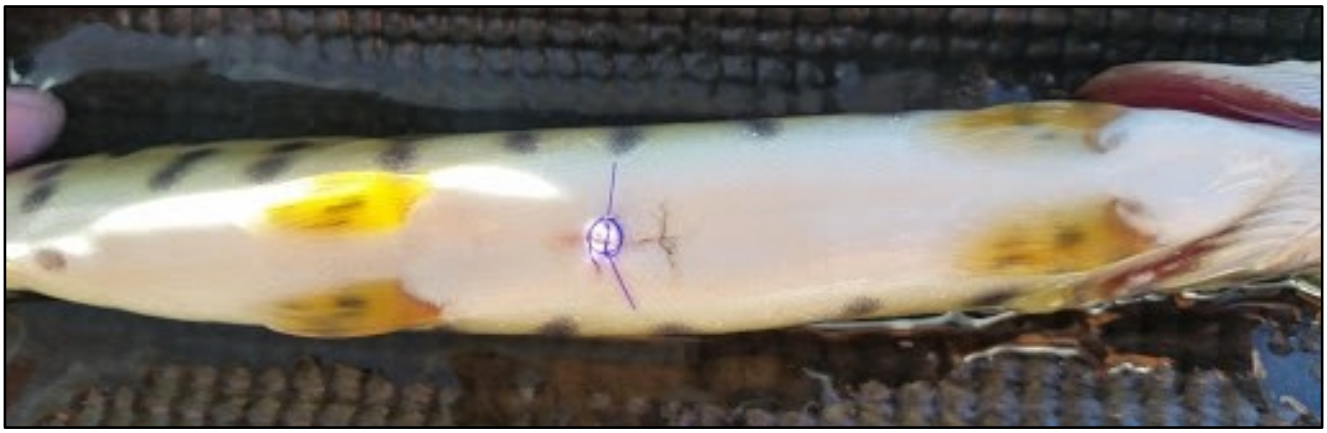


Figure S.3.13. A recaptured Muskellunge (tagged 933D on September 6, 2016) from Rose Bay retagged A76D on October 7, 2016. This fish was recaptured near its initial tagging location. It grew 78-mm and 49.3-g in four weeks. Note the former surgery is nearly healed and only one dissolvable suture is retained.

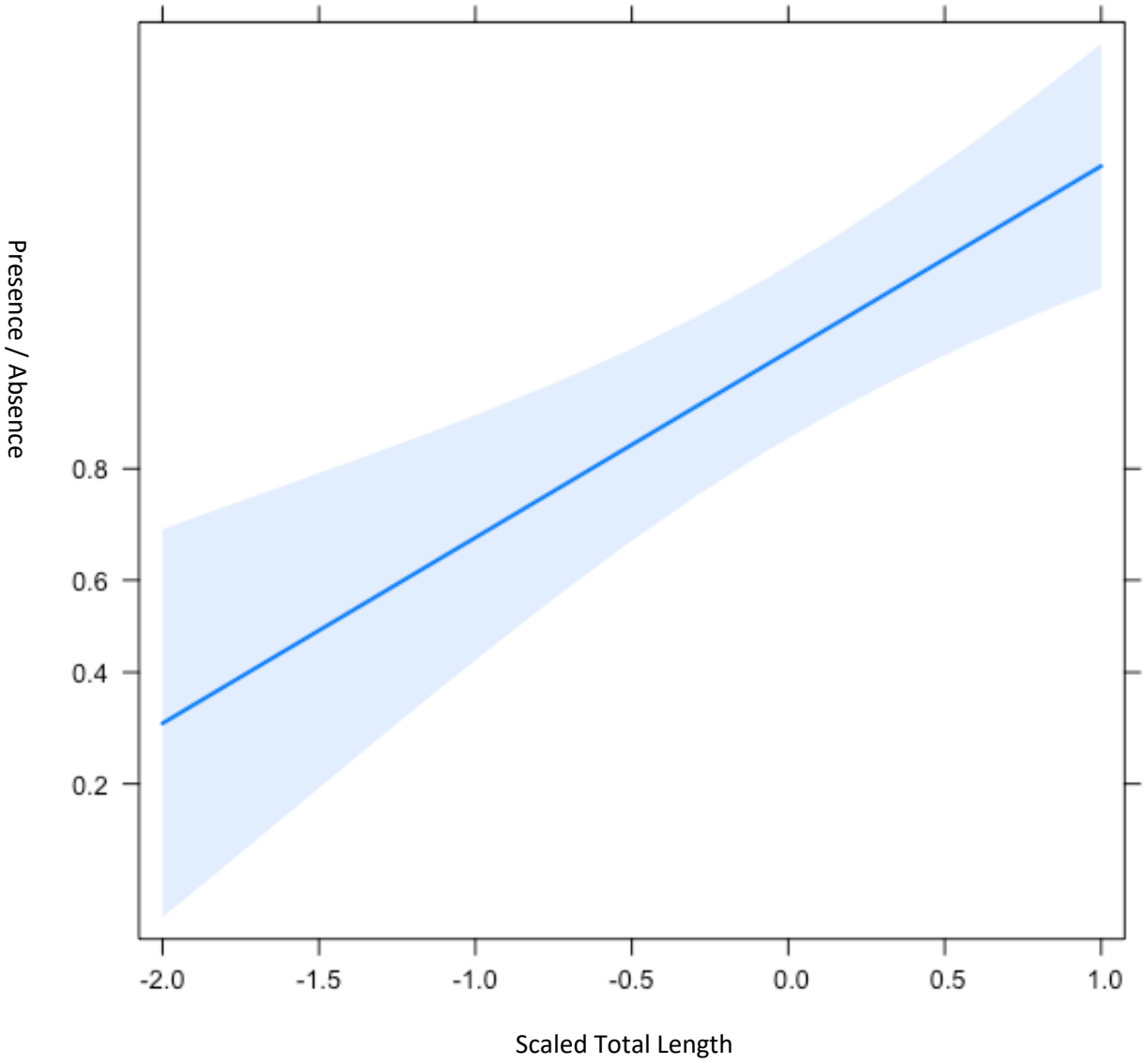


Figure S.3.14. Interaction plot indicating that the likelihood of an age-1 Muskellunge in Rose Bay being present in the array from October 2016 to March 2017 increased with the initial total length of a fish when captured as a young-of-year.

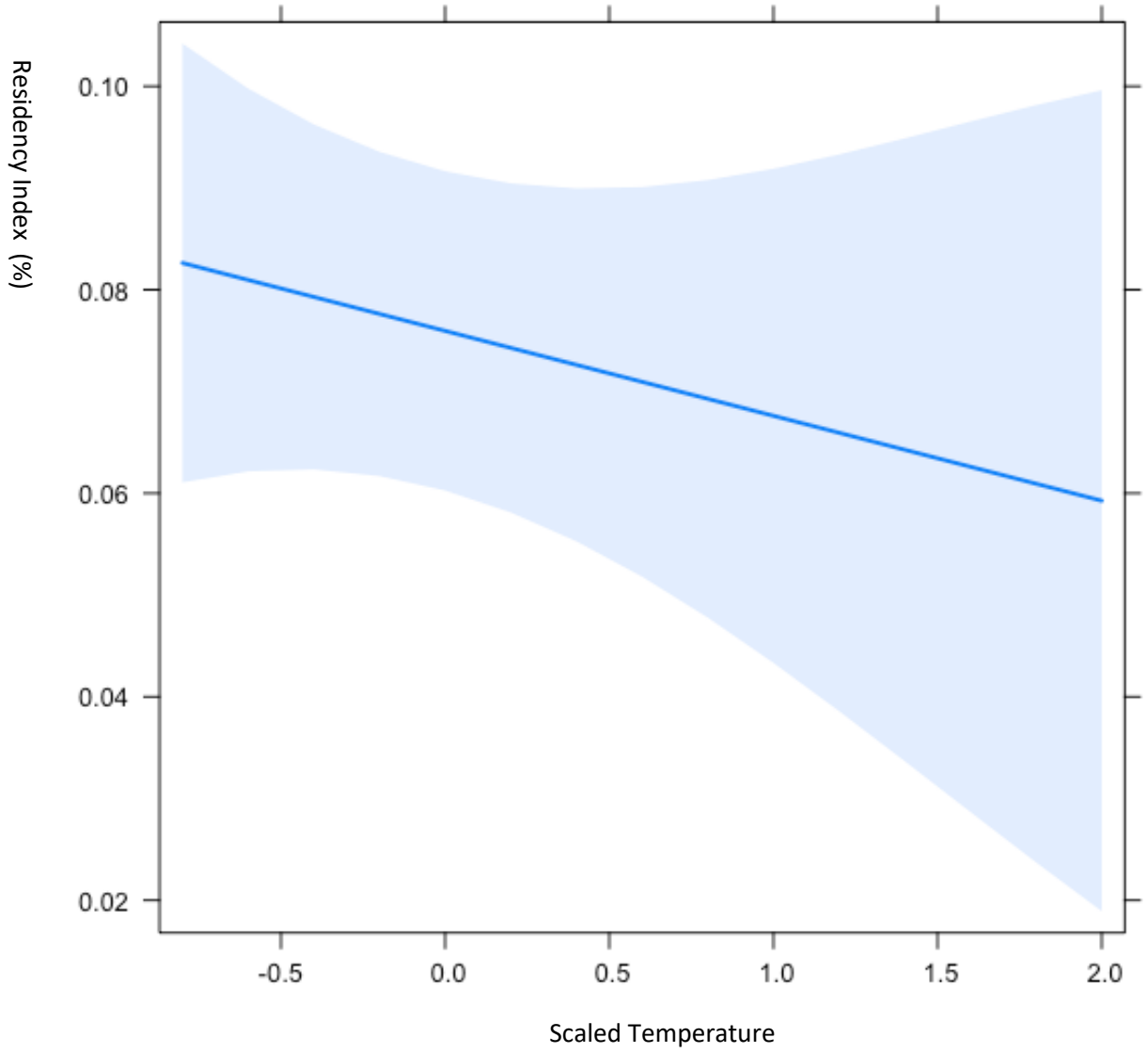


Figure S.3.15. Interaction plot indicating that the likelihood of an age-1 Muskellunge in Rose Bay residing in the array from October 2016 to March 2017 decreased as air temperatures increased.

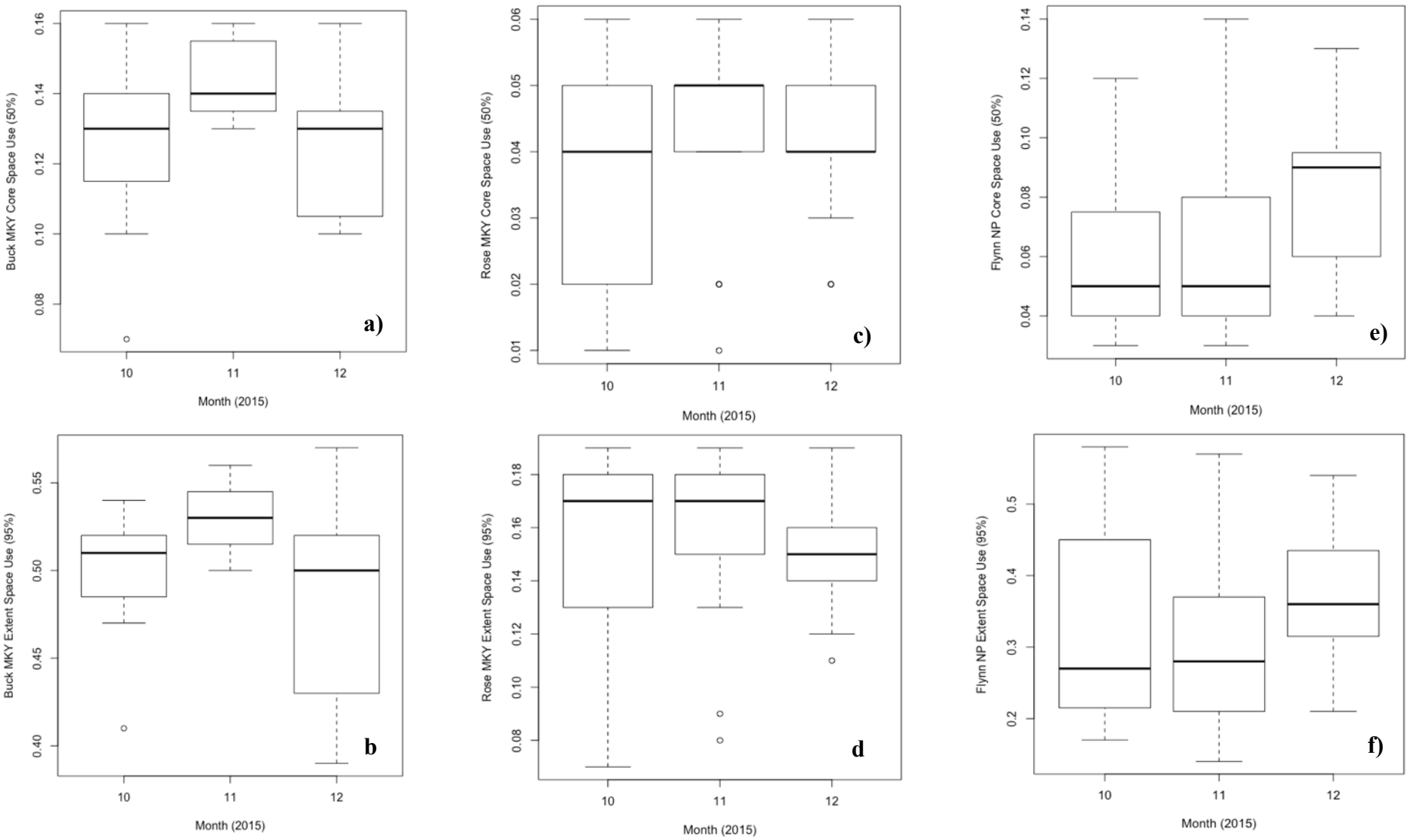


Fig. S.3.16. Space use for age-0 Buck Muskellunge (a, core; b, extent), age-0 Rose muskellunge (c, core; d, extent), and age-0 Flynn Northern pike (e, core; f, extent) by month in 2015; month is indicated by numbers (10 - October, 11 - November, 12 - December).

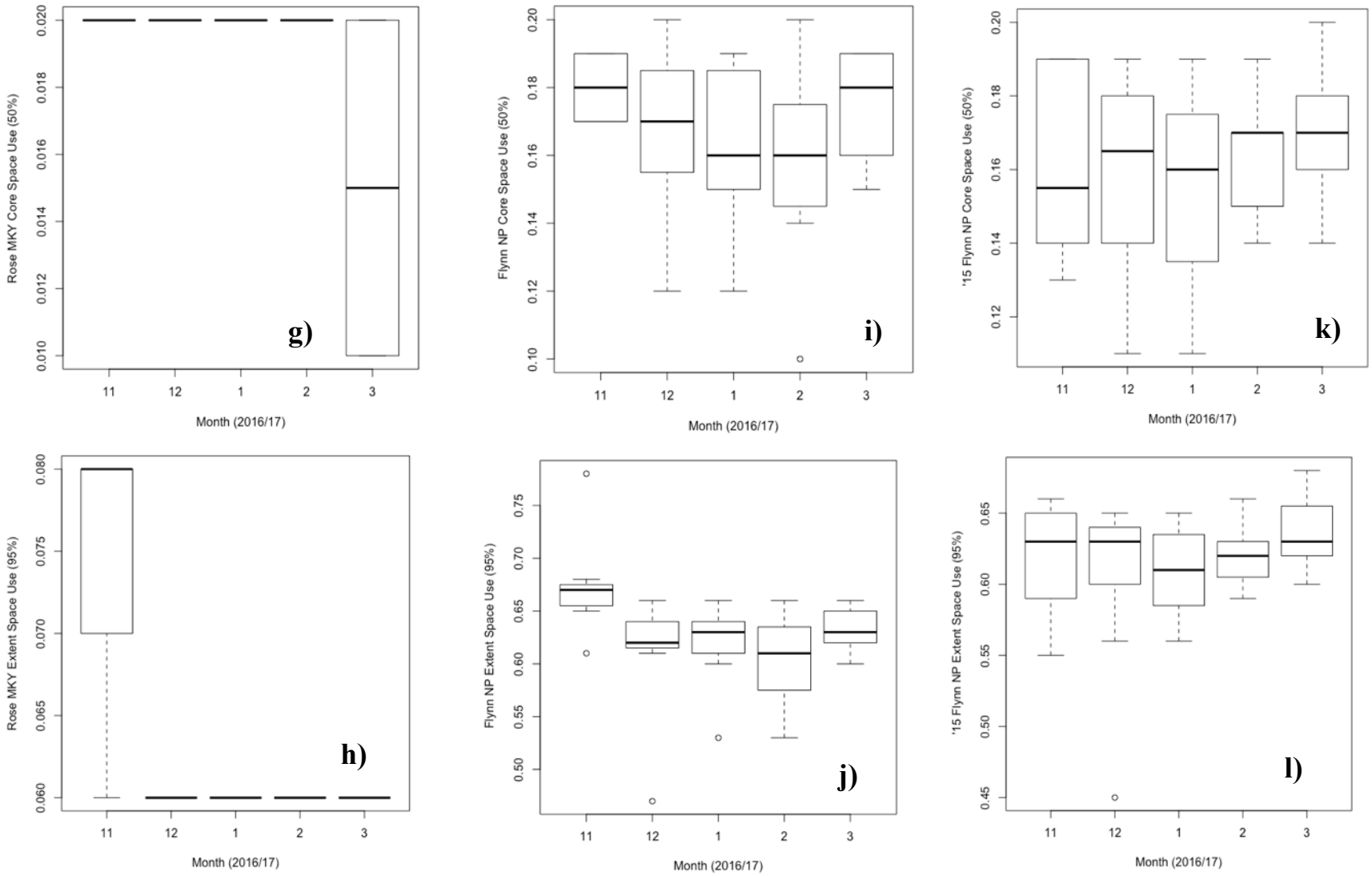


Fig. S.17. Space use for age-0 Rose Bay muskellunge (g, core; h, extent), age-0 Flynn Bay Northern pike (i, core; j, extent), and age-1 Flynn Bay Northern pike (k, core; l, extent) by month in 2016/17. Month is indicated by numbers (11 - November, 12 - December, 1 - January, 2 - February, 3 - March).

Table S.3.1 Biological and monthly detection data for individual age-0 Muskellunge and Northern Pike monitored in their natal embayments from October to December 2015. Total detections for an individual fish were documented after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other. 875E is the lone Muskellunge monitored in captured in Flynn Bay and monitored in Buck Bay.

JSAT TAG ID	Total Length ± SD (mm)	Bay	Total Detections October	Total Detections November	Total Detections December
0FEA	140	ROSE	153	169	53
4253	185	ROSE	47	23	5
4494	122	ROSE	37	22	12
49DA	122	ROSE	673	22	6
646B	145	ROSE	62	23	10
64E7	156	ROSE	83	24	4
757D	125	ROSE	50	36	14
8915	158	ROSE	30	28	10
9253	179	ROSE	10	16	5
A4BE	160	ROSE	3960	23	6
B156	174	ROSE	19	12	11
B690	126	ROSE	467	30	6
BD92	150	ROSE	72	20	4
BF23	148	ROSE	247	51	16
D0E7	171	ROSE	3621	12758	6
DA2A	149	ROSE	15	12	3
DF35	125	ROSE	30	24	8
E0A8	170	ROSE	2262	5378	699
E528	162	ROSE	4150	8418	7
FFA6	156	ROSE	80	56	19
5859	167	BUCK	13	21	5
730C	143	BUCK	66	57	23
AEF1	158	BUCK	78	15	9
C687	181	BUCK	48	34	13
E6CC	127	BUCK	20	18	5
F3B8	195	BUCK	30	64	10
F50E	177	BUCK	16	16	5
062C	200	FLYNN	70	11	2
1243	210	FLYNN	419	382	30
419B	255	FLYNN	1110	1224	648
424F	215	FLYNN	165	248	4
4BA2	298	FLYNN	7	10	3
4E15	250	FLYNN	234	391	5
53FE	205	FLYNN	362	906	3
5638	172	FLYNN	79	764	14
6944	356	FLYNN	138	71	91
6BA2	301	FLYNN	15	319	2

704D	241	FLYNN	281	1351	373
72C3	216	FLYNN	894	545	12
*875E	223	FLYNN	10	12	6
9088	235	FLYNN	508	290	3
93FA	222	FLYNN	900	1257	157
99EB	146	FLYNN	6	7	1
A6AE	240	FLYNN	307	3	1
AA29	247	FLYNN	18	3	2
BF60	380	FLYNN	54	49	17
C57F	275	FLYNN	964	779	1
CD5B	213	FLYNN	781	478	27
CF7F	247	FLYNN	166	318	37
D3B1	252	FLYNN	35	12	4
DDFD	171	FLYNN	120	137	38

Table S.3.2 Biological and monthly detection data for individual age-0 Muskellunge and age-0 Northern pike monitored in their natal embayments from October 2016 to March 2017. Total detections collected from an individual fish, after filtering for double detections (receiver overlap) and removing detections within 5-minutes of each other, for each month, respectively.

Species	JSAT TAG ID	Total Length ± SD (mm)	Weight ± SD(g)	Capture Bay	Total Detections October	Total Detections November	Total Detections December	Total Detections January	Total Detections February	Total Detections March
Musky	933D	156	18.0	ROSE	39	38	25	0	4	2
Musky	3605	168	25.5	ROSE	15	15	10	11	9	10
Musky	0274	118	11.9	GRASS	18	9	9	18	17	9
Musky	07DE	196	41.5	GRASS	41	4	49	37	38	52
Musky	33F4	176	32.1	GRASS	13	9	10	11	8	10
Musky	30EC	155	18.0	ROSE	9	8	11	10	8	10
Musky	790D	154	18.0	FLYNN	5	5	3	4	1	6
Musky	AAD4	178	32.8	GRASS	3	6	2	3	2	3
Musky	D14F	203	40.4	GRASS	7	7	6	9	4	13
Musky	810C	250	78.5	ROSE	22	13	19	21	12	16
Musky	**A76D	234	67.5	ROSE	321	377	2	1	1	5
N. Pike	413E	263	118.0	FLYNN	13	11	19	18	9	20
N. Pike	38C3	250	110.5	FLYNN	16	12	9	17	10	15
N. Pike	4D88	310	202.8	FLYNN	10	15	11	11	12	12
N. Pike	†EC39	259	115.5	FLYNN	6	4	9	5	11	9
N. Pike	†F60E	254	105.6	FLYNN	27	32	28	26	25	29
N. Pike	91FA	205	58.4	FLYNN	2	1	7	6	4	4
N. Pike	36B8	179	40.1	FLYNN	4	4	7	6	9	5
N. Pike	5A49	235	89.8	FLYNN	1	2	3	1	2	2

N. Pike	69B5	216	67.5	FLYNN	0	1	1	1	3	1
N. Pike	1A2B	219	66.8	FLYNN	2	6	4	7	6	6
N. Pike	0351	183	38.0	FLYNN	14	15	19	22	21	18
N. Pike	92F2	222	78.0	FLYNN	4	4	3	3	4	4
N. Pike	4317	195	43.8	FLYNN	19	17	21	9	10	20
N. Pike	0219	215	70.8	FLYNN	63	81	74	78	55	70
N. Pike	169A	197	47.8	FLYNN	1	5	3	3	3	5

Table S.3.3 Collinearity data (VIF) for presence/absence (PA), residency index (RI) and space use (SU) "Models" for age-0 Muskellunge in Rose Bay based on "Year" (2015 - 15, 2016/17 - 1617).

Year	Model	Factor	VIF
15	PA	cTL	1
		cTEMP	1.386425
		cLEVEL	1.386425
1617	PA	cTL	1
		cTEMP	1.503419
		cLEVEL	1.503419
15	RI	cTL	1.004039
		cTEMP	1.403956
		cLEVEL	1.40422
1617	RI	cTL	1
		cTEMP	1.588863
		cLEVEL	1.588863
15	SU	cTL	1
		cTEMP	1.588863
		cLEVEL	1.588863
1617	SU	cTL	1.036146
		cTEMP	1.495974
		cLEVEL	1.480366
15	HAB	cTL	1
		cTEMP	1.44
		cLEVEL	1.44
1617	HAB	cTL	1
		cTEMP	1.49
		cLEVEL	1.49

Table S.3.4 Model comparisons for age-0 Muskellunge in Rose Bay for presence/absence (PA), residency index (RI) and space use (SU) variables based on "Year" as 2015 (15) or 2016/17 (1617). "Formula" dictates the factors used in each model, the "AIC" value indicates which was lower, and the "p Value" shows whether the alternate model was significantly different. Formulas in bold indicate the alternative model was significantly different from the null model.

Year	Function	Variable	Formula	df	AIC	p Value
15	GLMER	PA	PA ~ cTEMP + cTL + (1| FISH)	4	50.82	
			PA ~ 1 + (1| FISH)	1	47.23	0.5288
1617	GLMER	PA	**PA ~ cTEMP + cTL + (1| FISH)**	**4**	**23.20**	**<0.001**
			PA ~ cLEVEL + cTL + (1| FISH)	4	29.21	
			PA ~ 1 + (1| FISH)	2	33.77	
15	LMER	RI	**RES ~ cLEVEL + cTEMP + cTL + (1| FISH)**	**6**	**-14.28**	**0.01**
			RES ~ 1 + (1| FISH)	3	-9.44	
1617	LMER	RI	**RES ~ cLEVEL + cTEMP + cTL + (1| FISH)**	**6**	**-9.43**	**0.002**
			RES ~ 1 + (1| FISH)	3	-0.72	
15	LME	SU	KUD_50 ~ cTEMP + cLEVEL + cTL , ~ 1| FISH/MONTH	7	-326.48	0.1
			KUD_50 ~ 1, ~ 1| FISH/MONTH	4	-326.41	
			KUD_95 ~ cTEMP + cLEVEL + cTL, ~ 1| FISH/MONTH	7	-228.65	
			KUD_95 ~ 1, ~ 1| FISH/MONTH	4	-231.20	0.32
1617	LME	SU	KUD_50 ~ cTEMP + cLEVEL + cTL, ~ 1| FISH/MONTH	7	-99.33	
			KUD_50 ~ 1 , ~ 1| FISH/MONTH	4	-99.26	0.11
			KUD_95 ~ cTEMP + cLEVEL + cTL , ~ 1| FISH/MONTH	**7**	**-80.69**	**0.01**
			KUD_95 ~ 1, ~ 1| FISH/MONTH	4	-75.52	
15	LMER	HAB	**HAB ~ HABITAT + cLEVEL + cTL + (1| FISH)**	**6**	**-325.10**	**<0.001**
			HAB ~ 1 + (1| FISH)	3	-45.40	
1617	LMER	HAB	HAB ~ HABITAT + cLEVEL + cTL + (1| FISH)	6	567.45	
			HAB ~ 1 + (1| FISH)	**3**	**148.95**	**0.001**

Table S.3.5. Model output for age-0 Muskellunge in Rose Bay for presence/absence (PA), residency index (RI) and space use (SU) models. "Factor" highlights the variable used in the model, "X^2" the Chi Square value from the Anova () model, and the "P Value" indicates significant differences between the factor to the dependent model variable. Bolded factors indicate those that significantly influenced the dependent model factor.

Year	Model	Factor	X^2	P Value
15	PA	(Intercept)	24.8209	6.29E-07
		ctl	0.3891	0.5327
		ctemp	0.01	0.9202
1617	PA	(Intercept)	0.5149	0.473
		ctl	0.0439	0.834
		ctemp	0.5898	0.443
15	RI	(Intercept)	171.835	< 2.2e-16
		ctl	0.0596	0.807
		ctemp	**7.5242**	**0.006**
		clevel	0.0206	0.886
1617	RI	(Intercept)	124.09	< 2.2e-16
		ctemp	**9.7294**	**0.002**
		clevel	0.1753	0.675
		ctl	**4.4903**	**0.034**
15	SU_50	(Intercept)	236.4473	< 2e-16
		ctl	1.4306	0.231
		ctemp	**4.5914**	**0.032**
		clevel	**4.1875**	**0.041**
	SU_95	(Intercept)	1338.5754	<2e-16
		ctl	2.4806	0.115
		ctemp	0.8263	0.363
		clevel	0.0052	0.943
1617	SU_50	(Intercept)	945.7814	< 2e-16
		ctl	2.0598	0.151
		ctemp	0.0431	0.836
		clevel	**5.07**	**0.024**
	SU_95	(Intercept)	2198.0766	< 2.2e-16
		ctl	0.5115	0.474

		ctemp	**14.3633**	**0.000**
		clevel	0.1888	0.664
15	HAB	(Intercept)	2.96E+05	<2e-16
		habitat	**9.28E+03**	**<2e-16**
		ctl	4.80E-03	0.945
		clevel	2.24E-01	0.636
1617	HAB	(Intercept)	2.13E+05	< 2.2e-16
		habitat	**1.40E+05**	**< 2.2e-16**
		ctl	**2.74E+00**	**0.098**
		ctemp	1.34E+00	0.247
		clevel	5.95E-02	0.807

Table S.3.6. Collinearity data (VIF) for presence/absence (PA), residency index (RI) and space use (SU) "Models" for age-0 Northern Pike in Flynn Bay based on "Year" (2015 - 15, 2016/17 - 1617). Air temperature was used as a proxy for water temperature in 2015, and collinearity values indicated correlation (VIF >5), water level was the sole environmental variable kept in the statistical formula.

Year	Model	Factor	VIF
15	PA	cTL	1
		cTEMP	67.82
		cLEVEL	67.82
15.2		cTL	1
		cLEVEL	1
1617	PA	cTL	1
		cTEMP	1.24
		cLEVEL	1.24
15	RI / SU	cTL	1
		cTEMP	67.82
		cLEVEL	67.82
		cTL	1
		cLEVEL	1
1617	RI	cTL	1
		cTEMP	1.24
		cLEVEL	1.24
1617	SU	cTL	1.04
		cTEMP	1.50
		cLEVEL	1.48
15	HAB	cTL	1.02
		cTEMP	15.23
		cLEVEL	15.23
		cTL	1
		cLEVEL	1
1617	HAB	cTL	1.04
		cTEMP	1.50
		cLEVEL	1.48

Table S.3.7. Model comparisons for age-0 Northern Pike in Flynn Bay for presence/absence (PA), residency index (RI) and space use (SU) variables based on "Year" as 2015 (15) or 2016/17 (1617). "Formula" dictates the factors used in each model, the "AIC" value indicates which was lower, and the "p Value" shows whether the alternate model was significantly different. Formulas in bold indicate the alternative model was significantly different from the null model.

Year	Function	Model	Formula	df	AIC	p Value
15	**GLMER**	**PA**	**PA ~ cTEMP + cTL + (1| FISH)**	**4**	**61.70**	**<0.001**
			PA ~ cLEVEL + cTL + (1| FISH)	4	62.94	
			PA ~ 1 + (1| FISH)	2	77.69	
1617	GLMER	PA	PA ~ cTEMP + cLEVEL + cTL + (1| FISH)	5	87.67	
			PA ~ 1 + (1| FISH)	2	88.14	0.09
15	**LMER**	**RI**	**RES ~ cLEVEL + cTL + (1| FISH)**	**4**	**-20.48**	**<0.001**
			RES ~ 1 + (1| FISH)	2	-2.934	
1617	**LMER**	**RI**	**RES ~ cLEVEL + cTEMP + cTL + (1| FISH)**	**6**	**-233.24**	**<0.002**
			RES ~ 1 + (1| FISH)	3	-229.78	
15	LME	SU	KUD_50 ~ cLEVEL + cTL, ~ 1| FISH/MONTH	6	-164.00	
			KUD_50 ~ 1, ~ 1| FISH/MONTH	4	-163.58	0.27
			KUD_95 ~ cLEVEL + cTL, ~ 1| FISH/MONTH	6	-52.52	
			KUD_95 ~ 1, ~ 1| FISH/MONTH	4	-56.34	0.91
1617	**LME**	**SU**	KUD_50 ~ cTEMP + cLEVEL + cTL, ~ 1| FISH/MONTH	7	-158.00	
			KUD_50 ~ 1 , ~ 1| FISH/MONTH	4	-156.58	0.06
			KUD_95 ~ cTEMP + cLEVEL + cTL, ~ 1| FISH/MONTH	**7**	**-104.95**	**0.01**
			KUD_95 ~ 1 , ~ 1| FISH/MONTH	4	-100.96	
15	**LMER**	**HAB**	**HAB ~ HABITAT + cLEVEL + cTL + (1| FISH)**	**8**	**-271.23**	**<0.001**
			HAB ~ 1 + (1| FISH)	3	-124.70	
1617	**LMER**	**HAB**	**HAB ~ HABITAT + cLEVEL + cTL + (1| FISH)**	**9**	**-425.93**	**<0.001**
			HAB ~ 1 + (1| FISH)	3	-226.02	

Table S.3.8. Model output for age-0 Northern Pike in Flynn Bay for presence/absence (PA), residency index (RI) and space use (SU) models. “Factor” highlights the variable used in the model, “ChiSqu” the value from the Anova() model, and the “P Value” indicates significant differences between the factor to the dependent model variable. Bolded factors indicate those that significantly influenced the dependent model factor.

Year	Model	Factor	X^2	P Value
15	PA	(Intercept)	7.4589	0.006312
		ctl	6.8881	0.853228
		clevel	**0.0342**	**0.008677**
1617	PA	(Intercept)	0.226	0.635
		ctl	2.44	0.118
		clevel	1.9534	0.162
		ctemp	2.4595	0.117
15	RI	(Intercept)	104.592	<2e-16
		clevel	**26.3046**	**<0.001**
		ctl	0.1358	0.713
1617	RI	(Intercept)	33.1815	8.395e-09
		ctl	0.5979	0.439
		ctemp	**9.0821**	**0.002**
		clevel	0.4860	0.486
15	SU_50	(Intercept)	96.4609	<2e-16
		ctl	0.0953	0.758
		clevel	2.5901	0.108
	SU_95	(Intercept)	133.5557	<2e-16
		ctl	0.0688	0.793
		clevel	0.1088	0.742
1617	SU_50	(Intercept)	1461.2612	< 2e-16
		ctl	2.7552	0.097
		ctemp	**5.4234**	**0.020**
		clevel	0.3354	0.563
	SU_95	(Intercept)	7035.7926	< 2.2e-16
		ctl	1.5117	0.219
		ctemp	**9.3907**	**0.002**
		clevel	0.2602	0.610
15	HAB	(Intercept)	1106.982	< 2e-16
		habitat	**514.7326**	**< 2e-16**
		clevel	**4.7068**	**0.03004**
		ctl	0.082	0.77459
1617	HAB	(Intercept)	243.0656	< 2.2e-16
		habitat	**182.8703**	**< 2.2e-16**
		ctl	0.0013	0.098
		ctemp	0.1343	0.247

Table S.3.9. Model comparisons for age-0 Muskellunge in Buck Bay for presence/absence (PA), residency index (RI) and space use (SU) variables in 2015. "Formula" dictates the factors used in each model, the "AIC" value indicates which was lower, and the "p Value" shows whether the alternate model was significantly different. Formulas in bold indicate the alternative model was significantly different from the null model. Collinearity was the same for all models: 1 for cTL and 5.08 for each cLEVEL and cTEMP. As air temperature was used as a proxy for water temperature, cTEMP was dropped from the formula

Function	Model	Formula	df	AIC	p Value
GLMER	PA	**PA ~ cLEVEL + cTL + (1| FISH)**	**3**	**16.593**	**0.003**
		PA ~ 1 + (1| FISH)	2	24.45033	
LMER	RI	PA ~ cLEVEL + cTL + (1| FISH)	6	-11.538	0.7
		PA ~ 1 + (1| FISH)	3	-6.948	
LME	SU	KUD_50 ~ cLEVEL + cTL, ~ 1| FISH/MONTH	6	-87.34628	
		KUD_50 ~ 1, ~ 1| FISH/MONTH	4	-90.33165	0.6
		KUD_95 ~ cLEVEL + cTL, ~ 1| FISH/MONTH	6	-55.06325	0.8
		KUD_95 ~ 1, ~ 1| FISH/MONTH	4	-58.61949	
LMER	HAB	**HAB ~ HABITAT + cLEVEL + cTL + (1| FISH)**	**9**	**-76.987**	**<0.001**
		HAB ~ 1 + (1| FISH)	3	-0.24	

Table S.3.10. Model output for age-0 Muskellunge in Buck Bay for presence/absence (PA), residency index (RI) and space use (SU) models in 2015. "Factor" highlights the variable used in the model, "ChiSqu" the value from the Anova() model, and the "P Value" indicates significant differences between the factor to the dependent model variable. No biological or environmental variables influenced spatial ecology in Buck Bay.

Model	Factor	X^2	P Value
PA	(Intercept)		
	ctl	0.8162	0.3663
	clevel	0	0.9974
RI	(Intercept)	56.0807	0.000
	clevel	1.3015	0.254
	ctl	0.0517	0.820
SU_50	(Intercept)	697.3808	<2e-16
	ctl	0.1358	0.713
	clevel	0.9037	0.342
SU_95	(Intercept)	2202.1689	<2e-16
	ctl	0.2184	0.640
	clevel	0.2301	0.632
HAB	(Intercept)	0.0711	0.7898
	habitat	**229.1481**	**<2e-16**
	clevel	0.2919	0.589
	Ctemp	0.1403	0.708
	ctl	0.2654	0.6064

Table S.3.11. Model comparisons for age-0 Muskellunge in Grass Point Bay for presence/absence (PA), residency index (RI) and space use (SU) models between 2016 and 2017. "Formula" dictates the factors used in each model, the "AIC" value indicates which was lower, and the "p Value" shows whether the alternate model was significantly different. Formulas in bold indicate the alternative model was significantly different from the null model. Collinearity was the same for all models: 1 for cTL and 2 for each cLEVEL and cTEMP.

Function	Model	Formula	df	AIC	p Value
GLMER	PA	PA ~ cTEMP + cLEVEL + cTL + (1| FISH)	5	26.659	
		PA ~ 1 + (1| FISH)	2	22.722	0.56
LMER	RI	RES ~ cLEVEL + cTEMP + cTL + (1| FISH)	6	-33.185	
		RES ~ 1 + (1| FISH)	3	-39.028	1
LME	SU	KUD_50 ~ cTEMP + cLEVEL + cTL , ~ 1| FISH/MONTH	6	-92.60082	
		KUD_50 ~ MONTH, ~1 | FISH	7	-94.27143	0.06
		KUD_50 ~ 1 + (1| FISH)	4	-92.71965	
		KUD_95 ~ cTEMP + cLEVEL + cTL , ~ 1| FISH/MONTH	6	-55.77731	0.42
		KUD_95 ~ 1, ~ 1| FISH/MONTH	4	-58.06800	

Table S.3.12. Model output for age-0 Muskellunge in Grass Point Bay for presence/absence (PA), residency index (RI) and space use (SU) models for 2016 and 2017. "Factor" highlights the variable used in the model, "ChiSqu" the value from Anova models, and the "P Value" indicates significant differences between the factor to the dependent model variable. No biological or environmental variables influenced spatial ecology in Buck Bay.

Model	Factor	X^2	DF	P Value
PA	(Intercept)	0.6744	1	0.412
	ctl	0.7329	1	0.392
	clevel	0.425	1	0.514
	ctemp	0.8479	1	0.357
RI	(Intercept)	7.1342	1	0.007
	ctemp	0.2968	1	0.586
	clevel	2.9113	1	0.088
	ctl	0.0994	1	0.752
SU_50	(Intercept)	187.8358	1	< 2e-16
	ctl	0.0181	1	0.893
	clevel	0.2254	1	0.635
	ctemp	0.8094	1	0.368
SU_95	(Intercept)	649.2671	1	<2e-16
	ctl	0.5354	1	0.464
	clevel	0.2847	1	0.593
	ctemp	0.0016	1	0.986

Table S.3.13. Model comparisons for age-1 Northern Pike detected in Flynn Bay for presence/absence (PA), residency index (RI) and space use (SU) models between 2016 and 2017. "Formula" dictates the factors used in each model, the "AIC" value indicates which was lower, and the "p Value" shows whether the alternate model was significantly different. Formulas in bold indicate the alternative model was significantly different from the null model. Collinearity was the same for PA, RI and SU models: 1 for cTL and 2 for each cLEVEL and cTEMP. Collinearity for the habitat model was 1.308 (cLEVEL), 1.026 (cTL), and 1.34 (cTEMP).

Function	Model	Formula	df	AIC	p Value
GLMER	PA	PA ~ cTEMP + cLEVEL + cTL + (1| FISH)	5	26.659	
		PA ~ 1 + (1| FISH)	2	22.722	0.56
LMER	RI	RES ~ cLEVEL + cTEMP + cTL + (1| FISH)	6	- 472.59	
		RES ~ 1 + (1| FISH)	3	- 477.50	0.77
LME	SU	KUD_50 ~ cTEMP + cLEVEL + cTL , ~ 1| FISH/MONTH	7	-252.95	0.15
		KUD_50 ~ 1 + (1| FISH)	4	-252.34	
		KUD_95 ~ cTEMP + cLEVEL + cTL , ~ 1| FISH/MONTH	7	-207.21	0.18
		KUD_95 ~ 1, ~ 1| FISH/MONTH	4	-213.34	
LMER	HAB	**HAB ~ HABITAT + cLEVEL + cTEMP + cTL + (1| FISH)**	**8**	**-350.54**	**<0.001**
		HAB ~ 1 + (1| FISH)	3	-228.26	

Table S.3.14. Model output for age-1 Northern Pike presence/absence (PA), residency index (RI) and space use (SU) models for 2016 and 2017. "Factor" highlights the variable used in the model, "ChiSqu" the value from Anova models, and the "P Value" indicates significant differences between the factor to the dependent model variable. Though cLEVEL was found a significant covariate to core space use, there was no difference between the null and alternate model.

Model	Factor	X^2	DF	P Value
PA	(Intercept)	0.6744	1	0.412
	ctl	0.7329	1	0.392
	clevel	0.425	1	0.514
	ctemp	0.8479	1	0.357
RI	(Intercept)	58.9521	1	<2e-16
	ctemp	0.7672	1	0.381
	clevel	0.0008	1	0.977
	ctl	0.1028	1	0.787
SU_50	(Intercept)	1305.8762	1	< 2e-16
	ctemp	2.4608	1	0.116
	clevel	**6.1078**	**1**	**0.013**
	ctl	1.6436	1	0.200
SU_95	(Intercept)	37.5081	1	<2e-16
	ctl	0.2351	1	0.628
	ctemp	0.3366	1	0.562
	clevel	0.0976	1	0.755
HAB	(Intercept)	2056.4869	1	<2e-16
	habitat	**252.7292**	**2**	**<2e-16**
	ctl	0.1986	1	0.6559
	ctemp	0.6172	1	0.4321
	clevel	**3.9596**	**1**	**0.0466**

Table S.3.15. Collinearity data (VIF) for presence/absence (PA), residency index (RI) and space use (SU) "Models" for age-1 Muskellunge in Rose Bay from October 2016 to March 2017. Habitat use was not modeled, as all fish used the same proportion of habitat features.

Model	Factor	VIF
PA	cTL	1
	cTEMP	1.381751
	cLEVEL	1.381751
RI	cTL	1
	cTEMP	1.381751
	cLEVEL	1.381751
SU_95	cTL	1
	cTEMP	1.503419
	cLEVEL	1.503419

Table S.3.16. Model comparisons for age-1 Muskellunge detected in Rose Bay for presence/absence (PA), residency index (RI) and space use (SU) models between 2016 and 2017. "Formula" dictates the factors used in each model, the "AIC" value indicates which was lower, and the "p Value" shows whether the alternate model was significantly different. Formulas in bold indicate the alternative model was significantly different from the null model. Models were not performed on habitat use; all fish used the deep zone >95% of the time.

Function	Model	Formula	df	AIC	p Value
GLMER	PA	**PA ~ cTEMP + cLEVEL + cTL + (1| FISH)**	**5**	**37.478**	**0.01**
		PA ~ 1 + (1| FISH)	2	37.234	
LMER	RI	RES ~ cLEVEL + cTEMP + cTL + (1| FISH)	6	- 155.91	
		RES ~ 1 + (1| FISH)	3	- 156.65	0.15
LME	SU	KUD_95 ~ cTEMP + cLEVEL + cTL , ~ 1| FISH/MONTH	7	-128.54	
		KUD_95 ~ 1 + (1| FISH)	4	-131.05	0.32

Table S.3.17. Model output for age-1 Muskellunge presence/absence (PA), residency index (RI) and space use (SU) models from October 2016 to March 2017. "Factor" highlights the variable used in the model, "ChiSqu" the value from Anova models, and the "P Value" indicates significant differences between the factor to the dependent model variable. KUD_50 was 0.02 for all fish, therefore, no analysis was completed on this parameter. Models were not performed on habitat use; all fish used the deep zone >95% of the time.

Model	Factor	X^2	DF	P Value
PA	(Intercept)	6.3791	1	0.012
	ctl	**4.7012**	**1**	**0.030**
	clevel	2.2198	1	0.136
	ctemp	0.1874	1	0.665
RI	(Intercept)	58.9521	1	<0.001
	ctemp	**0.7672**	**1**	**0.021**
	clevel	0.0008	1	0.240
	ctl	0.1028	1	0.839
SU_95	(Intercept)	2205.8749	1	<2e-16
	ctl	1.3926	1	0.2380
	ctemp	0.0274	1	0.8686
	clevel	1.8538	1	0.1733

Table S.3.18. Model output for age-1 Muskellunge presence/absence (PA), residency index (RI) and space use (SU) models from October 2016 to March 2017. "Factor" highlights the variable used in the model, "ChiSqu" the value from Anova models, and the "P Value" indicates significant differences between the factor to the dependent model variable. KUD_50 was 0.02 for all fish, therefore, no analysis was completed on this parameter.

Species + Bay	Cohort	Model + Year	Parameter	Comparison	Estimate	St. Error	Z Value	P Value
Northern Pike + Flynn	Age-1	RI + 2015	Water Level (meters)	**74.56 - 74.47**	**0.14208**	**0.03947**	**3.600**	**<0.001**
				74.67 - 74.47	**0.20750**	**0.03947**	**5.258**	**<0.001**
				74.67 - 74.56	0.06542	0.03947	1.658	0.22
Muskellunge + Rose	Age-0	RI + 2015	Water Temperature	10.5 - 9.3	-0.06562	0.04929	-1.331	0.378
				11.6 - 9.3	0.10272	0.04696	2.188	0.073
				11.6 - 10.5	**0.16834**	**0.04948**	**3.403**	**0.002**
Muskellunge + Rose	Age-0	RI + 2016/17	Water Temperature	(-3.0) - (-3.2)	0.05333	0.10536	0.506	1
				(-2.2) - (-3.2)	0.04000	0.10536	-0.380	1
				(-1.6) - (-3.2)	0.04333	0.10536	0.411	1
				4.8 - (-3.2)	0.02000	0.10536	0.190	1
				9.9 - (-3.2)	**0.42667**	**0.10536**	**4.050**	**< 0.001**
				(-2.2) - (-3.0)	-0.09333	0.10536	-0.886	0.95
				(-1.6) - (-3.0)	-0.01000	0.10536	-0.095	1
				4.8 - (-3.0)	-0.03333	0.10536	-0.316	1
				9.9 - (-3.0)	**0.37333**	**0.10536**	**3.543**	**0.005**
				(-1.6) - (-2.2)	0.08333	0.10536	0.791	0.97
				4.8 - (-2.2)	0.06000	0.10536	0.569	1
				9.9 - (-2.2)	**0.46667**	**0.10536**	**4.429**	**<0.001**
				4.8 - (-1.6)	-0.02333	0.10536	-0.221	1
				9.9 - (-1.6)	**0.38333**	**0.10536**	**3.638**	**0.003**
				9.9 - 4.8	**0.40667**	**0.10536**	**3.860**	**0.002**

Chapter 4. General Discussion

My thesis sought to validate the use of mini-acoustic for age-0 Muskellunge by measuring biologically relevant endpoints, and to improve our basic understanding of age-0 Muskellunge and Northern Pike spatial ecology to inform habitat restoration, spatial research studies, and water level management in the upper St. Lawrence River. In Chapter 2, captive reared, age-0 Muskellunge were subject to three treatments - tagged (sedated, laparotomy, mini-acoustic transmitter implantation), sham (sedated and laparotomy), and control (solely measured) - and their survival, tag retention, tag burden, incision healing, growth rates and flight initiation response post chemical anesthesia were assessed at specified sampling intervals over a four-month period. Chapter 3 focused on evaluating spatial ecology (i.e. presence, residency, space use) and habitat use of wild and stocked age-0 Muskellunge and free ranging age-0 Northern Pike overwinter and how environmental (e.g. water temperature and level) and biological (e.g. body size) parameters may influence spatial ecology based on passive-acoustic telemetry monitoring.

Research on the spatial ecology of earlier Muskellunge and Northern Pike life stages have primarily targeted summer, natal habitat uses (e.g. Leblanc et al. 2014, Farrell et al. 2014) and movement and dispersal of stocked fish in riverine systems (e.g. Wagner and Wahl 2011, Owensby et al. 2017). My thesis generated data which verified that mini-acoustic transmitter implantation is appropriate to conduct spatiotemporal studies on juvenile Muskellunge and *in-situ* results which supported the importance of environmental parameters on the fall and overwinter spatial ecology for age-0 Muskellunge and Northern Pike. Indeed, results elucidated that environmental parameters may drive fine-scale habitat segregation between the two species and provided a foundation on which future studies may tests hypotheses related to habitat restoration initiatives and riverine management associated with water level regulation.

Although variation in array design between the seasons in which fish were tracked inherently limited the ability to compare spatiotemporal patterns, each design permitted comparisons in overall habitat feature use in relation to embayment geomorphology. Furthermore, age-0 Muskellunge are elusive, and due to declining stocks, sample sizes of Muskellunge tagged varied year-to-year, resulting in a low catch per unit effort and few fish to monitor. Future studies are encouraged to use a consistent array design to better compare, and to elucidate patterns associated with movement through network analyses using the current dataset on Rose Bay Muskellunge and Flynn Bay Northern Pike monitored in 2015. Despite design and sampling challenges, this research generated useful information associated with the winter phenology of juvenile Muskellunge and Northern Pike in a large riverine system near the northeastern extent of their sympatric range.

4.1 Findings and Implications

4.1.1 Intracoelomic tagging and surgical process

In Chapter 2, I assessed whether the surgical process and presence of acoustic tags associated with passive telemetry monitoring influenced short-term biology and behaviour. Specifically, I aimed to quantify several endpoints after fish underwent sedation, laparotomy, and intracoelomic implantation of mini-acoustic transmitters. My overall findings strongly suggest that the implantation process (e.g. laparotomy, suturing, presence of intracoelomic tag) do not impose issues on the short-term growth and survival of juvenile Muskellunge, though chemical sedation may cause lingering behavioural effects which could increase predation risk in their natural environment. All fish survived the surgical process and no fish died due to complications with tag presence (e.g. infection, starvation); the two mortalities in the study were due to tank escapement. Tag retention was 100% for all fish, and necropsies of the two tagged fish that escaped indicated tags did not move post-insertion, and rapid healing (30- to 60-days) of the incision wounds likely attributed to tag retention. Tag burden was low (<1%) at the start

of the study, and without negative influence of process or tag on the growth of fish after four-months, burden progressively decreased.

Short-term healing rates between the free-ranging recapture and those Muskellunge retained in captivity were similar at 30-days post-surgery; however, captive reared Muskellunge implanted with an acoustic tag experienced significant increase in dehiscense (dermal rupture) after 60-days, concurrent with the lowest average water temperatures. Incisions of free-ranging Walleye (*Sander vitreus*), captured and tagged over five years in Lake Erie and Lake Huron between March and April, fully closed 62-days post-surgery (Schoonyan et al. 2017). To this end, increasing water temperatures in late spring (May, June) and higher water temperatures retained from summer in early fall (October) likely expedited wound closure and ejection of absorbable sutures (e.g. Walsh et al. 2000) in free-ranging fish. Indeed, no inflammation or dermal rupture were observed in the age-0 Muskellunge recaptured 30-days after its initial processing in the upper St. Lawrence River (Fig. S.13), and suture absorption had begun. Such rapid healing post-surgery in free-ranging fishes (e.g. Walsh et al. 2000, Schoonyan et al. 2017) was evident in both our free-ranging and hatchery reared juvenile Muskellunge, as wounds healed shortly after the 60-day period. Though control fish grew longer and heavier than sham and tagged fish the first week, as groups which underwent laparotomy may have allocated more energy to initiate wound closure to than somatic growth, specific growth rates of all treatment groups were similar after 120-days indicating no physical limitations (e.g. foraging capacity, somatic growth) associated with tag presence over this short-term period.

Reaction of fish to the moving object after initial exposure indicated that both tagged and sham fish experienced inhibited responses at different time scales. Tagged fish experienced a significantly inhibited response relative to sham and control fish immediately after chemical sedation, compared to sham fish's inhibited response seven-days beyond surgery. I postulate the inhibited response and reduced

growth rates of sham fish between 7- and 30-days post-surgery may be associated with greater exposure to MS-222 and may be linked to decreased blood levels of Na^+, Ca^{2+}, and K^+ previously observed with increased MS-222 exposure in juvenile Chinook Salmon (Wagner et al. 2014). As blood plasma samples were not collected, this cannot be confirmed. The inhibited response by tagged fish suggests the potential for sublethal effects (e.g. predation) immediately post-recovery, signifying the need for interdisciplinary studies to link short-term behaviour, post-tag implantation, with physiology. Moreover, my results reiterate the importance of allowing fish to recover and testing for RAMP metrics (e.g., Raby et al. 2012) prior to release. MS-222 induced knock out times for hatchery fish were substantially reduced (2-minutes vs. 5-minutes) relative to their wild congeners in the upper St. Lawrence River, likely due to prior narcosis by electrosedation for the hatchery fish.

Validating the effects of surgical procedures, tag presence, and anesthetic exposure is necessary to reduce harm associated with processing and manipulating fish for spatiotemporal or mark recapture studies. It offers insight on how to adapt surgical procedures (i.e. electro-sedation) and whether telemetry tools (e.g. mini-acoustic transmitters) are appropriate to monitor juvenile Muskellunge in real-time.

4.1.2 In-situ spatial ecology

In Chapter 3, I explored the spatial ecology of juvenile Muskellunge and Northern Pike within their natal embayments during fall and winter periods. Specifically, I modeled presence/absence, residency, space and habitat use variables against environmental (water/air temperature and water levels) and biological (total length) parameters. My overall findings suggested that both environmental parameters measured play a complex yet critical role in the spatiotemporal patterns of juvenile esocids. There was no evidence of mortality throughout the fall and early winter in 2015, or full 2016/17 overwintering period based on detections, though lack of detection by several age-1 Muskellunge in Rose may suggest predation in late winter of 2016.

Habitat use results suggest that, in fall and early winter periods, age-0 Northern Pike actively used nearshore habitats, close to deep littoral zones (i.e. similarly to age-1 Northern Pike, Farrell et al. 2014), as did age-0 Muskellunge, despite variation in Muskellunge embayment size, shape, and slope of the bay transitioning to deeper channel depths. As fish from either species seldom used their embayment mouths during flood events, I postulate they actively used shallow, littoral regions at high water levels. These regions are likely inhabitable in winter months when water levels recede due to river regulation; however, they may have fit the bill as appropriate winter habitat during a flood event - deeper, sandy littoral zones (relative to summer months) with a diversity of vegetation - negating the need to emigrate.

Due to the influence of environmental variables on spatial parameters, studying the impacts of the new IJC Plan 2014 on spatiotemporal patterns of juvenile (age-0-5) Muskellunge and Northern Pike is likely a worthwhile endeavour. Refining habitat use profiles is a key step to evaluated and measure essential habitat features within restored bays and may inform management considerations on the impact of altered water level regulation. Further, it may demonstrate future risk and efficacy of restoration and enhancement efforts (Langton et al. 1996). Research that targets overwintering habitat use in deeper (1.5 - 3 meters), littoral and limnetic regions as Plan 2014 commences may support and refine how these habitats are used with respect to more natural water level cycles. Moreover, results may either negate or encourage the need for restoration activities.

In a broader context, this study is the first to use acoustic telemetry to assess age-0 Muskellunge and Northern Pike spatiotemporal ecology in relation to fall and winter phenology in their northeastern range. This work is now part of a growing body of literature explicitly tailored to consider spatiotemporal patterns of juvenile fish to identify core habitat for riverine management and habitat restoration purposes. Such studies may further inform policy and provide science-based evidence for legislative protection (e.g. SARA critical habitat designation).

4.2: Future Research Opportunities

This thesis validates the use of telemetry tools to study juvenile Muskellunge and frames the story of how age-0 Muskellunge and Northern Pike may be using their natal embayments overwinter. Such insights may advise animal care protocols regarding juvenile esocids and inform future research objectives targeting spatial ecology and behavioural interactions between these species across earlier stages. Finally, changes in winter phenology due to climate change may substantially alter habitat use and interactions between these congeneric predators.

Based on the results from Chapter 2, further investigation should establish the best immobilization method to surgically implant acoustic tags in juvenile esocids. Despite the fact that no fish died as a result of predation after varying MS-222 exposure times in the field study, delayed reactions to moving objects post varying exposure times to MS-222 suggest that alternate methods should be considered. Successful narcosis (immobilization for <15 minutes without physical damage) using 60 to 90-V pulsed DC was noted for age-0 Northern Pike (130-190 mm; Walker et al. 1994), juvenile hybrid Striped Bass (female *Morone chrysops* × male *M. saxatilis*; Trushenski and Bowker 2012), and other small fish species (i.e. Bluegill *Lepomis macrochirus*; Rous et al. 2015). A complementary study on stocked juvenile Muskellunge, tagged for spatiotemporal analysis or mark recapture programs, should use electro-sedation and quantify physiological and behavioural limitations relative to chemical anesthesia.

As environmental parameters were found to influence spatial ecology of juvenile esocids in Chapter 3, I propose a future study which determines overlap of core space use in deep, littoral microhabitats within and beyond natal embayments (e.g. along the St. Lawrence River shoreline) and compares this overlap to fine-scale variations in water level. Variation in micro-habitat use based on depth and vegetation may elucidate how these congeneric predators overlap in earlier life stages, prior

to ontogenetic segregation, and the importance of these zones with respect to the nursery-role hypothesis (Beck et al. 2001). Continued, long-term monitoring may assess changes in sub-adult population estimates with respect to water level regulation to determine whether habitat restoration efforts are required to stimulate recruitment to sub-adulthood (Beck et al. 2001). Moreover, elucidating juvenile winter home ranges and the age and conditions under which their summer and winter ranges become established may fill knowledge gaps with respect to Muskellunge and Northern Pike natural history.

A longer-term study is further proposed to assess the spatial ecology of Muskellunge across life stages, from juvenile to adult. An expanded array, similar to those associated with Great Lakes Acoustic Telemetry Networking projects (Krueger et al. 2017), deployed from the point of outflow from Lake Ontario at Cape Vincent to Collins Landing, may elucidate successive movement patterns in association with ontogenetic change (juvenile to adult) and identify mechanisms that lead to the development of core summer and winter ranges in the Thousand Islands region. Such data may elucidate changes in reproductive strategies (e.g. Shuter et al. 2012) due to different extremes in winter conditions. Adverse environmental conditions are well-known to shape the physiological and behavioural strategies of fish (Shuter et al. 2012), and climatic changes (e.g. warming water temperatures) may impose spatiotemporal boundaries for Northern Pike (cool-water fish). A changing aquatic environment may further influence the energetic capacity of Muskellunge and, due to increased foraging efficiency (Shuter et al. 2012), alter how they distribute themselves with respect to winter habitat conditions and presence of Northern Pike during juvenile, sub-adult, and adult stages. Understanding the fundamental interactions between environmental parameters, space and habitat use, and movement patterns for each life stage may permit the development of a robust life-history based management framework (e.g. Nislow and Armstrong 2011); a key constituent needed to develop and implement stage-specific research objectives related to water level regulation and habitat restoration for esocids in the St. Lawrence River system.

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