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Telemetry reveals the movement, fate, and lure-shedding of northern pike (*Esox lucius*) that break the line and escape recreational fisheries capture

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ABSTRACT

Although many fish are captured and released following hook removal by recreational anglers, some fish break the line and are confronted by the potential impediment of a lure lodged in the jaw, buccal cavity, or throat. We simulated break-off events by releasing northern pike (*Esox lucius*) into Lake Opinicon, Canada with custom-built lures that were manufactured to contain radio transmitters. Treatment groups combined hook placements (lower jaw, upper and lower jaw, throat) and hook types (barbed and barbless) to investigate the effects on pike survival, movement, and lure shedding. Fifty-one pike were released (522 ± 64 mm), three of which died (6%; 95% CI = 2–16%). Data were analysed by dummy variable regression to investigate the main effects of hook placements and hook type in pike. Cumulative distance swam after release was significantly reduced by deep hooking and lower jaw hooking. All fish except for one shed the lures within 14 d of release, and barbed hooks and lures lodged in the lower jaw significantly increased the time required for pike to shed lures. In light with previous work, we documented significant short-term behavioural consequences of lure break-off for pike (i.e. hyperactivity) but the experimental fish rapidly and naturally shed the hooks within days in nearly every instance. Given our findings, for pike (and likely related species such as muskellunge), anglers can be reasonably confident that long-term damage to individuals is limited even when a lure is retained by an animal following a break off event. Nonetheless, use of barbless hooks facilitates lure shedding, and all efforts should be taken to avoid break off events in the first instance using appropriate gear (e.g., wire leader, heavy line) especially when angling for fish with sharp dentition.

1. Introduction

Recreational angling is a popular activity worldwide (Arlinghaus et al., 2007). Recreational anglers can induce a range of population- and ecosystem-level impacts by removing fish biomass (Lewin et al., 2006). Therefore, efforts to manage fish populations must account for impacts related to angling such as destruction and disturbance of habitat, selective harvesting of large fish, and unintended mortality of fish in catch-and-release fisheries (Arlinghaus et al., 2007; Lewin et al., 2006). One of the unintended outcomes that could result in delayed mortality of released fish is break off, in which a fish breaks away from the line with gear (e.g., hooks or lures) still embedded in its mouth (Arlinghaus et al., 2008a; Henry et al., 2009). The extent to which break off occurs is largely anecdotal, because empirical data are limited, and research to date has focused primarily on the impacts of lost lead (i.e. sinkers) on waterfowl (e.g., Radomski et al., 2006) or the toxic chemical impacts of swallowed hooks in marine fishes (e.g., McGrath et al., 2014; Alós et al., 2017).

Some fish species may be more heavily affected by break offs than others. Fish with sharp dentition (e.g., northern pike [*Esox lucius*] or barracuda [*Sphyraena barracuda*]), are at greater risk for break off as lines can be cut after contacting the teeth of the fish. In some fisheries where light tackle is preferred, break off rates may also be high, but quantitative data do not exist. The implications to the fish swimming with a lure embedded in the buccal cavity are only partially understood and have only been studied in a few species. Although most anglers optimistically assume that lures lost due to break off are eventually shed by the fish, the additional stress that the fish experiences may hamper its recovery and affect its physiology, behaviour, and fate (Arlinghaus et al., 2008a). Fish with embedded lures may also starve as a result of impaired feeding ability (Tsuboi et al., 2006). If the fish survives, it may still experience sub-lethal impairments such as a

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reduced ability to evade predators over the longer term (Cooke and Philipp, 2004) or succumb to a variety of delayed physiological impairments (Arlinghaus et al., 2007; Cooke et al., 2013). Sub-lethal impacts may also cause long-term impairment of fish fitness including slowed growth, reduced reproductive output or delayed mortality (Cooke et al., 2002; Klefoth et al., 2008; Richard et al., 2013). Some studies have assessed the impact of deep hooking with retained hooks on various fish species (Fobert et al., 2009; Margenau, 2007; Tsuboi et al., 2006) but typically these studies have used hooks without a lure. In an exceptional and recent laboratory study, Pullen et al. (2017) found that lure retention had no significant effect on metabolic rate, blood physiology or locomotor activity of northern pike. However, elevated cortisol levels in lure-treated fish compared to wild controls suggested that confinement produced prolonged stress that may affect the extrapolation of these results to the wild (Pullen et al., 2017). A field study by Arlinghaus et al., (2008a) provided further insights into the effects of lure retention on pike behaviour in the wild. A combination of visual tracking and traditional radio tracking suggested that lure retention caused short-term behavioural changes (e.g., lack of movement), but that typical behavioural patterns resumed as quickly as 24 h post-release. A limitation of that study was that the researchers did not know if or when the fish lost the lure and whether the retained lure was continuously influencing the observed behaviour.

The objective of the present study was to quantify the short-term (dispersal) and longer-term (14 d) behavioural consequences to free swimming northern pike of a retained lure simulating a break off in a field setting. Northern pike were chosen as models because these fish are in heavy demand by recreational anglers across the northern hemisphere (Arlinghaus and Mehner, 2004; Arlinghaus et al., 2010; Pierce, 2010), particularly in the trophy class where large mature fish are targeted and are prone to gear break off (Arlinghaus et al., 2008a) due to their sharp dentition. To evaluate the effects of lure retention after break off on fish behaviour and fate, we used telemetry techniques to track lures that were embedded into the mouth of pike in three different hooking positions using both barbed and barbless hooks. By tracking the lure (rather than the fish) we collected specific information about the length of time fish were affected by retained fishing gear and the relationship of the length of lure retention to behaviour and movement patterns.

2. Methods

2.1. Study site and animals

The study was conducted at the Queens University Biological Station (QUBS) in eastern Ontario, Canada, (44°31′N, 76°22′ W) between June 16th and July 11th, 2009. Water temperature ranged from 20 to 24 °C over the course of the field program and the predominant wind direction was out of the north east. Fish capture and tagging complied with guidelines set by the Canadian Council on Animal Care (protocol #1508) with scientific collection permits approved by the Ontario Ministry of Natural Resources.

Northern pike were collected from Lake Opinicon by conventional hook-and-line angling at a variety of locations throughout the lake. Angling gear consisted of medium action spinning rods and reels spooled with 15–20 lb test line. Lures, consisting of spoons and artificial fish imitations (crank baits), were attached to the line with wire leaders and swivels. Treble hooks did not have barbs to minimize injury and to increase ease of hook removal (Alós et al., 2008). On a given day, fish were collected from a location until enough fish were captured to complete a round of releases, no more than five fish at a time. Upon capture, fish were immediately brought to the boat, netted with a rubberized fish net keeping fighting time shorter than 60 s. Following hook removal, fish were assessed and those in good condition (i.e. no visible signs of excessive injury or bleeding) transferred to an onboard live well. The live well was covered and regularly flushed with fresh lake water to enhance stable conditions with holding periods less than 2 h (Arlinghaus et al., 2008a, 2009; Klefoth et al., 2008). Fish were then transported to the QUBS wet lab facility and transferred from the live well to insulated containers with fresh lake water. Water was circulated regularly through the containers to ensure water quality and every effort was made to reduce air exposure and maintain an optimal environment for the fish in the water. After a 1 h holding period, the fish were carefully netted and randomly allocated to control or treatment groups.

2.2. Transmitter lures

Medium size hollow crank bait type lures (90 mm TL x 90 mm circumference at widest point) were constructed from components ordered from a commercial lure components company (www.luremaking.com). These materials were used because plastic crank baits can float and the transmitter could be placed inside the lure. Radio transmitters (Model PD-2, 3.8 g radio transmitters: Holohil Systems Ltd, Carp Ontario Canada, serial number 144041 to 144090) having three months battery life were used. To assist buoyancy, a small amount of foam was placed in each lure to ensure that the lure would float in the event damage broke the watertight seal. Because the lures would not be used for angling they were assembled with one treble hook at the posterior and the transmitter antenna exiting the body through the anterior end where the eye for line attachment would normally be (Fig. 1). In this way, the lure would lay alongside the body of the fish with the transmitter antenna trailing.

Lures were painted with high visibility fluorescent paint to distinguish each treatment group (Fig. 1). The colour not only facilitated the visual identification of the various lures for treatments but also assisted with lure location on the water surface by increasing visibility from a distance.

2.3. Treatment groups

The sample comprised of 51 northern pike (416–690 mm; mean ± SD 519 ± 64 mm). On each sampling day, captured fish were sequentially assigned to one of four treatment groups or to the control

Fig. 1. Lure treatments included one treble hook at the posterior end of the lure assembly. The transmitter was embedded inside the lure body with the antenna extending out the anterior of the lure: Each colour was assigned to a specific treatment group for ease of recognition once assigned to a fish as well as for locating at a distance on the surface of the lake. Each lure was labelled with transmitter information, research affiliation and contact number. A nominal reward was provided to individuals who returned found lures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

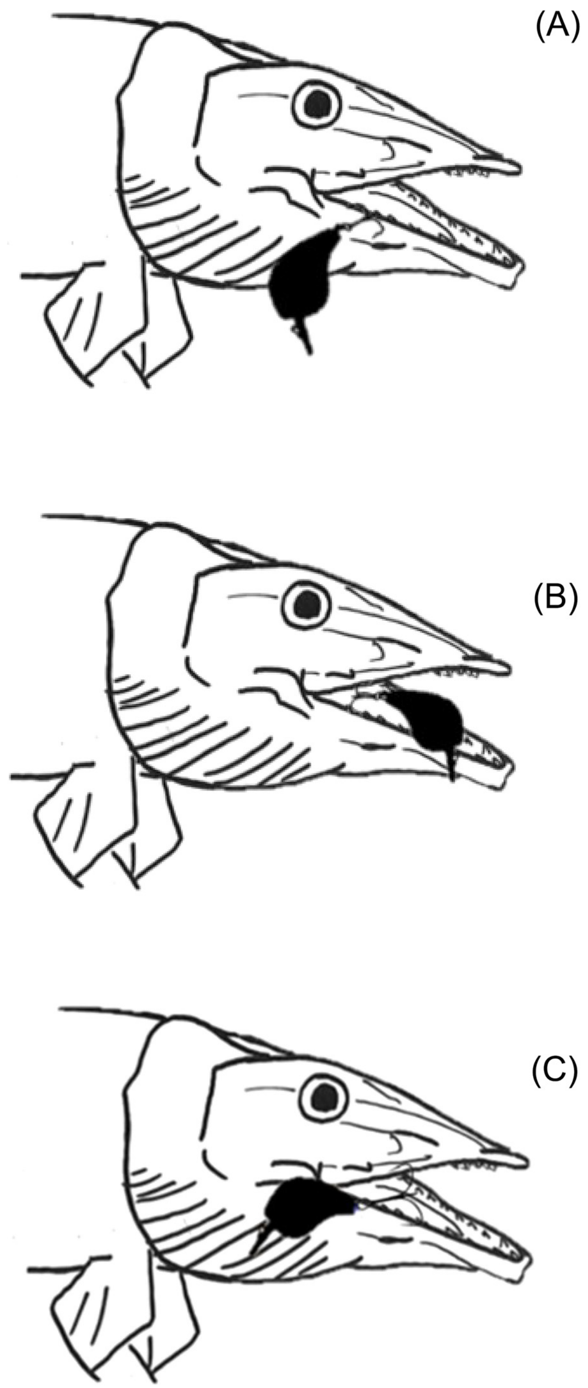

Fig. 2. Diagram of lure placements for treatments on northern pike (*Esox lucius*). Lures were embedded in the lower jaw (A), deeply in the throat (B), or in both the lower and upper jaws (C) consistent with this diagram. Lures were instrumented with radio transmitters to track the movement of the pike with the lure and the timing to shed the lure.

group (i.e. treatment 1, treatment 2, treatment 3, treatment 4, control, repeat). Prior to tagging, each fish was held prone in a foam-padded v-shaped sampling trough filled with fresh lake water, measured for total length (mm), and macroscopically evaluated for injury. Lures with unique frequency radio-telemetry transmitters were manually embedded in the mouth of fish (Fig. 2). Four groups of treatment fish were differentiated based on hooking orientation and hook type: 1) lure (barbed hook) hooked into the lower jaw; 2) lure (barbed hook) hooked into the throat (tissue at the base of the tongue; 3) lure (barbed hook) hooked through both the upper and lower jaw and 4) lure (barbless hook) hooked into the lower jaw. Hooks were held with pliers and embedded with force similar to being hooked on a line, by way of a strong unidirectional pull. All fish in the lure treatment groups were fitted with a sham tag made of rubber and a wire antenna affixed with a dorsal backpack to the base of the dorsal fin and fish assigned to the control group received a transmitter in the same fashion following the methods of Cooke (2003). The sham tags were used to account of the placement of transmitters on the control fish, which were dorsally affixed. In brief, to affix sham tags on treatment fish and transmitters to the control fish to the base of the dorsal fin, two 22-gauge hypodermic needles mounted on 3 ml syringes were pushed through the dorsal musculature ventral and posterior to the origin of the dorsal fin (Arlinghaus et al., 2009). Wires attached to the transmitter (20-gauge surgical stainless steel) were threaded through the needles and pulled out on the opposite side of the fish through a small (10 mm × 5 mm × 1 mm) backing plate made from rubber gasket material (Colotelo et al., 2013). The wires were twisted until the transmitter was snug to the fish and trimmed to minimize potential for snagging on lake debris and macrophytes. No anaesthetic was used during the transmitter attachment to not bias the immediate behaviour post-release.

2.4. Dispersal and tracking post-release with retained lure

Release and tracking days were staggered throughout a 26-d period, for computational purposes, the data set was standardized to 14 tracking days per individual. Tagged pike were released sequentially from the shoreline adjacent to the research station at points at least five m apart. The release site was located in a shaded area adjacent to the dock complex to ensure that the fish were not released into an area of active boat traffic, but close enough that the dock could be used for initial tracking and observation. Upon release, the behaviour of each fish was observed and the time it took the fish to move more than 1 m away from the release site was recorded.

Fish were then tracked using a combination of visual observation where possible (shallow near shore water) and manual radio tracking (Thompson et al., 2008) to determine their location within defined areas: 1 m, 10 m, and 100 m from the release point. The day after release, the position was taken to determine if the fish had moved more than 100 m from the release point within 24 h of release. These data were collected to evaluate the short-term behaviour of fish following the first moments after simulated break off.

Radio tracking was completed manually from a research vessel using a hand-held radio receiver (R1000 Telemetry Receiver, Communications Specialists Inc., Orange, California, USA) and a three-element Yagi antenna. Tracking occurred between 0800 and 2000 and every attempt was made to locate one position per fish per day. When a transmitter signal was located, the fish was positioned within 5 m of the boat. Each location was recorded with a handheld Garmin eTrex GPS.

Each fish was tracked for a minimum of 14 d. Tracking was terminated once the lure was located and recovered (lost by the fish), or the fish could not be located within the study area. In cases where a lure stopped moving it was assumed that the lure had been caught in submerged debris or sank; however, the position of the signal was recorded for the remainder of the two-week period. Where accessible, snorkelers were deployed to observe the fish or recover the lure. A reward was offered to anglers who caught the fish and returned the lure and provided an approximate location of the catch. Despite our best efforts, the remaining tags cannot be assigned a fate and they may have died or been shed in areas where we could not find them.

In cases where a fish did not move more than 50 m for three or more consecutive days, (whether the lure was found or not) the first 50 m point was selected to represent the location where the fish separated from the lure. This distance of 50 m was considered appropriate based on the following rationale: Arlinghaus et al., (2008a) reported that their study team could track a fish to within two meters before a fish would move as a result of their presence. Given that handheld GPS units typically have an error of ± 5 m, the location recorded could be substantially different from the observation point. Finally, the effect of lake depth and the direct distance of the boat from the fish add an additional 5 m of variability in boat position to the fish. In total, a minimum movement factor of 50 m was determined to be appropriate. Thus, a requirement of three or more consecutive days of less than 50 m movement provides allowances for random events of reduced movement.

2.5. Statistical analyses

Survival was calculated as a percentage and confidence intervals were produced by the Wilson method with the *binconf* function in the R package Hmisc (Harrell, 2017). Dispersal data were organized by time to leave 1 m, 10 m, and 100 m zones. Minimum distances from the release point were calculated using Google Earth. Rather than explicitly comparing treatment groups, dummy variables were coded in consideration of the different factors explored in the experiment. Barb, lower jaw, upper jaw, and throat were coded as dichotomous dummy factors with the control group represented by all zeroes. For example, group T1 (barbed hook in lower jaw) was coded 1,1,0,0. Time to leave the three areas was explored using linear regression with the *lm* function in R using the four dummy variables and fish length as predictors. Predictor variables to test were selected based on our understanding of the biological system and interest in testing explicitly for the effects of the treatments and fish length; model selection (i.e. reduction) to remove hypothesized predictors was therefore opted against given that the hypothesis was adequately tested by the full model. Based on visual inspection of model residual histograms, log transformations were applied where necessary to maintain normally distributed residual error.

Movement was calculated as the straight-line distance between successive tracking points, providing a minimum distance moved for each fish per day in ArcGIS (ESRI 2017). Where necessary, lines were inferred to avoid movement across land by fish. Daily displacement was modelled with each individual by mixed effects regression using the *lme* function in the nlme package (Pinheiro et al., 2017). In consideration of the potential effect of time on displacement, three models were considered and compared by the Akaike Information Criterion. The first included first order terms for binary hook characteristics barb, lower jaw, upper jaw, deep as well as a term for day post release. The second included all possible first and second order interactions between day after release and hooking variables and the third included only second-order interactions between hook characteristics and day as well as a first order term for day after release.

Fish with lures embedded following simulated break off events were observed by radio telemetry for 14 d after release. Cox proportional hazards survival analysis was implemented to compare the timing of lure shedding among treatment groups coded by the same dummy variables as above. Survival analysis was implemented by the *cph* function in the R package rms (Harrell et al., 2017). The survival plots were drawn using the *ggsurvplot* function in the survminer package (Kassambra and Kosinksi, 2017).

3. Results

3.1. Mortality

Three pike (6%; 95% CI = 2–16%) died after release, one of which succumbed immediately after being released with a deeply embedded hook and was excluded from the movement study. One other deeply hooked pike died three days after release and one hooked in the upper and lower jaw died six days after release. The small number of mortalities made it impossible to generate an effective model of survival related to hooking variables but evidently there is some contribution of embedded hooks to post-release mortality. One transmitter and one sham tag were captured by anglers during the study.

3.2. Dispersal

In general, after entry into the water, fish moved to the cover of macrophytes and then moved in an easterly direction into the basin in front of the research station from which fish were released. The majority (71%) of fish dispersed from the release area (> 1 m) in under 10 s regardless of treatment. Only two fish, a fish hooked in the lower jaw with a barbless hook and a control fish, remained in the immediate release site for longer than a minute (90 and 360 s respectively). Pike with a barbed hook in the lower and upper jaws took longest to disperse 1 m (9 ± 6 s). Body length and hooking dummy variables were not significant predictors of the log transformed time to disperse 1 m. Most (76%) pike emigrated the 10 m area within 1 h of release, with the pike hooked in the lower jaw with a barbed hook taking longest (300 ± 356 s) by median. There was a significant positive effect of body length ($t = 3.13$, $P < 0.01$) but not of any hooking variables on the time to disperse 10 m. Within 24 h, all pike were beyond 100 m from release. There was considerable variance among treatment groups in the time to disperse 100 m, all treatments having larger absolute deviation than median values. Pike hooked in the throat took the longest to disperse (8040 ± 9037 s) whereas fish hooked in both the upper and lower jaws were fastest (810 ± 1201s). Again, there was a significant positive effect of body length on the time to disperse 100 m ($t = 2.48$, $P = 0.02$) but not of hooking variables.

3.3. Distance moved

The model with second-order terms for hooking characteristics with a first order term for day was selected as the best model among the three hypothesized models ($\Delta AIC = 4.44$). All terms were significant, suggesting that the distance moved after release significantly increased with the day since release ($t = 14.85$, $P < 0.01$). The effect of hook characteristics was also best described when considered to interact with the day after release (all $t > 2.51$, all $P \le 0.01$; see Fig. 3). Average displacement per day was longer for pike hooked in the lower (286 m) and upper (318 m) jaws relative to controls (i.e. the null dummy variable for each hook placement; 231 and 247 m, respectively) and for pike hooked with barbs (274 m compared to 250 m with barbless). However, daily displacement was shorter when hooks were deeply lodged (172 m) relative to its null value when no hook was deeply lodged (281 m; see Fig. 3).

3.4. Lure shedding

One lure (2%; lower jaw/barbless hook) was shed during the initial release period and was observed floating 125 min post release. Two additional lures (4%; lower jaw /one with a barbed hook and one with a barbless hook) were found in the release area 24 h following release (first day of tracking). The precise time of lure shedding was not known, but lure shedding was considered to have occurred the day after release. Only one pike, hooked with a barbed hook in the lower jaw, did not shed the lure after 14 d. Because of singularity in the full model including the deep hooking dummy variable, only a model including the dummy variables for barbed hooks, lower jaw hooking, and upper jaw hooking was possible. Barbed hooks remained lodged for 5 ± 3 d on average compared to 3 ± 1 days for barbless hooks ($z = -3.34$, $P < 0.01$; Fig. 4). There was reasonable evidence that hooks in the upper ($z = 1.82$, $P = 0.07$) and lower ($z = -2.09$, $P = 0.04$) jaws remained longer, albeit only the lower jaw was significant.

4. Discussion

In our field study, lure retention failed to significantly impact the short-term behaviour (dispersal rate) and we were not able to model the survival of free-swimming pike because of a small number of mortalities. All but one fish successfully shed the hook within 14 d of

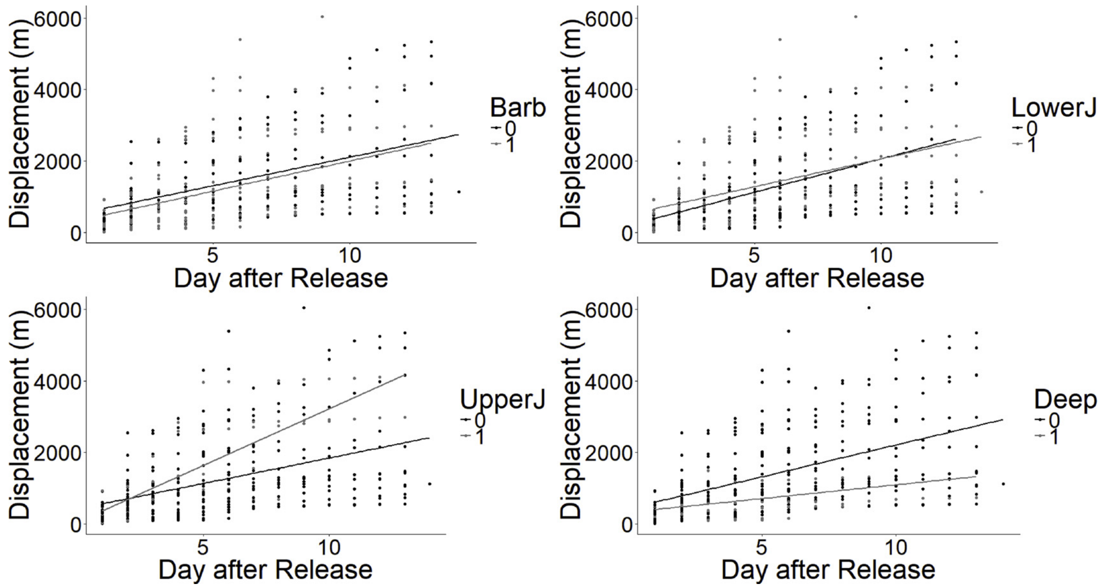

Fig. 3. Interactive scatterplots for the four hook variables against day after release. All interactions were significant according to mixed effects regression holding individual as a random effect. Each plot presents the daily displacement based on radio positions of Northern pike (*Esox lucius*) with transmitter-implanted lures embedded in the mouth. The treatment groups are described by barbless hook in the lower jaw, barbed hook in the lower jaw, barbed hook in both the upper (UpperJ) and lower jaw (LowerJ), deeply hooked (Deep) with barbed hook (Barb), and a control (coded by all zero dummy variables). In all instances the grey line indicates the presence (1) of the specified hook style/location and the black line the absence (0).

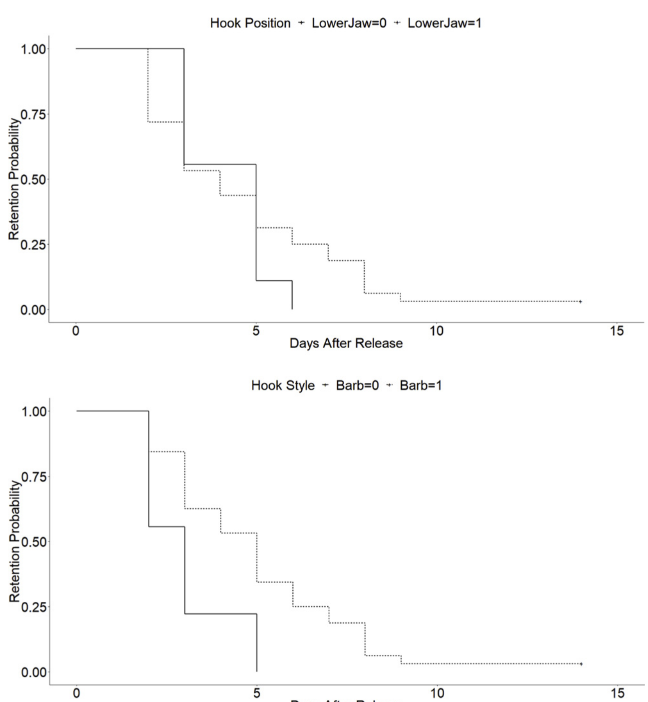

Fig. 4. Survival plot of the retention time of lures experimentally attached to the mouths of Northern pike (*Esox lucius*) in Lake Opinicon, Ontario based on dummy variables describing whether the hook was barbed (top panel) or hooked in the lower jaw (bottom panel). Data are right censored at 14 d after release for one pike that did not lose its lure after 14 d. Cox proportional hazards survival analysis indicated a significant difference between fish hooked with barbed and barbless hooks and fished hooked in the lower jaw or not. In both figures, the broken line indicates the absence of the hook style or position from a treatment and the solid line indicates the presence of that style or position.

release suggesting that any long-term impacts of break-off would be limited to physical or physiological trauma in most instances. These results agree with a previous field study by Arlinghaus et al., (2008a) that showed limited impacts on behaviour and mortality of northern pike after release with a retained lure. Our study also agrees with results of recent laboratory studies on the physiology and behavior of retained hooks in Atlantic cod (*Gadhus morhua*; Eckroth et al., 2014) and a laboratory investigation of northern pike (Pullen et al., 2017), cumulatively indicating that at least the two species tested are very resilient to even harsh treatments. However, it is possible that impairments were present in traits and endpoints not measured by us or by Eckroth et al. (2014).

The short-term impacts to fish that swim away with retained lures are often compared to those encountered during a catch and release event in that the fish is exposed to a period of exhaustive exercise with associated physiological changes, potential injury from the hook, but ultimately returns to the lake to swim free (Arlinghaus et al., 2007). However, unlike catch-and-release, in a break off event, the fish may not experience air exposure, the exercise may be very brief, there is little or no handling of the fish, but the fish swims away with a hook embedded in its jaw or soft tissue. Handling is known to be stressful to fish and may be one of the most salient components of a capture experience (Arlinghaus et al., 2007; Brownscombe et al., 2017), and this component is not present in break offs. Hooks and lures embedded in the jaw may be anticipated as a stressor for fish that consume spiny or clawed animals (e.g. centrarchids and crawfish) that may similarly become embedded in the jaw or throat. Perhaps for this reason, cutting the line is the standard best practice recommended to anglers that capture deeply hooked fish because research reveals fish are capable of disintegrating or passing hooks (Tsuboi et al., 2006; Weltersbach et al., 2016). It has so far not been recommended to release deeply hooked predators with artificial lures, because such practice may look counterintuitive. However, our research shows that fish may be able to shed even deeply hooked artificial lures under certain situations.

Research to date on the impact of lure retention has focused mainly on the consequences of deeply embedded single hooks using some variety of live or organic bait (DuBois and Kuklinski, 2004; Schill, 1996; Tsuboi et al., 2006; Warner, 1979). Conclusions from these studies centred on cutting the line as opposed to retrieving the hook from the fish. Henry et al. (2009) also investigated the impacts of break off in nesting male smallmouth bass (*Micropterus dolomieu*). The ability to collect data based upon direct observation of the fish while the lure was still retained in the mouth allowed the authors to infer behaviour attempting to dislodge the lure. In addition, they noted variation in response related to the lure type. Fish appeared to more actively work to rid themselves of floating, buoyant lures and were less impacted by the presence of neutrally buoyant lures such as soft plastic worms and jigs (Henry et al., 2009). Pullen et al. (2017) also observed the behaviour of pike to lures and found very little behavioural response in a tank environment. In the present study, we used indirect observations using radio telemetry and could not determine whether the fish were actively working to dislodge the lures. However, the finding that behaviour did not differ among treatment groups suggests that the impacts on pike were insubstantial, confirming earlier results by Arlinghaus et al. (2008a).

Fish in our study left the initial dispersal area quickly and most had moved beyond 10 m within the first 10 min of release. This may be inferred as a slow rate of movement for an animal in suboptimal habitat that would likely seek refuge if unimpaired. Brownscombe et al. (2014) found that handling stressors simulating fisheries interactions that were somewhat similar to the handling undergone by pike in this study resulted in cognitive impairment and delayed refuge seeking by great barracuda (*Sphyraena barracuda*) released onto a Bahamian flat. Similarly, Rapp et al. (2012, 2014) revealed that stressed common carp (*Cyprinus carpio*) were immobile for up to 12 h post release after being held in confinement for many hours. Arlinghaus et al., (2008a) also observed that pike showed very little initial movement and that fish with a lure moved less actively than fish without a lure. However, in the present study dispersal observations appeared to be independent of the lure break-off treatment. In addition, we saw no evidence to suggest that the hooking affected the treatment fish to the extent observed by Arlinghaus et al., (2008a) who found fish remained in the vicinity of the release site for 24 h before moving into the main body of the lake. The lures that we used were of a floating type and, based on the observations of Henry et al. (2009), may have caused pike to be more active in an attempt to rid themselves of the lure. The differences in our observations could be attributed to lure buoyancy as Arlinghaus et al. (2008a) used neutrally buoyant lures (rubber shads) that may not have elicited as active a response from the pike. Indeed, observations of pike in captivity bearing retained spoons (negatively buoyant lures) in the jaw suggested no efforts to dislodge the lure in a laboratory setting (Pullen et al., 2017).

Displacement after release was best described by time after release, with pike generally moving more as time elapsed. Our results here align with those generated by Arlinghaus et al., (2008a) where they noted that fish with a lure moved greater distances each day following release than the control fish, although those differences were not significant. They attributed the control fish behaviour to a faster recovery and resumption of normal activity (holding in macrophytes/ ambush predation) than the fish coping with the presence of a lure. Lures embedded in the tissue may stimulate nociceptors. Sneddon (2003) described nociceptors in the head of rainbow trout (*Oncorhynchus mykiss*). Innervation of nociceptors could stimulate the release of cortisol into circulation, the primary glucocorticoid in fish that is responsible for stimulating activity. Acute stress associated with innervation of the stress axis assists animals in rectifying homeostasis by providing fast energy substrates for activity and therefore more movement would have been predicted for pike with lures embedded, which we did not observe compared to control fish. However, it was interesting that the most critical location, hooking deeply in the throat, resulted in a reduction in movement whereas all other treatments led to increases. This is an important difference given that deep hooking is often considered to be a more critical outcome for fish in recreational fisheries; indeed, more mortalities were recorded for fish in this group although our sample size did not permit analysis.

One of the most important findings of our study is the quantification of the shedding rate of lures by free swimming fish post break off and the effects of hooking position and barbed or barbless hooks on the length of time the lure is retained, the first time that this type of data has been collected in this manner. Most of the lures that were released with fish were shed within the observation period of each fish within 14 days. Lures with barbless hooks were shed most quickly (see also Stein et al., 2012, but compare to Weltersbach et al., 2016). One pike hooked in the lower jaw with a barbed hook retained the lure throughout the entire study period moving 100–500 m for 5 d following release. Much research has focused on lethality of barbed compared to barbless hooks, generally showing greater mortality with barbed hooks (Hühn and Arlinghaus, 2011). Studies evaluating the effect of bait type and size on injury to pike reported a 2.4% mortality rate following release (Arlinghaus et al., 2008b), not dissimilar to other studies reporting delayed mortality rates for other fish species (DuBois and Dubielzig, 2004; Reeves and Bruesewitz, 2007). However, sublethal effects clearly include hook retention by animals (Stein et al., 2012). In the present study, hooking in the lower jaw also influenced lure shedding rates whereas hooking in the upper jaw did not. This model should, however, be interpreted cautiously given that pike were either hooked in the lower jaw or both the upper and lower jaw simultaneously, an additional treatment group with pike hooked only in the upper jaw would have improved estimation. Moreover, the model did not converge with deep hooking included and it is reasonable to suspect that this factor would also prolong retention. In laboratory behaviour studies, increased opercular pumping was observed among fish that were hooked deeply in the tissue of the throat (Pullen et al., 2017), perhaps indicating effort expended to dislodge the lure. Studies of other species have also shown that fish that are hooked deeply are able to expel the hook in a matter of days (Fobert et al., 2009) although expulsion rates may vary depending on hook size and style (Robert et al., 2012). The effect of being hooked through the upper and lower jaw may have limited feeding or hampered the fish's ability to ambush prey again stimulating greater effort to dislodge the lure. Klefoth et al. (2011) found depression of growth in caught-and-released pike suggesting that any lure embedded in the pike might affect growth even if shed at some point, but whether results would differ for fish that break off and are not landed is a question for future research. Further consideration in future studies should also be given to comparing hook sizes and configurations because it is reasonable to suspect differences in lure shedding for single and treble hooks and that shedding probability would scale with hook size.

Some caution must be used in the interpretation of our results given that not all lures were recovered from the lake and survival cannot accurately be assigned in all cases but we show that fish breaking off can die. Perfect simulation of breakoff is difficult because we had to handle the fish to apply tags, which is not experienced by fish that break off; however, we do not anticipate that handling would affect shedding rates. Future research should apply tags to both the fish and lure to determine whether they become separated. Recapture of the fish such as was done by Klefoth et al. (2011) would provide physiological data to help further understand sublethal impacts and determine latent consequences such as chronic stress. Lure retention in northern pike had little effect on short-term behaviour but it is notable that fish died even without handling. Although we had a small sample size of mortalities, two of the three were deeply hooked, suggesting that critical hooking could be an important factor contributing to mortality of fish with retained lures. Most lures were eventually shed, but retention times were reduced by barbless hooks. This is the first study to report this information and provides relevant information to anglers wishing to reduce potential impacts of break off. These results suggest that pike are relatively resilient to retained lures even though they may die; anglers and managers could consider modifying their fishing practices to minimize break off by using strong line, wire leaders when fishing for toothed fish, and lures sufficiently large to reduce the risk of deep hooking that prolongs retention. Barbless hooks could be additionally used to reduce the duration of hook retention among broken-off lures.

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