A field study combining biotelemetry and biologging to determine how long the behaviour of fish is impacted by catch-and-release angling

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Abstract

Assessing the behaviour of fish in the wild is challenging given the lack of relevant "controls" to assess recovery following capture. Our aim was to assess how long it takes largemouth bass (*Micropterus nigricans*) and northern pike (*Esox lucius*) equipped with pop-off biologgers to resume normal behaviour (i.e., return to baseline movement and exploration activity) once released. Both species were equipped with acoustic transmitters in a whole-lake positioning system to model their movement patterns and behaviour. We recaptured those same individuals at a minimum of 37d later and affixed pop-off biologgers that recorded acceleration and depth allowing us to combine data from two technologies to assess the post-release behaviour of the fish. In 20–28.5°C water temperatures, it took largemouth bass equipped with biologgers 129h (95% CI: 106-149h) to resume normal movement and 154h (103-195h) for exploration activity. Northern pike equipped with pop-off biologgers took 145h (110-174h) to resume normal movement activity. Exploratory behaviour of northern pike was not influenced. These results reveal that catch-and-release angling can yield post-release behavioural consequences for up to 7d.

Keywords: behaviour, recovery, catch-and-release, telemetry, tagging

Introduction

If catch-and-release angling is to be an effective conservation tool, it is important that fish survive with negligible long-term sublethal impacts from the angling event (Wydoski 1977, Cooke and Shramm 2007) especially given that billions of fish are captured and released annually (Cooke and Cowx 2004). Various aspects of angling events (e.g., hooking injuries, fight, handling, and air exposure time) as well as environmental conditions (e.g., water temperature) influence the extent that sub-lethal physiological and behavioural impairments can occur (reviewed in Muoneke and Childress 1994, Cooke and Suski 2005, Arlinghaus et al. 2007). Moreover, responses to the capture event can also vary depending on biotic factors such as body size and species (Raby et al. 2015). These changes can lead to important ecological consequences that can occur during the recovery period, such as reduced ability to avoid predators, cognitive disorientation and lack of foraging ability (Siepker et al. 2006, Danylchuk et al. 2007, Cooke et al. 2014). This occurs when swimming performance is hindered while anaerobic by-products (i.e., lactate) are being cleared and energy stores (e.g., glycogen) are replenished (Milligan 1996, Kieffer 2000). Understanding how long recovery post-capture takes and how different best fish handling practices (e.g., gear types, handling practices) affect fish can help inform anglers and fisheries managers on ways to maximise fish welfare and reduce unintended mortality (reviewed in Brownscombe et al. 2017).

Deviations in behaviour once released can be a qualitative indicator of longer-term impacts on survival and fitness such as impaired growth or ability to reproduce (Beitinger 1990, LaRochelle et al. 2025). Since the capture of fish can be energetically costly (Milligan 1996, Kieffer 2000), captured fish must replenish such energetic losses (i.e., body maintenance) from angling events prior to allocating energy towards growth and reproduction (Brett and Groves 1979, Richard et al. 2013). This is further exacerbated by the fact that angling events can reduce or halt feeding of fish, limiting energy acquisition during the recovery period (Aalbers et al. 2004, Siepker et al. 2006, Stålhammar et al. 2012). Therefore, the ability to monitor the post-release behaviour of fish in their natural environment during the recovery period can provide important information on the state of the animal and the fitness impacts that an angling event could have once released (reviewed in LaRochelle et al. 2025).

Monitoring the behaviour of fish in the wild is challenging given it is hard to observe animals underwater in large systems and often requires the use of electronic tags. Telemetry studies have often been used to monitor the long-term impacts that catch-and-release angling has on the fate of released fishes and their post-release behavioural recovery (Pollock and Pine 2007, Donaldson et al. 2008) the post-release behavioural recovery (Klefoth et al. 2008, Arlinghaus et al. 2009, Baktoft et al. 2013). Although a powerful tool for monitoring long-term impacts on behaviour, tagging fish with an acoustic transmitter can be invasive and have short-term behavioural consequences because the transmitters are usually placed intracoelomically with a surgical procedure that typically involves sedating the fish (Bridger and Booth 2003, Cooke et al. 2011). To effectively assess the impacts of catch-and-release angling on the behaviour of fish using acoustic telemetry, it is important to separate any negative effects of the tagging procedure (i.e., tagging effects; Shorgan et al. 2025) from the capture effects (Donaldson et al. 2008, Baktoft et al. 2013). This is challenging given that fish equipped with acoustic transmitters would need to be recaptured following a recovery period (Ferter et al. 2015). More recently, biologgers have been used to assess the short-term fine-scale behaviour of fish in the wild following capture events (Brownscombe et al. 2013, LaRochelle et al. 2021, Louison et al. 2023). The attachment method is generally less invasive than surgery because a Velcro strap (see LaRochelle et al. 2022, Madden et al. 2024) or a pop-off mechanism are used (see Whitney et al. 2016, LaRochelle et al. 2023, LaRochelle et al. 2024). The ability to combine these two technologies on fish that have behaviourally recovered from the tagging procedure provides unique opportunities to assess the fine-scale short-term and long-term behavioural deviations that occur from an angling event.

Largemouth bass (*Micropterus nigricans*) and northern pike (*Esox lucius*) are popular sport fish that are often subjected to catch-and-release angling (Quinn and Paukert 2009, Arlinghaus et al. 2018). Several studies have assessed the physiological status (e.g., Suski et al. 2006, Thompson et al. 2008, Arlinghaus et al. 2009, Louison et al. 2017) and post-release behaviour (e.g., Arlinghaus et al. 2008, LaRochelle et al. 2021, Chhor et al. 2022) of both species after being captured. These studies provide insight into the physiological and behavioural impacts of angling but typically lack the baseline state of animals prior to capture or uncaptured controls, ultimately inhibiting the ability to truly assess recovery (i.e., there is no comparator). Early work by Klefoth et al. (2008) used radio telemetry to assess the pre-capture and post-capture movement distance and habitat used by northern pike to determine recovery from an angling event. The study design captured coarse movement and habitat choice of northern pike by assessing these behaviours for a 24-hour period every 7 days. This study found that northern pike recovered from angling within 7 days of capture, but was not able to identify the exact time within the 7 day period that recovery occurred. Bakatoft et al. (2013) took a fine-scale approach to identify recovery of northern pike after an angling event. Those authors implanted northern pike with acoustic transmitters capable of providing high resolution-acoustic data and let them recover from the tagging event prior to recapturing them. This provided authors the ability to assess the pre-capture and post-capture behaviour of northern pike and allowed them to compare these results to non-captured controls to identify recovery in 5-16°C water temperatures. The authors found that northern pike in this system, with relatively cool water temperatures, recovered behaviourally within 48 hours of capture. However, warm water temperatures (>25°C) are known to be stressful and potentially lethal for similar *Esox* spp., especially when no thermal refuge is available (e.g., Bauerlien et al., 2022, Booth et al., 2023). To date, behavioural recovery studies have only been accomplished for northern pike in a range of relatively cool water temperatures and not water temperatures that are likely in the summer. Further, this type of study has not occurred for other popular sportfish like largemouth bass.

The primary objective of this study was to determine the behavioural consequences of catch-and-release angling events on fishes in relatively warm water temperatures when most angling occurs (i.e., summer) and quantify the duration of time it takes to resume normal behaviour (i.e., recovered) when equipped with a pop-off biologger. To achieve this, we used two popular sportfish that are commonly subjected to catch-and-release angling—largemouth bass and northern pike. We combined high-resolution positions (14-18 s) with acoustic telemetry using a whole-lake fish positioning system and fine-scale behavioural data from internal data storage biologgers. Together, these techniques allowed for detailed observations of fish behaviour in relation to catch-and-release angling, with pop-off biologgers providing additional fine-scale behavioural detail for the initial hours post-release. In addition to answering a key question about behavioural impacts from catch-and-release angling, our findings can inform the duration of time pop-off biologgers should remain attached to largemouth and northern pike to quantify post-release behavioural recovery from angling related stressors.

Methods

Acoustic tagging

All tagging practices were in accordance with the Canadian Council on Animal Care approved by Carleton University (AUP #110723). This research was conducted at Lindsay Lake (44°32'14.0"N, 76°23'23.1"W), a private research lake located at Queens University Biological Station that was equipped with 307 kHz HR3 high-residency acoustic receivers (Innovasea Systems Inc., Halifax, NS, Canada, *n = 33*). Acoustic receivers were strategically deployed within the lake (maximum distance of ~100 m apart; Figure 1), allowing for the triangulation of detections to obtain the fine-scale positioning of fish using Innovasea's High Residency system.

Largemouth bass (*n= 24*, 431 ± 32 mm total length [mean ± SD], 376-495 mm range) and northern pike (*n= 19*, 655 ± 59 mm total length, 545-735 mm range) were captured with rod and reel between May 4th and 5th, 2023, for tagging with acoustic transmitters. Once captured, fish were placed into a submerged recovery bag (Dynamic Aqua Ltd., Surrey, BC, Canada; 122 × 31 cm with a mesh of 0.5 cm on both ends) and transported to shore for surgical tag implantation. Fish were then transferred to a sling lined with a Transcutaneous Electrical Nerve Stimulation (TENS Units INC, Largo, FL, United-States) unit pads which temporarily immobilize the fish during surgery (see Reid et al. 2019). TENS units were used with a constant pulse rate (150 Hz) and pulse width (300 µs). The electrode leads were placed in the surgical sling such that the anode was placed toward the head and the cathode near the tail of the fish. Electrical intensity was increased incrementally until fish were immobilized and unresponsive to tactile stimulation, at which point surgery commenced (Reid et al. 2019; Reid et al. 2024). Following immobilization, a tube with fresh recirculating water was placed in the mouth of the fish allowing for oxygenated water to continuously flow over the gills. Both largemouth bass and northern pike were surgically tagged with V6-4x 307 kHz acoustic transmitters (low power 145dB, 14-18 s delay, 290-day life, 19.3 mm length x 6.3 mm diameter, 1.2g in air; Innovasea Systems Inc.) and a passive integrated transponder (PIT; 12 mm; APT12 Biomark, Boise, ID, United-States) tag for identification (placed in the body cavity). A small (< 1cm) incision was made between the pelvic fins and the cloaca to insert the tag into the coelomic cavity. The tagging process took less than two minutes and was closed with a single 3-2-2 surgeons knot using 3-0 absorbable monofilament PDS II sutures (Ethicon, NJ, United-States). All tools and tags were sterilized with betadine prior to tagging each fish. Tagged fish were then released and given at least one month to recover before attempting to recapture them.

Angling

Angling efforts to recapture acoustically tagged largemouth bass and northern pike occurred from June 11th to September 2nd, 2023. We allowed the fish to recover from the initial capture and surgery for at least 37 days, which is a sufficient amount of time for recovery (Føre et al. 2021, Shorgan et al. 2025). Surface water temperatures during this period ranged from 20 – 28.5°C. Fish that were recaptured were caught with either a bladed jig, topwater or soft plastic lure (size 1/0 octopus or extra wide gape hook). Once at the boat, fish were netted, and hooks were removed in < 20 s. Fish were then transferred to a water filled V-trough on board the vessel and scanned for the presence of a PIT tag.

After PIT tag identification, the fish remained in the water filled V-trough to be externally tagged with a pop-off biologger. Fish were air exposed for 60 s or less, which encapsulates a typical range for anglers practicing catch-and-release angling for largemouth bass and northern pike (guided by Cooke et al. 2002b). Air exposures of 60s or less have negligible impacts on fish (northern pike; Arlinghaus et al. 2009). Therefore, air exposure was not included as a variable in the analyses. Only the first capture event was included in the analyses avoid complications of multiple capture events on the behaviour of fish (similar to Baktoft et al. 2013).

Acoustic Telemetry Monitoring

Acoustic data were analyzed using Innovasea High Residency system that produced fine-scale positioning estimates for both species. Fine-scale positioning estimates were created using hyperbolic positions based on the timing of detections at three or more receivers (Smith 2013). Horizontal position error (HPE) was calculated based on five reference transmitters and provided HPE calculations for each position (Smith 2013). Detections with a HPE greater than 1.5 were removed (Smith 2013), giving us a mean positional error of 1.8 m with 99% of the measured errors occurring below 5.8 m. This was calculated using the horizontal distance between synthesized position (i.e., measured horizontal position error in meters - HPE_m) and the known receiver location based on reference tags (Figure 1). Based on visualizations (120–420 hours), a 360-hours post-release period was selected for the analyses to ensure that recovery curves could be captured (visual convergence of captured fish with control fish).

Total distance traveled (i.e., step length) by each fish was calculated using the Haversine formula (*distHaversine* function from the *geosphere* package; Hijmans 2022) between each consecutive position and the distances were summed for each respective hour. The equation for the total distance is presented below, where *j* represents the position between 1 and *n*, $d_{j,\,j+}1$ is the distance between consecutive points and the *n* is the number of positions within a respective hour.

$$total\,distance\ =\ \sum_{j=1}^{n} d_{j,\,j+1}$$

Total distance (hereafter referred to as movement) was used to provide information on the overall movement (in m) of each fish for all respective hours during the monitoring period. The one-hour period for total distance was selected to preserve the fine-scale nature of these data. Due to limitations of the system, positioning gaps were removed from the analyses. We also calculated the kernel density estimates for space use (meters squared) at 4-hour intervals using the *amt* package (Signer et al. 2019). The kernel density estimates were calculated in 6-hour groupings with a minimum of 30 positions. Only the 95% maximum area used was included in the analyses. This also allowed for the assessment of potential nuanced patterns in space use associated with recovery from capture.

Pop-off biologger and monitoring

The casing for the pop-off biologgers (50 × 30 × 15 mm; 11 g; casing without biologgers) were made from Smooth-on Feather Lite™ (Smooth-on, Inc., Macungie, PA, USA) and dyed orange. Each pop-off biologger was equipped with an internal data storage tag and a BD-2 radio transmitter (Holohil, Carp, ON, Canada; 1.2g in air) which was used to relocate the pop-off biologgers (Figure 2). The internal data storage tag was an AXY-5 XS (TechnoSmArt, Guidonia Montecelio, Italy; 20 × 10 × 6 mm; 2.5g in air) which recorded tri-axial acceleration, pressure, and temperature. The acceleration sensor of the AXY-5 XS biologger was programmed to record acceleration in all three axes (x = surge, y = sway, z = heave) at a rate of 25 Hz with an 8-bit resolution. Temperature and pressure (depth) sensors recorded at a rate of 1 Hz and had a resolution of ± 0.1 °C and ± 5 cm, respectively. Pop-off biologgers were positioned in the same orientation between the pelvic fins of largemouth bass and between the pectoral fins of northern pike (Figure 3; LaRochelle et al. 2023, 2024). The pop-off biologger was then fastened to the fish using two self-locking straps that were secured together using a ~3 cm piece of 4-0 plain catgut suture to create a dissolvable link (550B, Ethicon, Sommerville, New Jersey, United States). These self-locking straps were placed into the receptacle end of the self-locking strap which were attached to the pop-off biologger (see Figure 2C). The pop-off tags would dislodge from the fish when the dissolvable link broke, or the dissolvable link lost its tensile strength, which would prompt the entire pop-off biologger to slide off the body of the fish, allowing for retrieval. The tagging process took less than 45 s, and the fish remained submerged in water throughout the process.

To calculate the locomotor activity of the fish, the absolute dynamic acceleration was obtained by removing the static acceleration (i.e., gravity) from the dynamic acceleration (i.e., animal movement) using a 2-s box smoother (as described Shepard et al. 2008, Brownscombe et al. 2018). Post-release locomotor activity (i.e., ODBA – overall dynamic body acceleration) was calculated by summing the absolute dynamic acceleration across all three axes (Wilson et al. 2006, Halsey et al. 2011) for each minute. Similarly, depth was calculated as the mean depth per minute for each individual. Biologging data were recorded per minute to preserve the fine scale data but were visualized in the figures as hours to allow for consistency across all endpoints measured.

Controls

Fish that were not recaptured and affixed with a pop-off biologger during the study were classified as time-matched controls. Dead fish following the initial tagging event were identified by visually assessing movement activity (no movement) and removed from the control group (3 fish total). There were seven largemouth bass and four northern pike that were never recaptured and used as controls. To ensure controls were an accurate representation of the capture period, control periods were created for the respective capture time period. In other words, there were seven relevant controls for each largemouth bass capture event, while northern pike had four. There were four different classification periods related to capture – pre-control (control fish before capture), post-control (control fish after capture), pre-capture (captured fish before capture event) and captured (fish after being captured). This design allowed for direct comparisons between classification groups across a temporal scale. Controls and pre-captured fish were used to determine when captured fish affixed with a pop-off biologger returned to 'normal' or recovered. We followed the progressive change before-after-control-impact paired series (BACIPS) framework to identify when fish recovered (Thiault et al. 2017).

Statistical analysis

All data were analyzed using R studio (2024.12.0.467; RStudio Team 2024) via R version 4.4.2 (R Core Team 2024). All plots were produced using the ggplot2 package (Wickham 2016). Only fish where the pop-off biologgers remained affixed for at least 48 h were used during analyses (based on recovery in Baktoft et al. 2013). Due to defective acceleration sensor in some of the pop-off biologgers, there was a smaller sample size for the ODBA endpoint. Alpha (α) was set to 0.05 for all analyses. For both species, a t-test was used to assess if there were differences in the total length between the control and captured fish.

Recovery of movement, and area used for both species were determined using a BACIPS framework (Thiault et al. 2017). For both species, the movement per hour and area used (6-hour period) were applied as endpoints for identifying recovery. Shapiro-Wilk tests were used to determine the distribution structure of these data. Depending on the distribution, either a t-test or Wilcoxon non-parametric test were used as a global BACIPS test to compare if the capture event had a significant effect on the behaviour of fish. When results from the global BACIPS test were significant, further BACIPS assessments were used to estimate the time point of recovery. If the results were not significant, no further assessment for recovery were performed.

Following the global BACIPS test, the shape of the recovery curve was identified by the lowest corrected Akaike Information Criterion (AICc) score. A threshold of <7 delta (Δ) AICc was used for both species and endpoints. For each species and endpoint, four different models were fit (step-change, linear, asymptotic, sigmoid) and compared to determine the model with the best-fit. The best-fit model was selected based on the AICc scores and weights, which was then used for recovery modeling. If different models had ΔAICc scores <7, the model with the highest AICc weight (ω) was selected.

A unique recovery zone was established for each species and endpoint. Recovery zone was identified using baseline pre-capture data (0-360 h) by calculating the delta difference between the pre-capture and control (i.e., never captured). The mean delta difference ±1.25 S.D. for largemouth bass or ±1 S.D. for northern pike were used to establish a baseline recovery zone. Baseline recovery zone represented the normal range of each behaviour type in the absence of disturbance (i.e., capture). Largemouth bass had a larger S.D. for the recovery zone compared to northern pike to account for the greater spread in individual behaviour. The S.D. threshold was determined for each species by inspecting delta difference plots and adjusting the S.D. value until the recovery zone best represented the pre-capture baseline data. Delta differences between the captured and control fish were calculated for the post-capture period (360-720 h). The mean delta difference for each hour was also calculated.

The best-fit-model selected from the AICc scores was then used to project trajectory of delta differences of the post-capture data to estimate recovery. Recovery times were established when the projected trajectory entered the baseline recovery zone established from the delta differences from the pre-capture and control data. Once the projected trajectory entered the baseline zone, the behavioural impact from being captured was no longer distinguishable from the baseline behaviour prior to being captured and fish were deemed recovered. The lower and upper bounds of recovery time were determined using the 95% confidence interval around the model-predicted trajectory, representing the earliest and latest time points of recovery.

The biologging data were analyzed using an exploratory changepoint analysis (Gurarie et al. 2009). Because there were no control data for the biologgers, we were unable to suggest recovery using these data. Rather, the changepoint analyses were used to identify the time when behaviour (e.g., ODBA and depth) significantly changed during the post-release monitoring period for both species. To identify changepoints, we tested all potential temporal split points by comparing the respective endpoint before and after each hour using Wilcoxon rank-sum tests. Split points were only considered if there were a minimum of 10 observations before and after to ensure adequate statistical power. To control for the potential of Type I error with the multiple comparisons, we applied the Benjamini-Hochberg false discovery rate (FDR) correction (Benjamini and Hochberg 1995). The hour where the changepoint occurred was identified using the smallest FDR-adjusted p-value, indicating the more pronounced difference between the before and after periods. We also calculated the Cohen's d as a standardized measure of effect size to assess the magnitude of difference between the before and after period (Cohen 1988).

Results

Largemouth bass in the control group (*n=7*; mean = 449 mm ± 23 S.D., range = 376–485 mm) were ~8% longer than the recaptured fish (*n=10*; 417 mm ± 36, 376–481 mm; t_{15}= -2.690, p =

0.017). Similarly, northern pike in the control group (*n=4*; 713 mm ± 25, 690–735 mm) were, on average, 13% longer than the recaptured fish (*n=11*; 630 mm ± 61, 545–717 mm; t_{13}= -3.747, p = 0.003). Pop-off biologgers were affixed to largemouth bass for an average duration of 170 h (± 94 h S.D.) and 248 h (± 96 h) for northern pike. There were no mortalities of captured fish during the monitoring period.

Largemouth bass

Capture had a significant effect on the movement behaviour (t = -11.969, p<0.001) and area used by largemouth bass (t = -9.910, p<0.001). The linear model had the best-fit for both the movement and area used behaviour (Table 1), with all other models having negligible support (ΔAICc >7). Movement behaviour of largemouth bass recovered 25 h before recovery was identified for area used. Recovery for the movement behaviour of largemouth bass was estimated at 129 h post-release (95% CI: 106-149 h; Figure 4A). Movement of largemouth bass increased with increasing time post-release until recovery (Figure 4B). Area used by largemouth bass recovered 154 h post-release (95% CI: 103-195 h; Figure 5A) and increased until it reached a recovered state (Figure 5B).

A significant decrease in ODBA of largemouth bass was identified at 113 hours post-release (p < 0.001, Cohen's d = -0.736; Figure 6A). There was a 7% decrease in ODBA between the before (*n* = 540; 0.057 g) and after (*n* = 485; 0.053 g) changepoint periods. Post-release depth used by largemouth bass changed significantly at hour 147 after release (p = 0.007, Cohen's d = -0.206; Figure 6B). Largemouth bass were significantly deeper before the changepoint (*n* = 1059; mean = 2.0 m), and largemouth bass went shallower by 9.5% (change of 0.2 m) after the changepoint (*n* = 386; mean = 1.8 m).

Northern pike

The movement behaviour of northern pike was significantly influenced by capture (t = - 14.054, p < 0.001), while area used was not influenced by capture (t = 0.033, p = 0.974). Linear model had the best-fit for the movement behaviour data of northern pike (Table 2). Movement behaviour of northern pike recovered 145 h post-release (95% CI: 110-174 h; Figure 7A) and movement activity increased slowly until it reached the same level as the control fish (Figure

7B). There were minimal differences in the area used by northern pike throughout the monitoring period (Figure 8).

There was no changepoint identified for the post-release ODBA of northern pike. All potential splits found no significant differences ($p > 0.05$; Figure 6C). However, post-release depth used by northern pike increased significantly at 122 h post-release ($p < 0.001$, Cohen's d = 0.230; Figure 6D). Northern pike had a mean depth of 4.7 m (n = 1230) prior to hour 122 and increased by 7.4% (change of 0.4m) to a mean of 5.1m (n = 1309) after the changepoint.

Discussion

Our study provides evidence that catch-and-release angling caused alterations in the post-release behaviour of largemouth bass and northern pike for several days. Behavioural responses to the catch-and-release angling varied across the species in our study. Overall, recovery occurred at a similar time for both largemouth bass (129-154 h) and northern pike (145 h). Endpoints used to assess recovery for largemouth bass showed different recovery times, with the movement endpoint recovering before the proxy for exploratory behaviour (area used). A similar trend in behaviour was observed with the biologging data, where a shift in behaviour was first identified in the ODBA followed by a later change in depth used. Recovery in northern pike could only be identified using the movement data and suggests that area used by northern pike is not influenced by capture. However, there were no identified changes in behaviour identified for the ODBA of northern pike, but there was an identified change in depth at 122 h post-release. Recovery from catch-and-release angling has mostly been assessed using physiological parameters (Cooke et al. 2013a) and few studies have used the return of post-release behaviour to baseline levels (e.g., Klefoth et al. 2008, Baktoft et al. 2013). However, to assess physiological recovery requires keeping fish in captivity for physiological biopsy (Wenderlaar Bonga 1997; Barton 2002) and true behavioural recovery requires either pre-capture baseline data or uncaptured control fish for comparisons (LaRochelle et al. 2025). Here, we had the opportunity to assess the recovery of wild fish at liberty in nature with high-resolution behavioural data allowing us to compare captured fish to uncaptured controls. These results demonstrate that catch-and-release angling can cause multi-day alterations to the behaviour of wild fish, the extent and duration of which vary across species and endpoints.

This is the first study to assess the behavioural recovery of largemouth bass in the wild relative to uncaptured controls. Similar studies have previously been done with northern pike (e.g., Klefoth et al. 2008, Baktoft et al. 2013). Our results suggest northern pike recovery took up to 4 days longer to recover compared to the 2-day recovery period identified in Baktoft et al. (2013). Interestingly, movement of northern pike in our study recovered within 6 days, which is similar to the suggested <7-day recovery period in Klefoth et al. (2008). Ultimately, the mechanism extending the recovery period for northern pike in our study compared to the Baktoft et al. (2013) study is not clear. We speculate that it could be related to capturing northern pike in warmer water temperatures which might have increased stress levels (Gale et al, 2013, Kamara et al. 2025). Water temperatures in the Baktoft et al. (2013) study were up to 22°C cooler than the water temperatures in our study and water temperature at the time of capture in the Klefoth et al. (2008) were likely similar. It was also interesting that there were no mortalities that occurred during our study. Water temperatures that were within the range of our study (20–28.5°C) have been known to cause mortality in other *Esox* species (e.g., Bauerlien et al., 2022, Booth et al., 2023). It is likely that our system had adequate thermal refuge, providing important habitat for the recovery for both species and ultimately reducing the risk of post-release mortality. Beyond the water temperature differences, we introduced a confounding tagging effect on our fish in this study with the addition of a pop-off biologger. The addition of the pop-off biologgers can cause drag increasing the energetic demand of the fish (reviewed in Jepsen et al. 2015) and might have increased the time to recovery of northern pike relative to the previous studies. Longer recovery times could also be present in largemouth bass, however, there are no other studies that use similar methods to assess behavioural recovery.

Recovery of largemouth bass and northern pike took several hours longer relative to physiological parameters measured in other studies (e.g., rate of oxygen consumption and plasma concentrations of lactate, cortisol, glucose, ions; Suski et al. 2006; Arlinghaus et al. 2009). It is unclear as to why there is a disconnect between the behavioural recovery period and recovery times assessed using blood physiology. Although physiology and behaviour are tightly linked (Tinbergen 1951; Barton and Iwama 1991; Johnson et al. 1992), behavioural recovery in our study took several days longer than physiological recovery estimates from previous studies. Blood physiology results from Suski et al. (2006) suggest that largemouth bass take up to 4 hours to return to baseline levels after catch-and-release angling, while Arlinghaus et al. (2009) found that it took northern pike 6 hours to return to baseline levels. Behavioural recovery might take longer than blood physiological parameters to recover because behaviour of animals has two important components that work in tandem: cognitive abilities (e.g., knowing what to do and where to go) and physical capacity (e.g., capacity for locomotion). Physiological parameters (e.g., lactate, blood pH) are useful for identifying physical recovery, yet may be poorly linked to cognitive recovery. Without gathering blood samples from these individuals at different time points post-release, it is challenging to be certain on the physiological status and if fish are completely recovered from the capture event. It is entirely possible that the physical capacity (i.e., ability to move) of the animal recovered at roughly the same rate as the blood physiology parameters assessed in the previous studies (Kieffer 2000; Suski et al. 2006; Arlinghaus et al. 2009). Ultimately, physical capacity is only part of the forces acting on the behaviour of animals. There is much less known about the cognitive recovery aspect of fish caught and released into the wild. Indeed, if fish superficially appear to be 'recovered' based on the physiological metrics commonly measured, it is unclear what is motivating the fish to delay resumption of 'normal'. It could be that other physiological assessments more closely linked to activity in the nervous system are needed to predict behavioural recovery (e.g., electroencephalogram or expression of genes related to behaviour).

Behavioural observations obtained from this study might suggest that cognitive impairment of fish following a capture event is the driving force for the longer recovery periods beyond the 4-6 hours periods that have been previously shown with blood physiology parameters for the same species (Suski et al. 2006; Arlinghaus et al. 2009). If physical capacity was driving behaviour, then movement behaviour should recover relatively quickly post-capture at a similar rate to the physiological parameters from previous studies (Suski et al. 2006; Arlinghaus et al. 2009). Instead, the delay in movement and area used (largemouth bass only) could suggest that cognitive implications hinder the capacity of the animal to move horizontally and vertically in their environment. This stationary behaviour, or lack of exploration prior to being recovered, has also been seen in other freshwater fish species where hook retention inhibited their ability to leave refuge (Hlina et al. 2021) or explore (Arlinghaus et al. 2008). Cognitive impairment, or fear, can occur post-capture and can hinder the ability to explore their environment (reviewed in van Kampen 2015). Capture events can make fish timid and less likely to explore their environment (reviewed in Arlinghaus et al. 2017b). Therefore, it is likely that the cognitive component of behaviour following capture is driving impairment for a longer duration of time than the physical capacity and might be the primary driver of behaviour alterations observed in our study. Further, the fact that fish can learn to avoid hooks long-term following capture suggests that capture can have cognitive impacts on fish (Beukema 1970, Arlinghaus et al. 2017a, Lucas et al. 2023). Using the post-release behaviour of fish in the wild may be more suitable and sensitive to impairments associated with catch-and-release angling compared to using blood physiology measurements of fish in captivity.

The biologging method used in this study was able to identify significant changes in the post-release behaviour of largemouth bass and northern pike. The changepoint analysis was able to identify a significant change in the ODBA (proxy for swimming activity) of largemouth bass at hour 113 post-release which was 16 h earlier than the identified recovery for the movement with the more reliable data generated using acoustic telemetry. Interestingly, there was a significant change in post-release depth used of largemouth bass identified within 4 h of the identified area used recovery endpoint. However, the biologging data were not able to identify a significant change in the ODBA of northern pike, yet the data were able to identify a significant change in the depth used. Northern pike are regarded as being sedentary (Eklöv 1992, Craig 1996), and as such, even the northern pike that were not captured moved very little during the monitoring period. It is possible that the change in depth used was more sensitive to behavioural recovery and might be more useful as an important endpoint for assessing recovery time in northern pike. This comparison of results from the different technologies is interesting given that acoustic data were able to identify a recovery time for the movement of northern pike, but not the area explored. Similarly, biologging data analyses were able to identify a shift in depth used (potential proxy for exploration) and not ODBA (proxy for swimming activity). The combination of these technologies provided important insight into how these animals were behaving following capture. Although the biologger data could not be used to determine recovery, it found changes in behaviour around the same time as the acoustic data for largemouth bass. As for the northern pike, the fine-scale data gained from the biologgers provided the ability to identify subtle changes in the exploration behaviour (i.e., depth used).

Quantifying the moment-to-moment behaviours of wild fish can be challenging (Arlinghaus et al. 2007). The unique study design of combining biologging data with biotelemetry data provided valuable insight on the fine-scale post-release behaviour of fish in the wild. The pop-off biologgers used in this study were able to provide fine-scale behavioural information of the fish in the wild. Attaching pop-off biologgers to fish is quick (< 30 s), does not require surgery, and allows for measurements of locomotor activity and depth use across individuals. Comparatively, acoustic telemetry relies on the propagation of a signal from intracoelomic surgically implanted transmitters to a stationary receiver and in most systems, stationary receivers have excellent reliability when it comes to downloading data (Cote et al. 1998; Heupel and Hueter 2001). However, the effectiveness of acoustic telemetry is limited by the array size and the cost of maintaining the array. Not being able to constantly have signals propagating from individuals to receivers leads to periods of time without data that can be problematic when trying to identify total area used and movement rate of individuals. Having to perform surgery to implant the acoustic tag can also dampen the ability to observe nuances in the behavioural response related to an acute stress event (i.e., capture) given that the fish would also be recovering from the surgery and the sedation (Ross and Ross 2008; Priborsky and Velisek 2018) or immobilization (Reid et al. 2019) method used during surgery (Bridger et al. 2003; Cooke et al. 2013b; Clemens et al. 2023). Another downfall of this technology occurs when fish leave the receiver array or are located in shallow macrophytes where transmitter signals are not propagated far enough to reach the receiver (Kessel et al. 2014; Brownscombe et al. 2019). Due to these downfalls, pop-off biologgers could provide more insight into the behavioural changes associated with recovery of fish given the ability to constantly record the animal at high frequencies. Yet, there is currently no information available on the impacts that these pop-off biologgers have on the buoyancy and the swimming performance of both species and how that might influence the true recovery of the fish. Based on our results, recovery times across different endpoints were identified prior to the average release time of pop-off biologgers for both species. These findings provide some support that pop-off biologgers did not hinder the ability to assess the behavioural recovery from the angling events for largemouth bass and northern pike. Other limitations surrounding these tags include the lack of control over the duration of time they stay affixed to the fish (e.g., premature pop-off), necessity of recovering the pop-off biologgers to download the data which can be challenging in large systems, potential malfunctions of sensors (e.g., acceleration – ODBA) and lack of being able to identify the location of individuals or habitat used. Both technologies provide pros and cons and together provided some good insight into the post-release behaviour of captured fish.

As research on the effects of catch-and-release angling continues to advance and use new technologies, more studies could consider pop-off biologgers for quantifying behaviour of fish in the wild following capture. Information gathered from the behaviour of fish is valuable because behaviour is sensitive to stress and serves as a good biomarker of the welfare of the animal (Schreck et al. 1997). Results from this study suggest that behavioural alterations from catch-and-release angling can manifest for up to 7 days for largemouth bass and northern pike are equipped with a pop-off biologger in water temperatures of 20–28.5 °C. Catch-and-release angling research could benefit from more research focused on assessing the cognitive impairments and fear resulting from capture using the post-release behaviour of fish. Most research on catch-and-release angling has focused on physiology, physical capacities (i.e., movement), mortality, and injuries. Although a catastrophic injury (e.g., severed gill arch) is likely to directly kill the animal, most behavioural impairments lead to indirect pathways for mortality such as via post-release predation or starvation (if fish are unable to resume normal foraging in a reasonable time period). Overall, the pop-off biologgers used during this study were able to identify significant changes in the behaviour of largemouth bass but were less accurate and reliable for determining behavioural changes for northern pike. Future studies using post-release behaviour as an endpoint should aim to keep pop-off biologgers affixed to largemouth bass and northern pike for at least 7 days to ensure that recovery is thoroughly assessed.

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Competing interests

No competing interests declared.

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Data and resources availability

Data are available in figshare repository and can be accessed at 10.6084/m9.figshare.29832584.

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Table 1. Model selection results for both movement and area used of largemouth bass (*Micropterus nigricans*) following the progressive change before-after-control-impact paired series (BACIPS) framework. Bolded rows represent the models selected for the respective endpoint. Models were selected based on the lowest corrected Akaike Information Criterion (AICc) score.

Endpoint	Model	AICc score	ΔAICc	AICc ω
Movement				
	Step-change	4696	102	0
	Linear	**4594**	**0**	**1**
	Sigmoid	4708	112	0
	Asymptotic	4699	105	0
Area used				
	Step-change	1286	21	0
	Linear	**1266**	**0**	**1**
	Sigmoid	1293	27	0
	Asymptotic	1289	23	0

Table 2. Model selection results for the movement behaviour of northern pike (*Esox lucius*) following the progressive change before-after-control-impact paired series (BACIPS) framework. Bolded row represents the model selected. Model was selected based on the lowest corrected Akaike Information Criterion (AICc) score.

Endpoint	**Model**	**AICc score**	**ΔAICc**	**AICc ω**
Movement				
	Step-change	3914	45	0
	Linear	**3869**	**0**	**1**
	Sigmoid	3926	57	0
	Asymptotic	3916	47	0

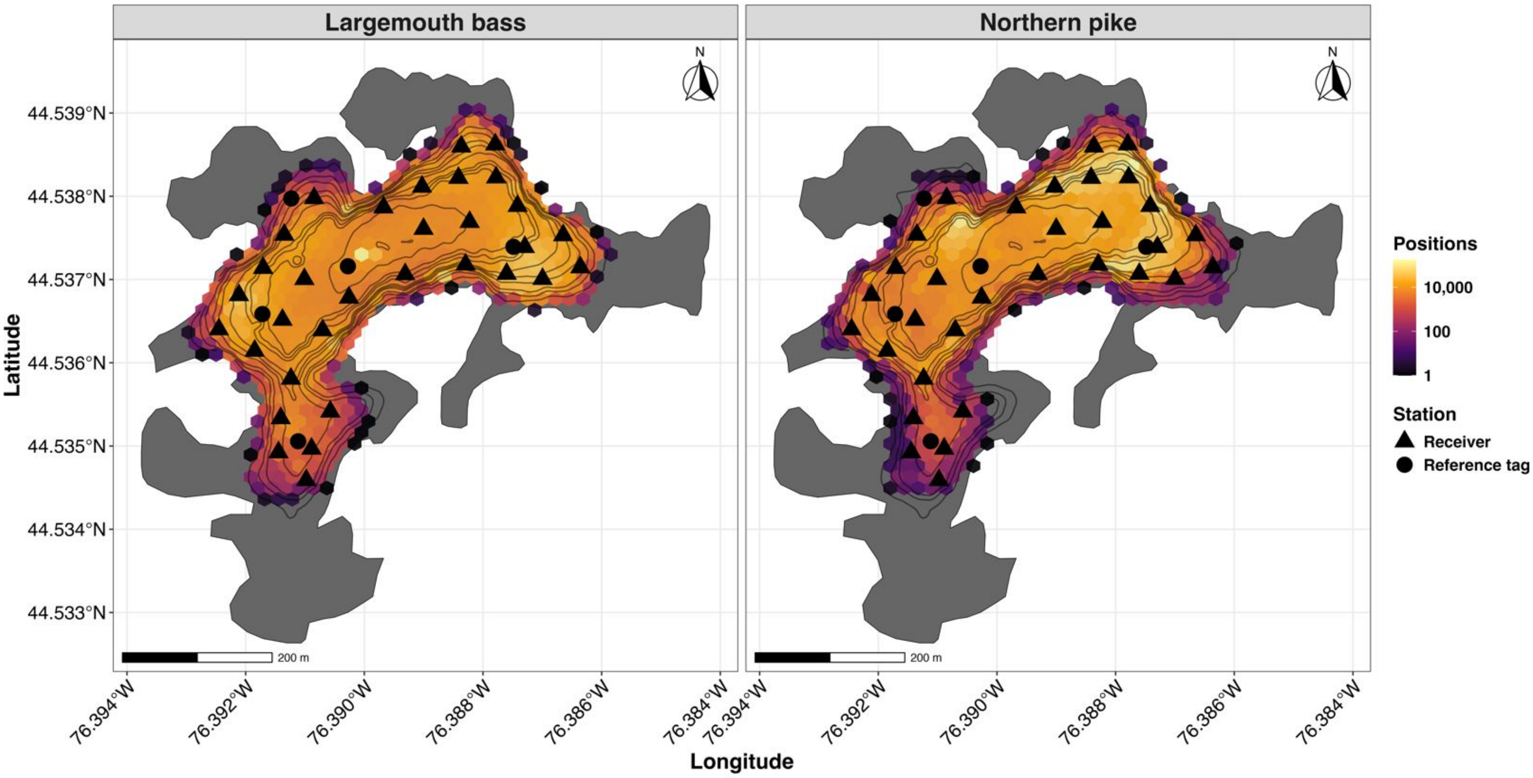

Figure 1. Heat map showing positioning density (log scale) of largemouth bass (*n*= 16; *Micropterus nigricans*) and northern pike (*n*=15; Esox *lucius*) in Lindsay Lake during the monitoring period (June 2nd – September 12th, 2023). The grey areas are shallow (~ < 1m) vegetated areas where positions did not occur but fish could theoretically be located within the lake, indicating spatial gaps in the system. Bathymetry is represented with 2m contour lines. Black triangles indicate the receiver locations and the black circles show the location of refrence tags.

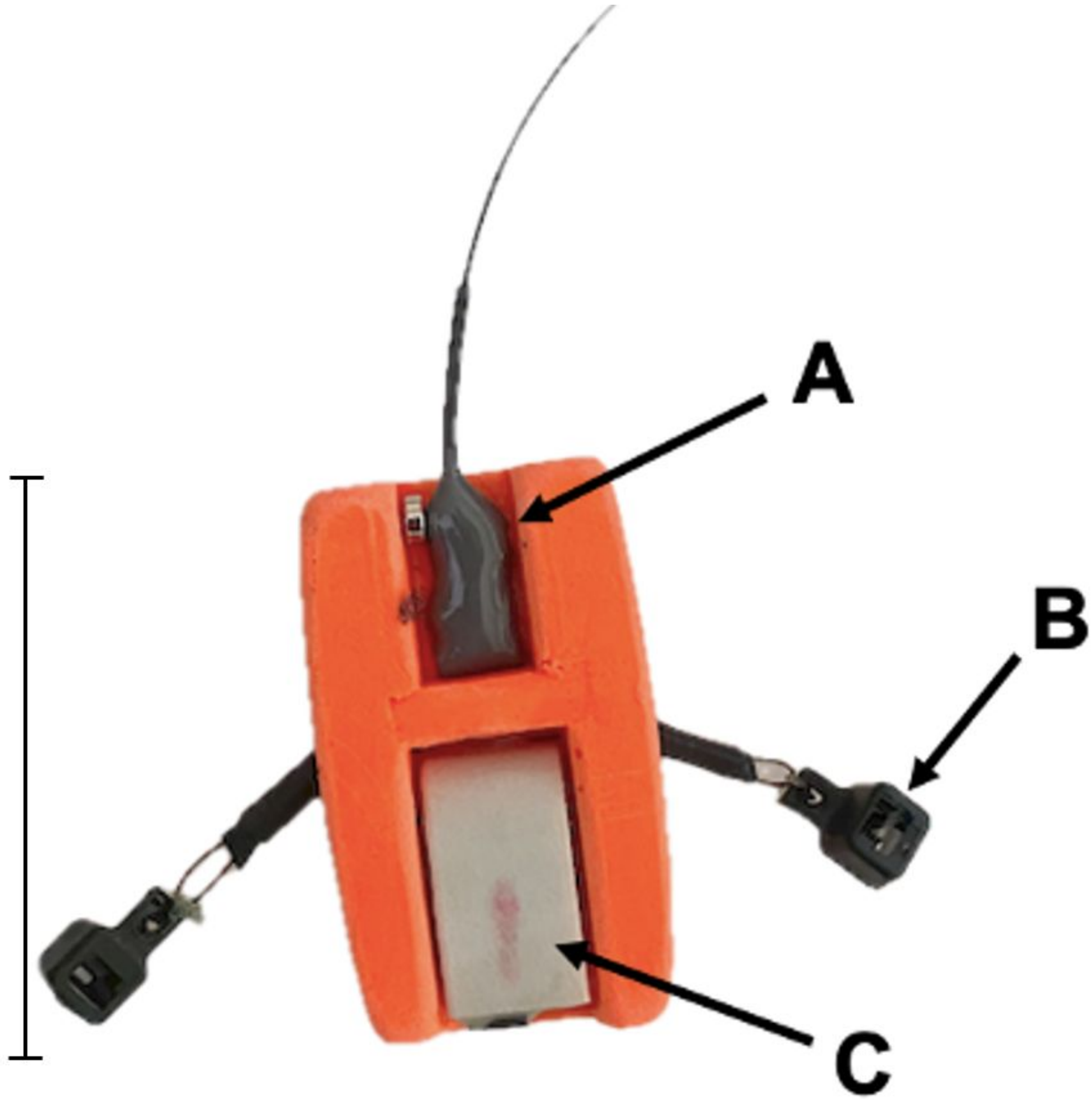

Figure 2. Pop-off biologger that includes a radio transmitter (A) used for relocation, the receptacle of self-locking strap used to secure the strap with a dissolvable link (B), and an internal data storage tag that records acceleration, depth and temperature (C).

Figure 3. Pop-off biologger affixed between the pelvic fins of largemouth bass (*Micropterus nigricans;* A) and between the pectoral fins of northern pike (*Esox lucius*; B).

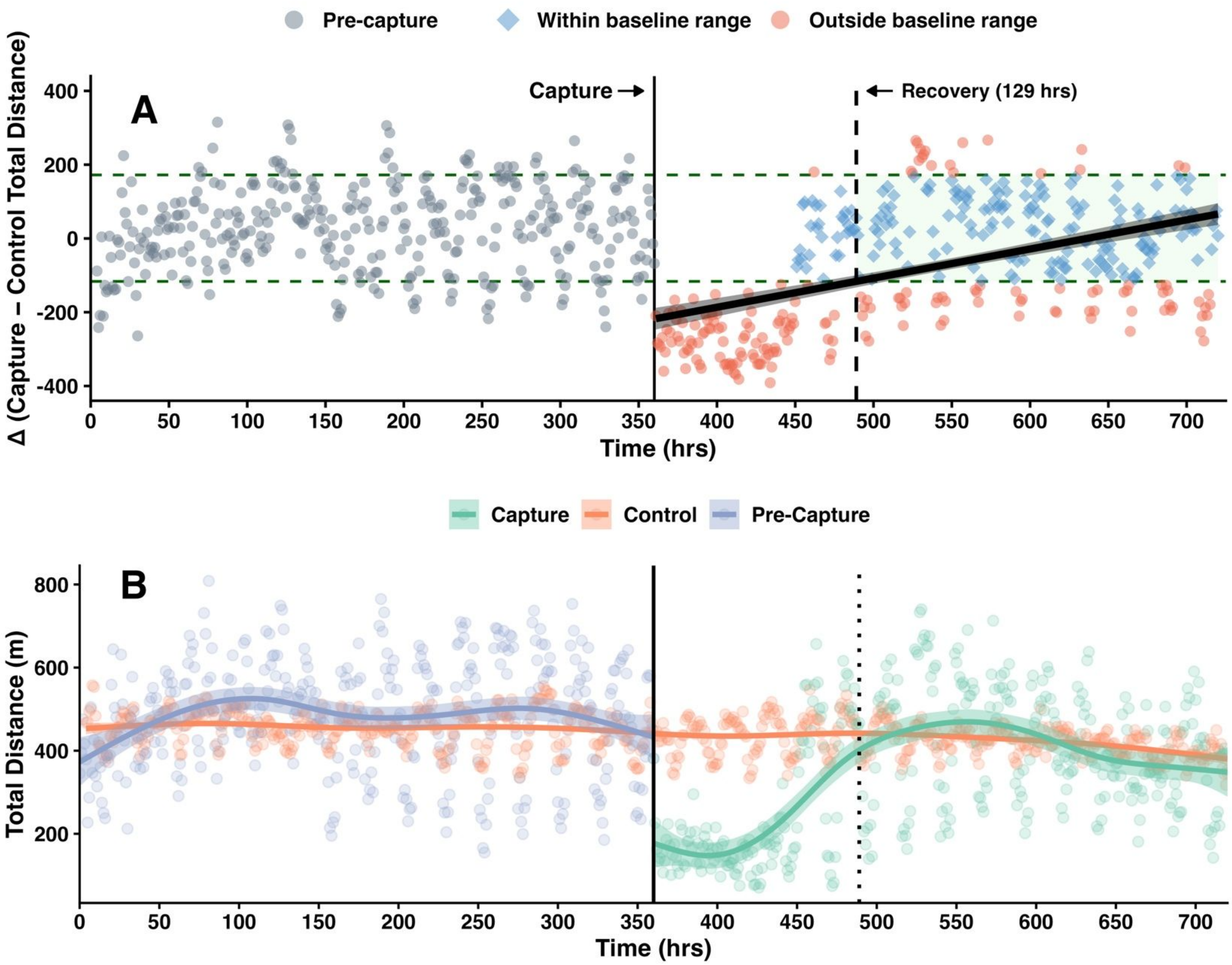

Figure 4. Movement (i.e., total distance) activity of largemouth bass (*Micropterus nigricans*) before (0-360 h) and after a capture event (360-720 h). Panel A represents the difference in total distance (Δ = capture – control) across time with pre-capture baseline measurements (grey circles, 0-360 h) and classification of post-capture measurements (360-720 h). Post-capture measurements were classified as within (blue diamonds) or outside (red circles) the defined pre-capture baseline recovery zone (green dashed lines). Baseline recovery zone was the mean delta difference ± 1.25 S.D. of the pre-capture data. The black linear trend line with 95% confidence interval is used as a model based projected recovery. For both panels, the solid vertical line represents the time of capture (360 h), and the vertical dotted/ dashed line represents the identified recovery time (129 h post-capture). Panel B shows the hourly total distance of pre-captured (purple), control (orange) and captured (green) largemouth bass.

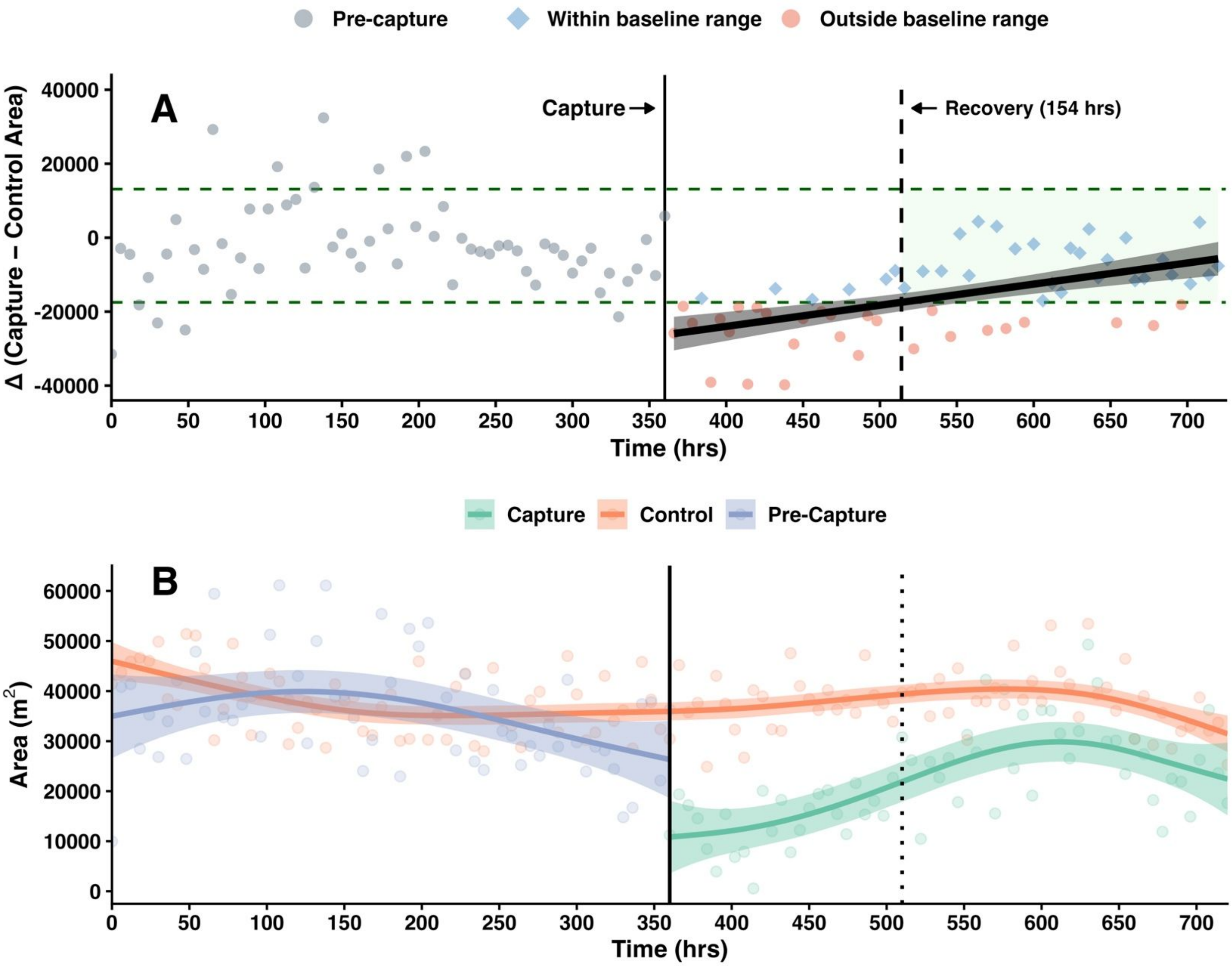

Figure 5. Area used by largemouth bass (*Micropterus nigricans*) before (0-360 h) and after a capture event (360-720 h). Panel A represents the difference in area used (Δ = capture – control) across time with pre-capture baseline measurements (grey circles, 0-360 h) and classification of post-capture measurements (360-720 h). Post-capture measurements were classified as within (blue diamonds) or outside (red circles) the defined pre-capture baseline recovery zone (green dashed lines). Baseline recovery zone was the mean delta difference ± 1.25 S.D. of the pre-capture data. The black linear trend line with 95% confidence interval is used as a model based projected recovery. For both panels, the solid vertical line represents the time of capture (360 h), and the vertical dotted/ dashed line represents the identified recovery time (154 h post-capture). Panel B shows the area used in 6-hour periods of pre-captured (purple), control (orange) and captured (green) largemouth bass.

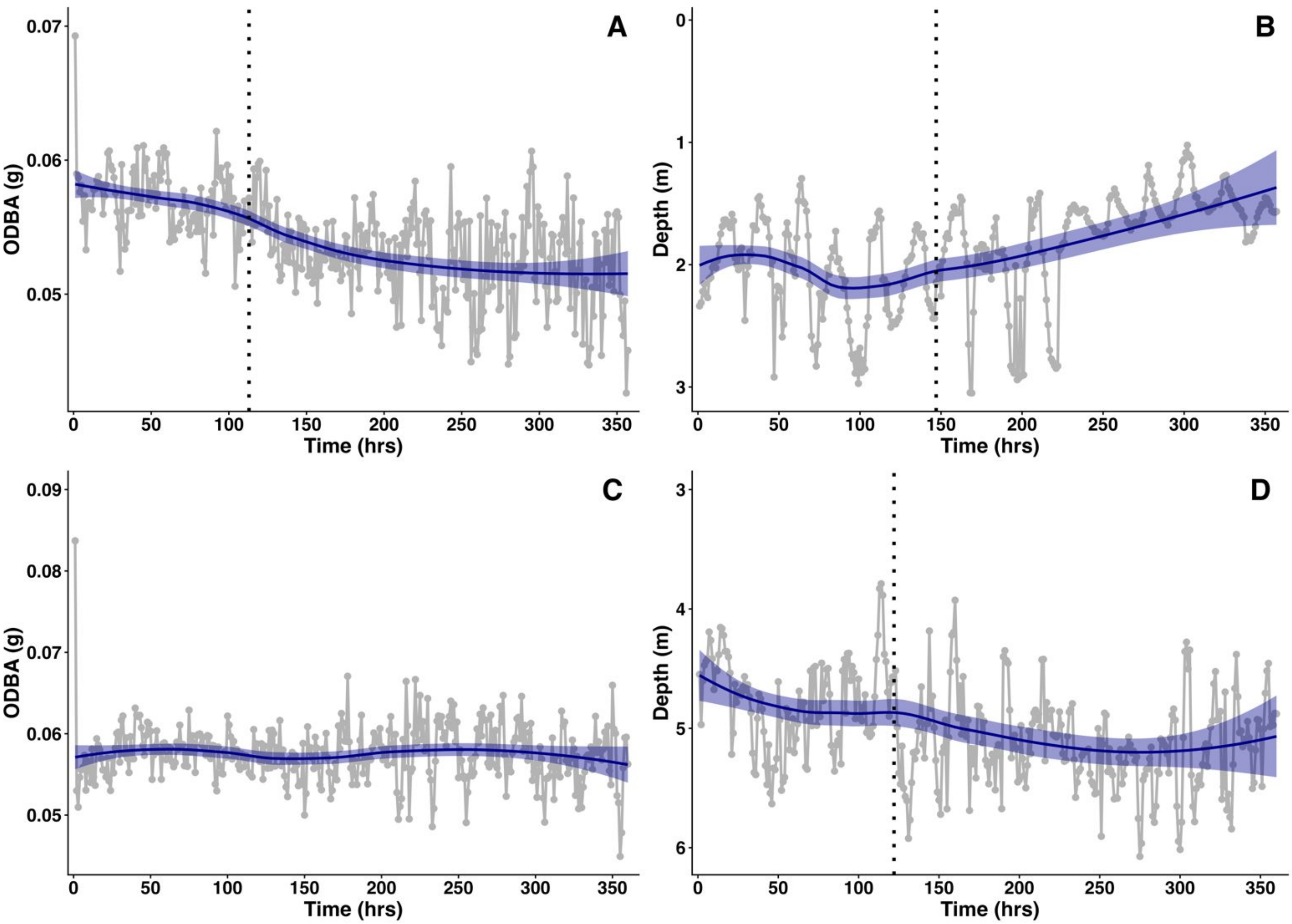

Figure 6. Post-release overall dynamic body (ODBA) acceleration and depth used by largemouth bass (*Micropterus nigricans;* A-B) and northern pike (*Esox lucius;* C-D) collected from pop-off biologgers. The dotted black lines represent a shift in behaviour identified using a changepoint analysis.

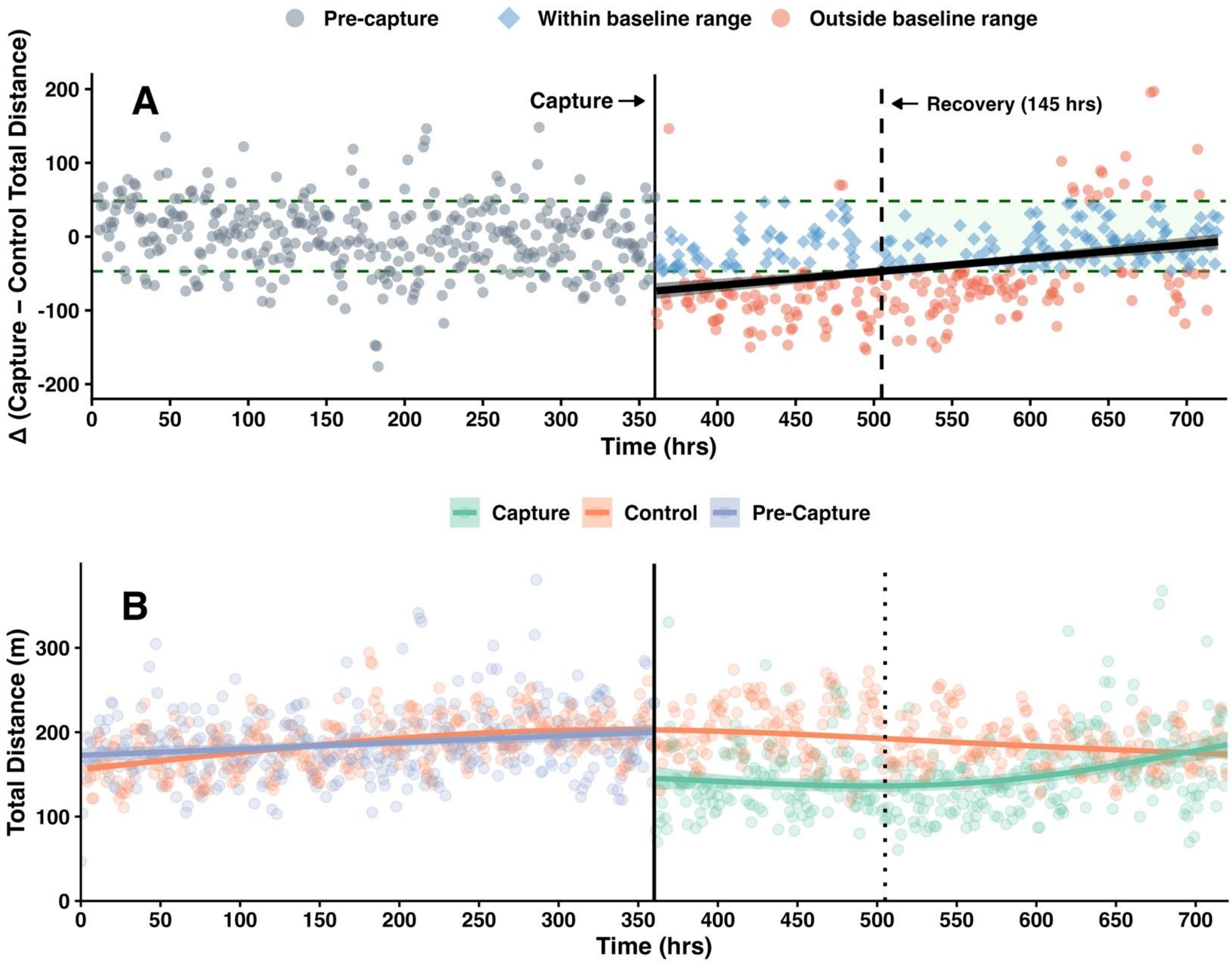

Figure 7. Movement (i.e., total distance) activity of northern pike (*Esox lucius*) before (0-360 h) and after a capture event (360-720 h). Panel A represents the difference in total distance (Δ = capture – control) across time with pre-capture baseline measurements (grey circles, 0-360 h) and classification of post-capture measurements (360-720 h). Post-capture measurements were classified as within (blue diamonds) or outside (red circles) the defined pre-capture baseline recovery zone (green dashed lines). Baseline recovery zone was using the mean delta difference ± 1 S.D. of the pre-capture data. The black linear trend line with 95% confidence interval is used as a model based projected recovery. For both panels, the solid vertical line represents the time of capture (360 h), and the vertical dotted/ dashed line represents the identified recovery time (145 h post-capture). Panel B shows the hourly total distance of pre-captured (purple), control (orange) and captured (green) northern pike.

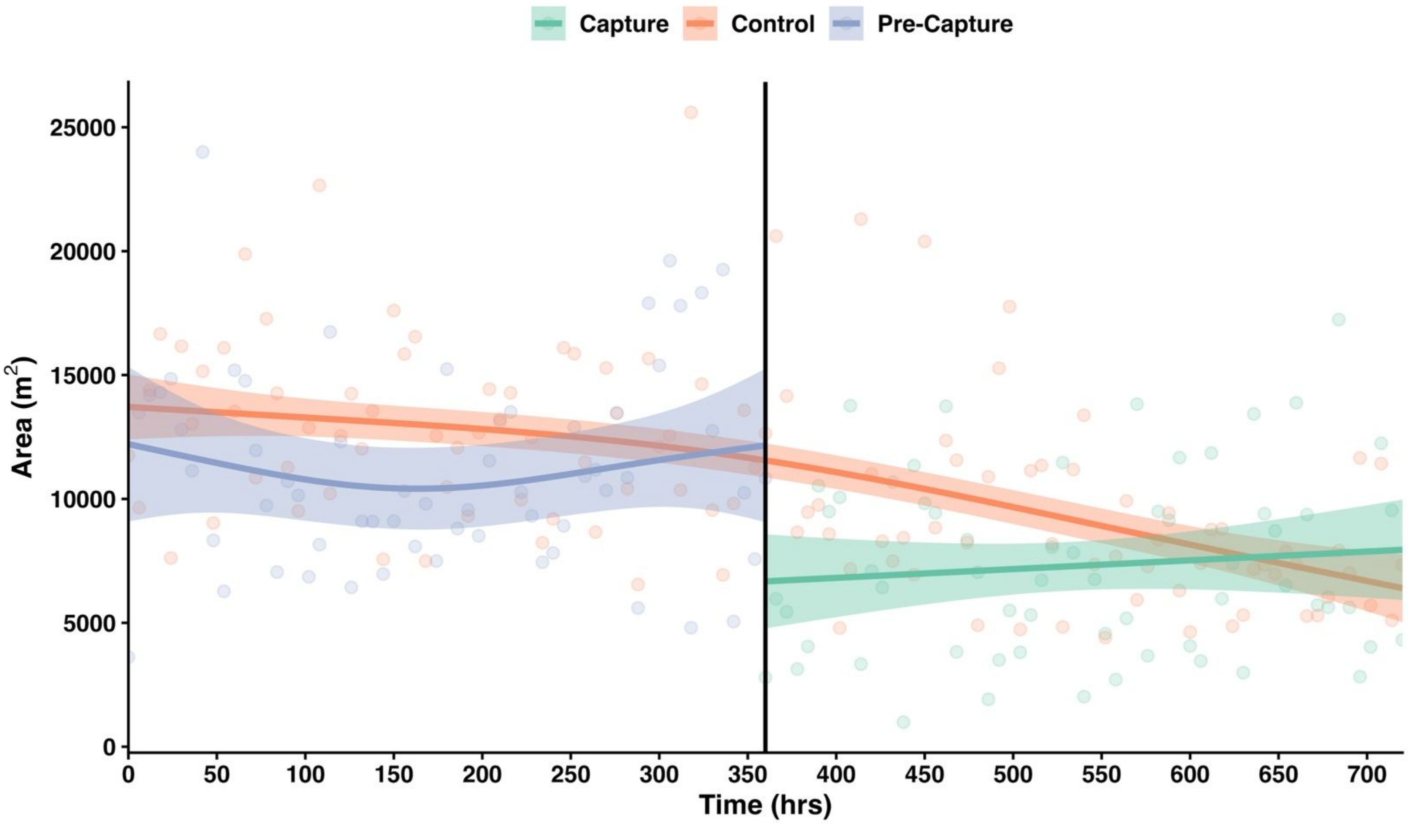

Figure 8. Area used of pre-captured (purple), control (orange) and captured (green) northern pike (*Esox lucius*). The vertical black line represents the capture time (360 h). No recovery time was identified for the area used by northern pike.