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Survival and swim speed performance of Alewife, a small, laterally compressed prey fish, following acoustic transmitter implantation

Sarah M. Larocque[1] | Kurtis Smith[1] | Benjamin L. Hlina[2] | Silviya V. Ivanova[2] | Laura Vrooman[1] | Timothy B. Johnson[3] | Aaron T. Fisk[2] | Jacob W. Brownscombe[1]

[1]Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Science, Burlington, Ontario, Canada

[2]School of the Environment, University of Windsor, Windsor, Ontario, Canada

[3]Ontario Ministry of Natural Resources, Glenora Fisheries Station, Picton, Ontario, Canada

Correspondence
Jacob W. Brownscombe, Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Science, Burlington, ON, Canada.
Email: jakebrownscombe@gmail.com

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Abstract

Alewife (*Alosa pseudoharengus*) is a small, pelagic fish that is an important prey source for piscivores in the Laurentian Great Lakes, yet its spatial ecology is poorly known, which limits the ability to monitor populations. Acoustic telemetry is a tool to understand spatial ecology; however, there may be tagging effects on a smaller body-sized population of Alewife where tag burden is higher than in larger-bodied marine populations. We assessed survival, swimming abilities and healing of Alewife from Lake Ontario after acoustic transmitter implantation. In a laboratory setting, tagged Alewife were compared across tag sizes (Innovasea models V6 and V7-4x), controls and shams (surgery conducted with no tag implantation) in fall 2024 ($n = 76$). Tagging survival was also assessed in spring 2025 (variety of V7 tags) when Alewife had developed gonads and across sex ($n = 126$). Capture, transport and laboratory introduction resulted in moderate mortality in fall 2024 (40%), which was reduced in spring 2025 (4%), an improvement we attribute to the refined protocols reported here. Post-treatment (transmitter, sham, control) survival was high (100% in fall; 91% in spring) with tag burdens from 2 to 8%. We attribute lower spring survival to gonad development, but it was also influenced significantly by a holding tank effect. Two weeks post-tagging, Alewife achieved critical swimming speeds of 37.9 ± 7.6 cm s^{-1}, with no significant differences among treatments. Incisions were all scored as moderately to highly healed 2 weeks post-surgery. Our findings establish the feasibility of tagging smaller, freshwater Alewife with acoustic tags, following best practices reported here, for telemetry applications in the Great Lakes to better understand the spatial ecology of this lower trophic species of major management and ecosystem importance.

KEYWORDS
critical swim speed, Great Lakes, surgery, tag burden, tagging effects, telemetry

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1 | INTRODUCTION

Alewife (*Alosa pseudoharengus*; Wilson, 1811), a small, laterally compressed, pelagic prey fish native to the Atlantic coast of North America, was introduced in the Laurentian Great Lakes (hereafter Great Lakes) in the early 20th century and led to significant ecological changes (Madenjian et al., 2008). Alewife proliferated in the late 1950s and 1960s due to reduced predator abundances of native Lake Trout *Salvelinus namaycush* and Burbot *Lota lota* (Madenjian et al., 2008). Alewife prey upon pelagic fish larvae (e.g., Lake Trout, Krueger et al., 2014; Walleye *Sander vitreus*, Brooking et al., 1998; Yellow Perch *Perca flavescens*, Brandt et al., 1987) and their rapid population growth contributed to the decline of other prey fish, such as Yellow Perch and Emerald Shiner in Lake Ontario (Madenjian et al., 2008). To help alleviate the impacts of increased Alewife abundances, Pacific salmonids were introduced to the Great Lakes to biologically control Alewife populations with Alewife being their primary prey (Dettmers et al., 2012). The Alewife-induced declines in native prey contributed to native salmon and trout (e.g., Lake Trout and Atlantic Salmon *Salmo salar*) also becoming highly dependent on Alewife as prey. While a fishery for Pacific salmon rapidly developed, generating in excess of $5 billion annually for local economies (Great Lakes Fishery Commission, 2022), high levels of thiaminase in Alewife are negatively impacting the reproductive output and population recovery of the native salmonids (Fisher et al., 1996; Fitzsimons et al., 1999, 2010). Thus, monitoring Alewife populations is crucial for maintaining healthy Great Lakes fisheries and fish communities, particularly in lakes Michigan and Ontario where Alewife are the dominant prey species. Accurate characterization of Alewife abundance relative to predator demand, incorporating the spatial ecology and the environmental factors that drive distribution of Alewife, are needed to inform stocking plans for predatory fishes to maintain an appropriate predator–prey balance, and promote fisheries and minimize ecological impacts of this invasive fish.

Acoustic telemetry is a valuable tool for understanding the spatial ecology of fishes, providing insights into their habitat use, migration patterns and interactions with ecosystems (Cooke et al., 2013; Donaldson et al., 2014; Matley et al., 2022); however, there are challenges with using acoustic telemetry on smaller-bodied fishes (Klinard et al., 2025). In the Great Lakes, acoustic telemetry has generally been used to study larger-bodied fishes (e.g., Lake Sturgeon *Acipenser fulvescens* – Colborne et al., 2021; Lake Trout-Binder et al., 2018; Walleye-Hayden et al., 2019), while tracking smaller-bodied pelagic fishes has been more limited primarily due to tag burden challenges. Internally implanting tags into fish, particularly smaller-sized fish, requires a good understanding of tag burden (i.e., weight/volume of tag relative to size of fish) and how the additional weight could impact fish behaviour and survival (Brownscombe et al., 2019; Cooke et al., 2011; Jepsen et al., 2005; Klinard et al., 2018). A guideline that tags should not exceed 2% of a fish's body mass, commonly termed the "2% rule", has been widely applied in telemetry studies (Winter, 1996). That threshold has no strong empirical basis, and the studies that have tested it directly report tolerable burdens well above 2% in several species (Brown et al., 1999; Childs et al., 2011; Smircich & Kelly, 2014), though not universally (Brown et al., 2006). An appropriate tag burden instead depends on species morphology, life history, life stage and the objectives of the study (Cooke et al., 2011; Jepsen et al., 2005; Ramsden et al., 2025; Shorgan et al., 2026), so a species-specific evaluation of tagging effects is more informative than a single blanket limit (Brownscombe et al., 2019). Presence of developed gonads can further reduce body cavity space for tags and create additional injury risks during surgery and influence survival. Furthermore, the tag size required for detecting a fish in an acoustic telemetry array and battery life duration can also impact tag choice and thus the imposed burden. In the Great Lakes, grids of 69 kHz receivers are widely used to understand lake-wide spatial movements of fishes (Kraus et al., 2018). Thus, to effectively integrate with the existing grid arrays in the Great Lakes, small pelagic fishes need to be equipped with compatible tags (i.e., Innovasea's 69 kHz V6 to V16 tags). The 69-kHz tags are larger than the commonly used Juvenile Salmon Acoustic Telemetry System (JSATS) and 180-kHz tags for small fishes and can substantially increase the tag burden on the fish and impact the ability to tag smaller pelagic prey fishes.

Acoustic telemetry and tagging studies have been previously conducted on anadromous Alewife from the Atlantic Ocean but not on potamodromous freshwater populations in the Great Lakes. Tsitrin et al. (2020) conducted a tagging study to assess tagging effects over 72 h on Alewife (mean fork lengths among treatments = 232–251 mm) tagged with relatively small V5-HR tags (180 kHz; 0.77 g in air; tag burden of 0.3–0.6%) and found minimal adverse tagging effects. Since then, Alewife (total length = 247–311 mm) have been acoustically tagged with larger V7-4L tags (69 kHz; 1.8 g in air; no fish weight provided for tag burden) to determine the annual migration between river and ocean in Maryland (Ogburn et al., 2024). Piczak et al. (2025) also assessed anadromous Alewife (fork length = 230–282 mm) post-spawning movements using V7-TP tags (69 kHz; 1.9 g in air; tag burden of 0.7–1.4%) in the Bay of Fundy. A major discrepancy between these anadromous Alewife studies compared to potamodromous freshwater Alewife in the Great Lakes is that adult Alewife in the Great Lakes are considerably smaller, nearly half the size at ages >1 (e.g., approx. total length = 125–200 mm; Norden, 1967; Weidel et al., 2023). Thus, the potential tag burden of using similar tags (e.g., V7-4L and V7-P tags) on smaller fish would be considerably higher; a 1.9 g V7-P tag in a 33 g Alewife equates to a tag burden of approximately 6%. Also, the potential tagging effects beyond 72 h (e.g., delayed mortality, infection) are unknown including whether the ability of individuals to swim normally is impacted. As a pelagic prey fish, if tag burden impairs Alewife's swimming abilities, predation would be artificially increased and detection data compromised.

Prior to using acoustic telemetry to understand the spatial ecology of Alewife in the Great Lakes, it is important to ensure that acoustic tagging does not impair post-surgery swim performance and survival, particularly for a population of smaller-bodied individuals. In this study, we assessed tagging effects in two seasons (spring and fall) using V6 and/or V7 tags (with/without sensors) in smaller-sized Great Lakes Alewife, across tag burdens of 2–8%. The assessment in the

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spring allowed us to determine if reduced fish cavity space from gonads further impacted survival. Fish were monitored for 2 weeks post-surgery to understand if delayed mortality was a concern for tagged Alewife. Thus, the goals of this study were to (1) evaluate the possible effects of tagging and tag size on the survival and swim performance of potamodromous freshwater Alewife; (2) assess surgery healing; and (3) determine whether survival may vary by reproductive state and sex by comparing spring tagged Alewife that had developed gonads to fall tagged Alewife that did not have enlarged gonads.

2 | MATERIALS AND METHODS

Alewife were captured in western Lake Ontario and transported to the Aquatic Life Research Facility (ALRF) at the Canada Centre for Inland Waters (CCIW), Burlington, Ontario, to study survival, healing and swimming impacts from surgically implanting acoustic telemetry tags. The primary study occurred in fall 2024, with additional Alewife that were tagged in spring 2025 for wild release incorporated into the study.

2.1 | Ethics statement

All collection, transport, holding and experimental procedures were conducted in accordance with and complied with the Canadian Council of Animal Care, under the Fisheries and Oceans Canada – Ontario and Prairie Sub-committee (AUP # OPA-ACC-2024-65 and OPA-ACC-2025-10).

2.2 | Fish capture

Alewife were captured, held onboard and transported using the Fisheries and Oceans Canada (DFO) Research Vessel Cisco (11.58 m length, 3.66 m beam). Alewife were angled using Sabiki rods (RSB-700 Sabiki Stick – Bait Catcher Rod, AHI, Gardena, California) with size 4 or 6 Sabiki rig lures that have 6 individual hooks, and 3 oz. triangular weights tied at the bottom. Schools of Alewife were located using 2D sonar and the lures were then lowered to the depth of the schools. Once fish were hooked, they were reeled in and immediately released into a circular polyethylene (2 m diameter x 1 m height) tank, pre-filled with lake water and supplemented with an aerator. A temporary flow-through water system was plumbed from the surface water pump of the vessel to the tank, enabling continuous circulation of the holding water to maintain water quality. A multiparameter digital water quality sonde (EXO3S, YSI Inc./Xylem Inc., Yellow Springs, OH) was placed in the holding tank to constantly monitor water temperature and dissolved oxygen (DO).

In 2024, 127 fish were angled October 16–17 (surface water temperatures = 15.5°C), in waters that were 0–2 m off bottom at depths ranging between 14 and 25 m, near the mouth of Sixteen Mile Creek (43.42438 N, 79.66447 W). In 2025, 176 fish were angled June 2–3 (surface water temperatures = 9.6–10.9°C), in waters that were 0–5 m off bottom at depths ranging between 11 and 18 m, between the mouth of Sixteen Mile Creek and Credit River (43.48369 N, 79.60029 W). In 2024, Alewife larger than 100 mm total length were kept, while in 2025, Alewife larger than 140 mm total length were targeted as larger tags were being implanted in these fish. Captured fish were then transported to the ALRF. During transport, the circular tank was covered with tarp to reduce stress and escapement. Once docked, fish were transported by truck to the ALRF using a ~ 680 L insulated fish box (PB1545, Bonar Plastics, Waterloo, ON) filled with water from the ALRF (details below) at temperatures comparable to the lake.

2.3 | Holding conditions

The ALRF supplies filtered, dechlorinated municipal water via a Recirculating Aquaculture System (RAS) comprising three circular tanks (1606 L each), a biofilter (661 L), a sump (684 L), ultraviolet disinfection and a cannister filter. In both 2024 and 2025, three circular tanks served as the Alewife holding tanks. In fall 2024, prior to holding tank introduction, all individuals underwent a 30-min saltwater bath (1.0% NaCl) at similar temperatures to the capture location to reduce the risk of parasites and external infections. Following the saltwater bath, Alewife were transferred to freshwater holding conditions and distributed among the three tanks (Tank 1 = 25 fish; Tank 2 = 25 fish; Tank 3 = 77 fish; distribution numbers were uneven as an artefact of maintaining source segregation), and water temperatures were held at 13°C. Due to persistent but low mortality prior to the fall 2024 experiments (15 mortalities and 36 euthanized for welfare reasons; 40% loss of fish; $n = 51$ of 127), we raised the salinity of the holding tanks to 0.7% to reduce stress. Note that some fish showed injury from angling (particularly loss of scales and damage to the epidermis from fishing lines) that contributed towards mortalities and euthanasia numbers. The RAS system was then maintained at this salinity level (0.7% NaCl) for the duration of their holding period, until it was reduced to 0.5–0.6% a day prior to swim trials. Following swim trials and to aid in recovery, the salinity level was increased to 0.7%.

Based on our observations from the fall 2024 experiments, we did not perform the saltwater bath and instead introduced the Alewife captured in spring 2025 directly into their holding tanks at a higher salinity (0.8–1.0%) to reduce stress (Tank 1 = 73 fish; Tank 2 = 70 fish; Tank 3 = 33 fish). Also, while angling, greater care was taken during dehooking fish where less scale loss and epidermal damage occurred. A salinity of approximately 0.6–0.8% was then maintained throughout their holding period at 13°C until it was gradually reduced to 0.2% for 3 days prior to release. Prior to tagging, 7 individuals were euthanized due to poor health ($n = 7$ of 176; 4% loss of fish) following the Canadian Council on Animal Care's animal welfare assessment guidelines (Canadian Council on Animal Care (CCAC), 2021).

Across both seasons, fish health (fungal growth, external lesions, abnormal behaviour) and water quality (DO, NH_4/NH_3, NO_2, pH) were monitored and recorded following ALRF standard operating

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procedures. An underwater camera (AquaVu, Minnetonka, Minnesota) was installed in each tank to facilitate observations and fish health assessments while minimizing interaction-induced stress. Fish were fed a mixed diet, including frozen bloodworms, brine shrimp (San Francisco Bay Brand Inc., Hayward, CA) and jumbo *Mysis* shrimp (Hikari USA, Hayward, CA) once or twice daily, depending on staff availability. Fish were fed until satiation and feeding concluded when an excess amount accumulated on the bottom of the tank. The weight (grams) and type of feed were recorded for each tank. Following introduction, fish in fall 2024 were observed readily consuming feed after approximately 1 week, whereas fish in spring 2025 began feeding within approximately 3 days. Tagging did not occur until fish went 2 weeks without any additional mortalities.

2.4 | Tagging

In 2024, Alewife ($n = 76$) were put into one of four different tagging treatments: control ($n = 23$; handled, no surgery), sham ($n = 23$; surgery but with no tag inserted), V6 ($n = 22$; V6 dummy transmitter inserted; V6-2x – 6.3 mm diameter, 13 mm length, 0.5 g in water, 0.9 g in air, Innovasea, Halifax, NS) and V7 ($n = 8$; V7 dummy tag inserted; V7-4x – 7 mm diameter, 21.5 mm length, 0.9 g in water, 1.8 g in air, Innovasea, Halifax, NS). The acoustic dummy tags are matched in size and weight to active transmitters to replicate implantation procedures, while reducing costs. These treatments were split equally among the three holding tanks to minimize tank effects. Fish were fasted for 48 h prior to surgical procedures. The first surgeries ($n = 8$, all V6 treatment) were conducted on 20 November 2024 and were closely monitored to assess recovery. The remaining 68 surgeries and handling procedures occurred on 25 November 2024. Fish were held in their respective housing tanks for 2 weeks (14 days) to assess survival. After 2 weeks, fish were exposed to a Ucrit swimming trial procedure in a swim tunnel (see swim trials section) to assess the effects of tagging on swimming performance.

In 2025, Alewife ($n = 126$) were tagged with one of four different V7 tag types: V7-2x ($n = 15$; 7 mm diameter, 19.5 mm length, 0.7 g in water, 1.5 g in air, Innovasea, Halifax, NS), V7-4x ($n = 15$), V7-D ($n = 30$; 7 mm diameter, 22 mm length, 0.8 g in water, 1.7 g in air, Innovasea, Halifax, NS), and V7-P-4x tags ($n = 66$; 7 mm diameter, 23 mm length, 1.0 g in water, 1.9 g in air, Innovasea, Halifax, NS). Larger V7 tags were used to carry sensors and for increased battery life and detection range compared to V6s. The tagging process was the same as the fall 2024 V6 and V7 treatments. Tagging occurred on 16 June 2025. These fish were held for approximately 2 weeks following surgeries, prior to release into Lake Ontario (field data not part of this study). However, the increased number of larger tags and spring tagging (prior to spawning) provided additional information regarding survival and are reported in this study.

For surgeries in the sham, V6 and V7 treatments, Alewife were electro-immobilized using a TENS unit (TENS 7000®, Middleburg Heights, OH) with two shocking pads laid on a small foam cradle on either side of the fish with an assistant to help ensure the gills were constantly irrigated with water (Figure 1). For each fish, power was increased on the TENS unit from zero until a point that fish exhibited electrotetanus. Prior to the incision, Alewife were injected subcutaneously with lidocaine (10 mg/kg body mass with a 2% solution; 20 mg mL^{-1}) as a local anaesthetic. Electro-immobilization does not provide analgesia and as such a local anaesthetic was administered at the incision site as a welfare refinement. Analgesic use in fish remains limited, and infiltration of lidocaine has been reported to cause no adverse behavioural effects in Rainbow Trout (Chatigny et al., 2018a, 2018b). A 10–15 mm incision was made vertically between ribs, along the side of the fish, posterior to the pectoral fins and ventral to the lateral line, similar to Tsitrin et al. (2020; Figure 1). Typical incisions for acoustic telemetry tags are parallel to the linea alba (running horizontal); however, making the same incision on Alewife with their laterally compressed shape and extension of ribs to the linea alba would involve cutting through ribs, and incur greater potential injury and longer recovery. Once the incision was made, V6 and V7 treatments had their respective tags inserted into the peritoneal cavity while the sham treatment had no tag inserted. In fall 2024, all three treatments had a PIT tag (12 mm length, 106 mg, Biomark, Inc., USA) inserted into the peritoneal cavity to facilitate individual identification. The incision was closed with one simple interrupted suture (size 5–0 with 3/8 circle curvature, 13 mm long reverse cutting needle, polydioxanone [PDO] absorbable monofilament; Synergy Surgical, Mokena, IL). The knot was tied with three throws: two double-wrapped surgeon's throws followed by a single square throw. All tools and tags were cleaned prior to surgery using a Virkon® Aquatic solution (Syndel, Nanaimo, BC), and recirculating water temperatures were maintained at 13°C.

After surgery was completed, fish were measured for mass (0.01 g precision) and total length (mm) and returned to the appropriate holding tank. Control fish were also handled and measured before being returned to the holding tanks. As the mass of fish was measured post-surgery, the air weight of the tag was subtracted to compare mass among groups. This corrected mass was also used to determine total tag burden (tag mass in air/fish mass in air).

Following surgeries, all fish and tanks continued to be monitored for incision healing, behaviour, fungal growth, feeding and water quality following CCAC Animal Welfare Monitoring procedures (Canadian Council on Animal Care (CCAC), 2021). Individuals exhibiting health issues or signs of infection were euthanized following the same CCAC guidelines (Canadian Council on Animal Care (CCAC), 2021). Fish were fed the standard diet of frozen bloodworms, brine shrimp and jumbo *Mysis* shrimp, but with amounts adjusted to approximately 2% of total body mass per tank, based on weights recorded during surgeries.

2.5 | Swim trials

Swim trials were conducted from December 9–13, 2024, a minimum of 14 days post-surgery. Half of the 2024 Alewife ($n = 37$) across all four treatments were individually transferred into a 185 L swim tunnel respirometer (control: $n = 9$; sham: $n = 10$; V6: $n = 10$; V7: $n = 8$; Loligo Systems Inc., Viborg, Denmark), filled with freshwater similar in

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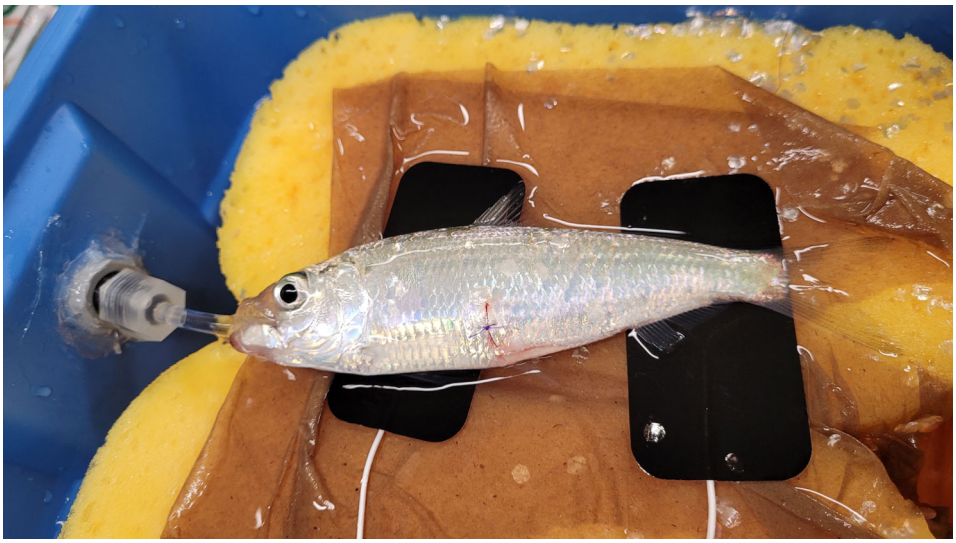

FIGURE 1 Example of surgery incision and surgery setup of Alewife (*Alosa pseudoharengus*) being electro-immobilized using a TENS unit (TENS 7000®, Middleburg Heights, OH) with two shocking pads laid on a small foam cradle on either side of the fish and water pumped through tubing to ensure the gills were constantly irrigated with water. Note the vertical incision and single suture from the surgery. Incision location was always vertical between the ribs and could be further anterior but not posterior beyond the pelvic fins. For scale, the TENS pads on either side of the fish are 40 mm wide and 85 mm long.

temperature to the holding tanks and with aeration delivered via air stones. The enclosed swimming portion of the chamber (88 × 25 × 25 cm) was partially covered and contained an electric grid (8 V; BK Precision DC Regulated Power Supply, model 1621A; BK Precision, USA) at the rear to encourage swimming when needed.

Water temperature and dissolved oxygen were monitored and recorded throughout the trials using temperature and oxygen probes (Firesting O_2, Pyroscience, Aachen, Germany) and the corresponding software (Pyro Workbench, Pyroscience). However, the chamber was not treated as a respirometer due to the low fish mass-to-water volume ratio precluding collection of these data. Instead, the flush pump (1250 L h^{-1}; Sicce, Pozzoleone, Italy) continuously supplied oxygenated water into the swimming portion of the chamber from its surrounding water bath. Fish were identified by PIT tag (except for controls) and introduced to the swim tunnel; the chamber lid was sealed, and each individual was acclimated for 20 min at a flow of 10 cm s^{-1}. Fish were tested individually, with one fish in the swim tunnel per trial.

Following acclimation, fish were then subjected to a ramp-Ucrit swimming procedure (Brett, 1964; Jain et al., 1997; Lee et al., 2003), involving incremental flow speed increases of 5 cm s^{-1} every 3 min, starting at 15 cm s^{-1}. If a fish was not maintaining position, the grid at the rear was electrified to encourage swimming. If the individual could still not maintain position after three successive shocks with less than 5 s of resumed swimming, the trial was ended and the speed and end time recorded (Brownscombe et al., 2024).

Photographs of trial fish were taken in the swim chamber before and after each trial to assess both the healing rate of the incision 2 weeks post-surgery and whether an increased duration of intense swimming impacted the incision and increased inflammation. Incision healing was scored based on Klinard et al. (2018), which used a modified scale (range from 1 to 6; ranging from closed wound/no inflammation to completely open wound/moderate to high inflammation around edges) from Wagner (1999; Table 1). Scoring was completed by three people independently, due to the potential for subjectivity on scoring. Mass was recorded post-trial, and individuals were returned to a holding tank. All 2024 fish ($n = 76$) were euthanized on December 19, 2024 via immersion in 250 mg L^{-1} Tricaine methanesulfonate buffered with sodium bicarbonate. Following the completion of swim trials, total length, weight and general health conditions were recorded.

TABLE 1 Description of criteria for wound healing scores used to rank the progress of wound healing after surgical insertion of dummy acoustic tags in Alewife (*Alosa pseudoharengus*), as presented in Klinard et al. (2018) as a modified Wagner scale (Wagner, 1999).

Score	Description
1	Incision completely closed; no inflammation.
2	Incision closed; some inflammation along incision site.
3	Incision held in proximity, but edges slide if fish moves; moderate inflammation.
4	Incision partially opened at one end or middle; moderate to high inflammation.
5	More than 50% of wound open; moderate to high inflammation along wound edges.
6	Completely open wound; moderate to high inflammation along edges.

Note: Lower scores represent a less extreme inflammatory response.

2.6 | Analyses

All analyses were conducted in R (Version 4.4.3, R Core Team, 2025). Assumptions of normality were checked for all statistical tests. Significance was assessed at $\alpha = 0.05$. Length, mass and tag burden (excluding treatments with no tags) were each compared across treatments for each year using one-way ANOVAs. If any significant differences were found with an ANOVA, a Tukey HSD test was conducted. For both 2024 and 2025, we assessed whether there was a difference in Alewife survival 14 days post-surgery between the treatments/tag

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types using Fisher's exact tests. We also assessed if there was a difference in survival between the three housing tanks using a Fisher's exact test. We assessed whether tag burden influenced survival using a binary logistic regression. In 2025, sex was identified in some fish, and we assessed if there was a sex difference in survival with the Fisher's exact test. We also assessed reproductive state by comparing survival of V7-4x tagged fish in fall 2024 to spring 2025 with the Fisher's exact test. If a significant difference was found with Fisher's exact test, pairwise Fisher's exact tests were conducted with a Bonferroni correction using the {rstatix} package (Kassambara, 2025).

As surgery-induced mortalities occurred in 2025, post-surgery survival of Alewife was monitored over time prior to release. Kaplan–Meier survival curves were made for each tag type, housing tank and sex, and we used a non-parametric log-rank test to compare the survival curves between groups. Cox proportional hazards could not be used due to some categories having zero events (no mortality). If there was a significant difference with log-rank tests with multiple categories, then specific differences were determined using pairwise log-rank tests with a Bonferroni correction using {survminer} package, *pairwise_survdiff()* function (Kassambara et al., 2025). A Cox proportional hazards model was used to determine if survival curves varied by tag burden.

Critical swimming speed (U_{crit}; cm s^{-1}) was calculated based on Brett (1964): $U_{crit} = Vf + [(T/t)(dV)]$, where Vf is the last full speed completed, T is the duration at final increment, t is the duration at each speed increment and dV is the speed increment. Critical swimming speed (cm s^{-1}) between treatments was tested with a one-way ANOVA. We also compared 2-week post-surgery healing scores (ordinal data ranging from 1 to 6) across treatments, and before/after the swim trial (score time), with scorers as a random effect using a Cumulative Link Mixed Model (CLMM) using the {ordinal} package (Christensen, 2025). Significance of main effects was determined using a type II analysis of deviance.

3 | RESULTS

In 2024, Alewife length varied across treatments ($F_{3,72} = 9.254$, $p < 0.001$), where V7 tagged fish (175 ± 5 mm) were significantly larger than V6 (162 ± 10 mm), shams (159 ± 8 mm) and controls (157 ± 10 mm; $p < 0.002$). Similarly, Alewife mass varied across treatments ($F_{3,72} = 13.07$, $p < 0.001$), where V7-4x tagged fish (40 ± 3 g) were significantly larger than V6 (32 ± 6 g), shams (29 ± 4 g) and controls (28 ± 5 g; $p < 0.001$). Larger Alewife were surgically implanted with the larger V7-4x tags considering they have a larger body cavity. Even in larger fish, however, the overall tag burden was significantly greater in fish implanted with V7-4x (4.5 ± 0.3%) than V6 treatments (2.9 ± 0.6%; $F_{1,28} = 54.39$, $p < 0.001$). Overall tag burden ranged between 2.1 and 5.1% for fall 2024.

In spring 2025, similar to 2024, the V7 tags were implanted into larger fish (168 ± 9 mm; 33 ± 5 g) but length or mass did not vary across the V7 tag types (length: $F_{3,122} = 0.13$, $p = 0.942$; mass: $F_{3,122} = 0.17$, $p = 0.917$). Tag burden, however, did vary across the V7 tag types ($F_{3,122} = 7.34$, $p < 0.001$); fish with V7-P tags had greater tag burden (5.8 ± 0.8%) than V7-2x (4.7 ± 0.7%) and V7-D (5.3 ± 1.0%) tags. The tag burden in fish with V7-4x tags (5.5 ± 0.5%) was similar across all tag types. Overall tag burden ranged between 3.6 and 8.0% in spring 2025.

In 2024, all fish survived the full 14-day post-surgery recovery across all treatments. In 2025, 115 of 126 fish (91.3%) survived 14 days post-surgery. Although most fish that died had V7-P tags (the largest of the tags; $n = 9$ of 11 mortalities), there were no differences in survival across tag type (Fisher's exact test, $p = 0.269$) or tag burden ($z = -0.453$, $p = 0.651$). Survival across tanks, however, was significantly different (Fisher's exact test, $p < 0.001$), with Tank 1 having significantly more mortalities ($n = 10$ of 11 mortalities, with 3 additional mortalities of untagged fish) than Tank 2 ($p = 0.004$) and Tank 3 ($p = 0.024$). We could discern sex for 83 fish (49 females, 34 males), of which 6 of 7 mortalities were female; however, survival by sex was not significantly different (Fisher's exact test, $p = 0.231$). Notably, necropsies indicated that three of the six female mortalities showed blood in the egg sac and one of the three had their egg sac damaged during surgery. Between the two tagging seasons, survival of V7-4x tagged fish was similar between 2024 and 2025 (with only 1 mortality in spring 2025) and was not impacted by reproductive state (Fisher's exact test, $p = 1.00$).

Similarly, 2025 survival curves over the 14-day recovery period did not vary by tag type (log-rank test, $\chi^2(3, N = 126) = 4.7$, $p = 0.2$; Figure 2), sex (log-rank test, $\chi^2(1, N = 83) = 2.3$, $p = 0.1$; Figure 2) or with tag burden (Cox proportional hazards, $z = 0.481$, $p = 0.631$). Survival curves did vary by tank (log-rank test, $\chi^2(2, N = 126) = 16.6$, $p < 0.001$), with Tank 1 having lower survival than Tank 2 ($p = 0.005$) and Tank 3 ($p = 0.018$; Figure 2). Note that Tank 1 also had mortality of 3 untagged fish during the post-surgery period, with no other untagged fish mortalities in the other tanks.

Swim trials 2 weeks post-surgery showed no difference in critical swimming speeds (cm s^{-1}) between treatments ($F_{3,33} = 0.453$, $p = 0.717$; Figure 3), where in general fish swam at 37.9 ± 7.6 cm s^{-1} or 2.33 ± 0.46 body lengths s^{-1} (Table 2). When critical swim speed was adjusted for body lengths per second, there were still no differences between treatments ($F_{3,33} = 0.490$, $p = 0.692$).

Healing scores did not vary across treatments ($\chi^2(2) = 0.599$, $p = 0.741$), or before or after the swim trials ($\chi^2(1) = 1.651$, $p = 0.199$), when accounting for individual scorers. At 14 to 23 days post-surgery, most fish wounds were nearly healed, with healing scores primarily at a 2 (incision closed with minor inflammation; 44–47% probability), followed by 1 (incision closed, no inflammation; 25–39% probability) or 3 (incision held in proximity, but edges slide if fish moves; moderate inflammation; 15–24% probability; Figure 4). Healing scores of 4 occurred but at very low probability (incision partially opened at one end or middle; moderate to high inflammation; 2–5%; Figure 4) and no scores occurred greater than 4.

4 | DISCUSSION

Evaluating burden and any effects on the survival and swim performance after the surgical implantation of acoustic transmitters on

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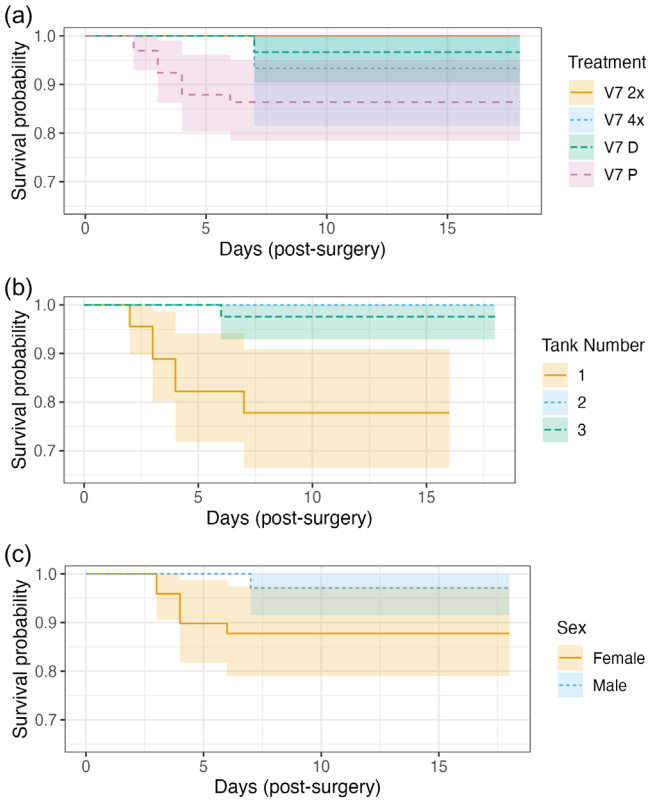

FIGURE 2 Survival curves (±95% confidence intervals) of acoustically tagged Alewife (*Alosa pseudoharengus*) in spring 2025 after surgery, by different tag type (a), different housing tanks (b) and sex (c). Note that only tank effects were significantly different, with Tank 1 experiencing more mortality than other tanks. Groups are distinguished by colour and line type.

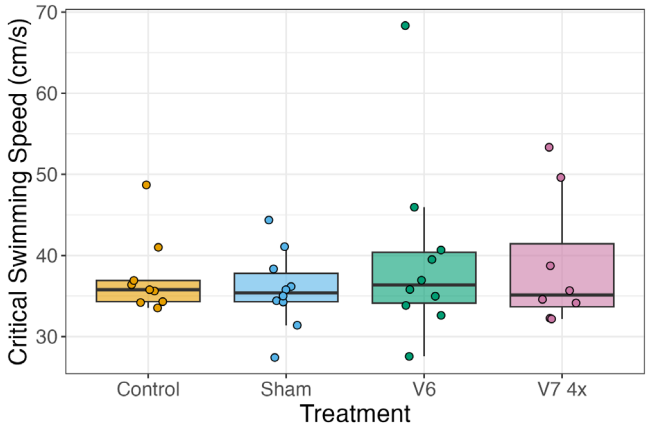

FIGURE 3 Boxplots with individual data points overlaid, showing critical swim speed (cm s^{-1}) of Alewife (*Alosa pseudoharengus*) across different acoustic tagging treatments 2 weeks post-surgery.

TABLE 2 Mean (± standard deviation; SD) critical swimming speeds of Alewife (*Alosa pseudoharengus*) across different tagging treatments, by water velocity (cm s^{-1}) and relative to Alewife size (body lengths s^{-1}).

		Critical swimming speed			
		cm s^{-1}		Body length s^{-1}	
Treatment	*n*	Mean	SD	Mean	SD
Control	9	37.4	4.8	2.38	0.35
Sham	10	35.8	4.7	2.27	0.33
V6	10	39.6	11.2	2.45	0.65
V7-4x	8	38.8	8.1	2.21	0.45

laterally compressed, small-bodied prey species is important for avoiding bias and advancing the ecological knowledge on these species. Further, survival of these fish may vary by reproductive state and sex given the limited space in the coelom with gonad development for tag placement and no studies have attempted to address this concern for Alewife. Thus, here we show that Alewife, a small, laterally compressed prey fish in Lake Ontario, had high survival after tag insertion, and tolerated tag burdens of 2.1 to 8.0%. Our results support the findings of Tsitrin et al. (2020) who reported high survival (97%) of Alewife for 72 h post-tagging. Further, our results show survival was similar for tagging in both fall 2024 (100% survival) and spring 2025 (>90% survival). The higher tag burden (tag burden range = 2.1–8.0%) from using larger tags (V6 and V7s) on smaller fish (total length range = 139–194 mm) did not affect survival with incisions healing well and no detected effects on swimming capacities, thus showing the feasibility of using larger tags (e.g., the 69 kHz range of tags by Innovasea) on smaller, freshwater Alewife for improved detection range and battery life. By monitoring individuals for 2 weeks, we were able to measure delayed mortality. In spring 2025, survival was 98% after 2 days and 96% after 3 days, which are very similar to the results in Tsitrin et al. (2020). However, a delayed mortality within the 1st week post-surgery reduced the overall survival to 91%. While overall size of individuals, the increased tag burden of using V7 type tags (>3%), gonad development in fish, and tank effects in spring 2025 could all have influenced the delayed mortality observed in one of the two tagging sessions, our key findings demonstrate very high overall survival. Given this, we suggest that with proper care during capture and laboratory introduction (e.g., saline water during the holding period, care during angling), Alewife show substantial resilience to tag burdens of up to 8%, above the 7% limit Smircich and Kelly (2014) recommended for Brook Trout on tag retention grounds, with no detected effect on swimming performance or survival.

An important consideration for survival when implanting a tag internally into a small laterally compressed fish such as Alewife is the reproductive state of the fish due to reduced space in the body cavity as a result of gonadal development. Further, the reduced space can add complications and increase potential mortality during the tagging surgery procedure. By tagging in the spring and fall we were able to compare indirectly the effects on survival of tagging Alewife with and without gonadal development, respectively. There were no significant differences in survival by reproductive state with no mortalities for V7-4x tags in fall 2024 ($n = 8$) compared to 1 mortality in spring 2025 ($n = 15$). Although there was no statistical significance in survival

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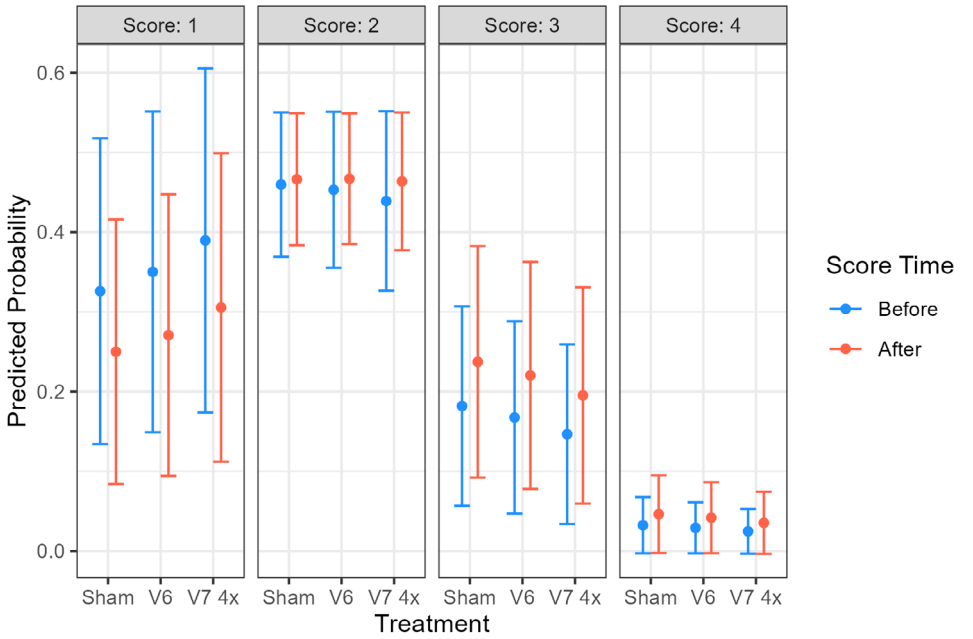

FIGURE 4 Modelled mean (±95% confidence intervals) predicted probability of Alewife (*Alosa pseudoharengus*) surgery wounds receiving a healing score (1 through 4; no scores occurred above 4) based on tagging treatment. Scoring occurred 2 weeks post-surgery before and after the swim trials.

between sexes, the majority of mortalities in 2025 were females (6 of 7 individuals). Females generally have a higher gonadosomatic index than males (Hutchings, 2002; Tsikliras et al., 2010), which reduces body cavity space more in females compared to males and may have contributed to a reduced survival. When gonads have developed or are developing there is a potential additional risk of egg or sperm sacs being ruptured internally either during making the incision or pressure from the tag insertion (from lack of room) causing stress or potentially mortality for the fish. In small-bodied fishes like Alewife, this could be exacerbated at the higher tag burdens examined here. Tsitrin et al. (2020) found that ripe Alewife were more likely to have punctured gonads from the tag than spent Alewife. Although it was unclear if gonadal development resulted in additional mortality in our study, when the sex of the fish was known the majority of those mortalities were ripe females, and extra care and caution is warranted when tagging small-bodied fish when ripe with gonads to reduce tagging effects.

Tagging effect studies often focus on assessing survival and healing (e.g., Klinard et al., 2018; Robinson et al., 2021; Tsitrin et al., 2020), but it is also important to consider other biological impacts tagging may have on organisms like reducing swim speeds that may artificially decrease survival post-release (Shorgan et al., 2026). Altered swimming abilities from tagging may increase potential predation or reduce an individual's ability to forage and capture prey. Alewife in the Great Lakes are preyed upon by a number of species (e.g., salmonines) and tagging influences on swim abilities are a valid concern. No study to date has assessed tagging effects on swim speeds for Alewife and whether the procedure or tag burden could influence the behaviour or spatial ecology of the individuals. Swim performance has been assessed in other species and while the majority found no tagging influences (e.g., Chittenden et al., 2009; Cote et al., 1999; McCabe et al., 2019), 34% reported lower critical swim speeds in tagged fish (Brown et al., 2006; Shorgan et al., 2026). In our study, critical swimming speeds in Alewife were not significantly different between treatments confirming the majority of previous observations and indicating that tagged Alewife are capable of similar physical performance to that of untagged Alewife when released after surgery. Transmitter implantation may also alter oxygen consumption and aerobic scope, neither of which was measured here. For a small-bodied fish carrying a tag of several percent of its body mass, the added cost of transport could raise routine energy expenditure and any reduction in aerobic scope would matter most when energetic demands are already high, such as during gonad development and the spawning migration. Both warrant attention in future work on Alewife.

Conducting a laboratory study on the tagging effects of wild potamodromous freshwater Alewife provided an opportunity to verify the survival of Alewife but also assess capture, transportation, tagging and holding methods for optimal performance. Smaller-bodied fish are more likely to be injured or experience mortality across various gear types (Portt et al., 2006; Veldhuizen et al., 2018). Pelagic prey fish are especially difficult to capture without injury, particularly in pelagic trawls, which can have 96% mortality, such as for Atlantic Herring (*Clupea harengus*; Tomás et al., 2024). Anadromous Alewife spawn in rivers and can more easily be captured in those waters, but in the Great Lakes Alewife inhabit open waters year-round. Angling for Alewife using Sabiki rigs proved to be an effective way to reduce injury and mortality during capture in our study; however, care should be taken to reduce deep hooking and epidermal injury from the fishing line (Brownscombe et al., 2017). Our transportation methods also seemed to cause negligible issues. However, while holding fish in the lab, having water with salinity of approximately 0.6–0.8% in the holding tanks helped reduce stress, infection and delayed mortality prior to tagging. Fall 2024 had some initial mortality of fish and signs of

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infection until low levels of salt were added to the tanks, and this was negligible in spring 2025 with the salinity adjustment. Low levels of NaCl have been used in fish aquaculture for a variety of reasons including treatment of infection and reduction in stress, yet due to salinity tolerances, this may be less effective in some species (Tavares-Dias, 2022). Alewife being euryhaline and capable of a wide variety of salinity levels makes this type of stress reduction treatment in aquatic facilities more effective, which was observed in our study. Part of the need for salinity may be related to the water in the ALRF being from a municipal source rather than local lake water, and changes in water source is an important consideration with how fish may react to being in an aquatic facility. Thus, the laboratory study was beneficial for not only assessing tagging effects but for providing methods for acquiring pelagic fishes, transporting and holding them as well.

When implementing tagging studies in the wild, there are trade-offs by bringing fish back to an aquatic facility, holding, tagging and releasing back into the wild versus capture, tagging and releasing on-site in the wild. The tagging effects study itself was extremely valuable to verify the survival of Alewife at tag burdens of 2.1–8.0%, using different sized populations of fish from what has been published on marine populations and different life stages (spawning/non-spawning). However, tagging large numbers of fish (>100) in the field may take more time and present more logistical challenges than tagging fish in a controlled environment back in the lab. If delayed mortality occurs, this can be observed in the lab and the tag reused in another fish, but not in the field. We did have significantly more post-surgery mortality in one of our tanks in spring 2025, including mortality of three untagged fish. Density does not account for this pattern, as Tank 1 and Tank 2 held similar numbers of fish (73 and 70, respectively), and the untagged fish that died had not undergone surgery. Mortality among tagged fish was also concentrated in the first week after tagging. These observations point to a tank-level factor rather than to surgery, tag burden or sex, and the most plausible explanation is a pathogen introduced or transmitted within the shared tank, although we could not identify a causative agent. For future holding of Alewife, we recommend distributing fish among a larger number of smaller tanks, quarantining new arrivals and monitoring tanks independently so that a tank-level source of mortality can be detected and contained early. Although there is the potential for additional stress of transportation and holding, it may be outweighed by ensuring survival of tagged fish, particularly those carrying higher tag burdens or more prone to mortality from stress. For example, Reubens et al. (2012) recommended holding fish for a week to ensure tagging survival prior to release. Taking into consideration both animal welfare and logistical constraints is needed to ensure the best possible survival when acoustically tagging fishes and reduce behavioural impacts that would affect the data.

Overall, here we report that acoustically tagging relatively small-bodied Alewife from the Great Lakes with larger, that is, V6 and V7 Innovasea, tags did not affect survival or swimming abilities and demonstrate increased opportunities to conduct telemetry studies on this species in the Great Lakes that may expand our knowledge on the spatial ecology of small fishes in this region to assist management. This study verified that tag burdens of 2.1–8.0% are tolerated by smaller Alewife, albeit with caution when gonads are ripe and body cavity space is more limited. Acoustic telemetry studies on Alewife in the Great Lakes can help to inform their seasonal movements, habitat use and the associated environmental drivers. Alewife spatial ecology can be used to improve population estimates and population dynamics from monitoring surveys, which in turn will assist with decisions regarding stocking and management of salmonine predators. Having the ability to use acoustic telemetry tags in small fishes that are compatible with the current array in the Great Lakes is a cost-effective way to improve our knowledge of Alewife and other small fishes of management and ecosystem importance.

AUTHOR CONTRIBUTIONS

SML assisted with acquiring funding, study design, field work, statistical analyses and writing of the manuscript. KS assisted with field work, fish husbandry and writing of the manuscript. BLH assisted with acquiring funding, field work and editing the manuscript. SVI assisted with acquiring funding and editing the manuscript. LV assisted with data collection, writing and editing the manuscript. TBJ and ATF assisted with acquiring funding, study design and editing the manuscript. JWB assisted with acquiring funding, study design, field work and editing the manuscript.

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CONFLICT OF INTEREST STATEMENT

There are no conflicts of interest with co-authors in relation to this study.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Sarah M. Larocque https://orcid.org/0000-0002-2088-4988
Benjamin L. Hlina https://orcid.org/0000-0002-4178-4900
Silviya V. Ivanova https://orcid.org/0000-0003-2886-8533
Laura Vrooman https://orcid.org/0009-0008-4488-5484
Timothy B. Johnson https://orcid.org/0009-0006-8757-9060
Aaron T. Fisk https://orcid.org/0000-0002-4208-4068
Jacob W. Brownscombe https://orcid.org/0000-0003-2496-8764

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