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# Movement patterns and predator–prey interactions of domestic Atlantic salmon (*Salmo salar*) following an experimental release in a highly dynamic marine environment

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## Abstract

Atlantic salmon (*Salmo salar*) are reared in marine net-pens and may escape due to operational errors and structural failures. The fate of these fish is poorly understood. This study sought to identify spatial patterns and the fate of Atlantic salmon post-smolts following a simulated escape event from an aquaculture site in the Bay of Fundy, Canada. Farm-raised salmon ($N = 99$) were implanted with an acoustic tag and released from a commercial aquaculture facility with their movement patterns and mortality tracked over a 4-month period. Fish took ∼5 h to leave the release site and initially opted to either move inshore ($N = 8$) or out to sea ($N = 73$). Although, many fish returned to the release site. Most fish (72.7%) succumbed to predation shortly after release (64% by 48 h). Together, site fidelity and early stage predation could substantially reduce the ecological risks associated with farm-raised salmon that escape from commercial aquaculture facilities.

**Key words:** acoustic telemetry, Bay of Fundy, fisheries management, recapture, aquaculture

## Introduction

Demand for seafood products has been ever increasing (Kidane and Brækkan 2021). As many of the world's wild fisheries stocks are overexploited (Britten et al. 2021), the use of aquaculture production has increased to meet demand. Indeed, aquaculture has become a dominant method of seafood production representing 49% of the total global seafood production in 2020 (e.g., 4% in the 1950s; FAO 2022). In the coming decade, aquaculture is expected to rise by 10%–20% in many nations across the globe (FAO 2022).

In the marine environment, aquaculture systems raising finfishes (e.g., Atlantic salmon (*Salmo salar*), gilthead seabream (*Sparus aurata*), European seabass (*Dicentrarchus labrax*)) typically stock animals at high densities, relative to their wild counterparts, within large, free floating nets-pens situated near the coast (Belle and Nash 2008). However, these growing conditions present several potential impacts to the local environment, notably escape events of cultured fish into the wild (Volpe et al. 2000; Jensen et al. 2010; Toledo-Guedes et al. 2014) that may in turn may alter ecological interactions and functions (Felsing et al. 2005; Rubio et al. 2010; Tičina et al. 2020).

Fish escape events include any unintentional release of cultured fish from captivity into the environment and are broadly categorized as small (i.e., 1–100 (e.g., https://open.canada.ca/data/en/dataset/691dd994-4911-433d-b3b6-00349ba9f24e)) or large escape events where thousands of fish are released (>10 000 as in Jensen et al. (2010)). In European aquaculture systems, large-scale escape events are typically attributed to equipment failures (e.g., nets, mooring lines, structural elements) following large weather events (Føre and Thorvaldsen 2021). Consequently, the frequency of these events is relatively low (Jensen et al. 2010; Jackson et al. 2015). Conversely, small-scale release events, which are typically attributed to operational errors with handling and human error, occur with greater frequency (Jensen et al. 2010; Jackson et al. 2015). Indeed, across European Atlantic salmon farming operations, small-scale releases represented ∼11% of all escaped salmon comprising of more than 88 000 reported escaped fish (Jackson et al. 2015). However, smaller release events are generally data deficient and understudied (Thorstad et al. 2008; Jensen et al. 2010), particularly in systems where reporting of small-scale releases is not mandatory. As such, large numbers of fish derived from small-scale releases events could potentially result in a large number of unaccounted farmed finfish entering the wild (Fiske et al. 2006; Skilbrei and Wennevik 2006). This is supported by the weak correlation between the number of escapee fish detected in nearby rivers and the reported number of fish that escaped from the commercial aquaculture facilities (Green et al. 2012; Mahlum et al. 2021).

Establishing the spatial patterns of fish following an escapee event can allow fisheries managers and the aquaculture industry to develop strategies and guidelines for containing and recovering fish in a manner that is not only effective but that also maximizes resources (e.g., target areas where fish are likely to go; Bungay et al. 2021). In Southwestern New Brunswick, Canada, a region of significant salmon aquaculture (Government of Canada 2023), only a single study has examined the post-release movement of salmon following escape from aquaculture net-pens. Using a mock escape event in Cobscook Bay (Maine, United States), Whoriskey et al. (2006) found that Atlantic salmon released from an aquaculture facility dispersed rapidly and experienced considerable mortality (54%–86%), likely as a result of marine mammal predation. Although, tagged fish did not make it to any of the nearby river systems (Whoriskey et al. 2006). Outside of North America, there are a limited number of studies addressing spatial patterns of salmon escaping from small-scale release events (Chittenden et al. 2011; Solem et al. 2013; Hamoutene et al. 2018; Bungay et al. 2021). The Norwegian studies (Chittenden et al. 2011; Solem et al. 2013), found dispersal of fish from the release site was usually rapid with aquaculture-raised salmon being detected in nearby river systems. As well, recapture rates of escaped salmon also appear to be quite low (Skilbrei 2010*a*; Skilbrei et al. 2015), which may be a product of rapid dispersal combined with low marine survival rates. Few of these works explicitly characterised predation of aquaculture salmon in the wild, which may be an important consideration in assessing the relative impact of an aquaculture escape event (i.e., fish eaten before they can interact with wild conspecifics).

In the absence of truly closed containment, understanding the behavioural dynamics and predator–prey interactions of escapee Atlantic salmon is of crucial importance in effectively managing aquaculture practices in Southwestern New Brunswick. Consequently, the purpose of this work was to (1) characterise the residency and movement patterns of post-smolt Atlantic salmon following a mock escape event, (2) quantify rates of natural predation on these simulated escapees in the wild, (3) address if escapee salmon are reaching riverine habitats, and (4) develop a temporal framework for effectively responding to an escape event that is useful for both fisheries managers and the industry at large.

# Materials and methods

## Ethics approvals

All animal care and surgical procedures were conducted under approval from the Fisheries and Oceans Canada Regional Animal Care Committee (AUP# 21-46) in conjunction with the guidelines and standards set by the Canadian Council on Animal Care.

## Study site

To this aim, we surgically tagged 99 Atlantic salmon post-smolt with intracoelomic acoustic tags (Vemco V9TP-2x) and released them from a typical aquaculture site in Passamaquoddy Bay in Southwestern New Brunswick (45.093, −66.964, Fig. 1); a region of concentrated salmon aquaculture (Chang et al. 2014). Fish were tracked over the course of several months using a wide-ranging acoustic array in the region. In addition to spatial use patterns, we assayed predation using temperature and depth sensors within the transmitters.

## Description of the acoustic array

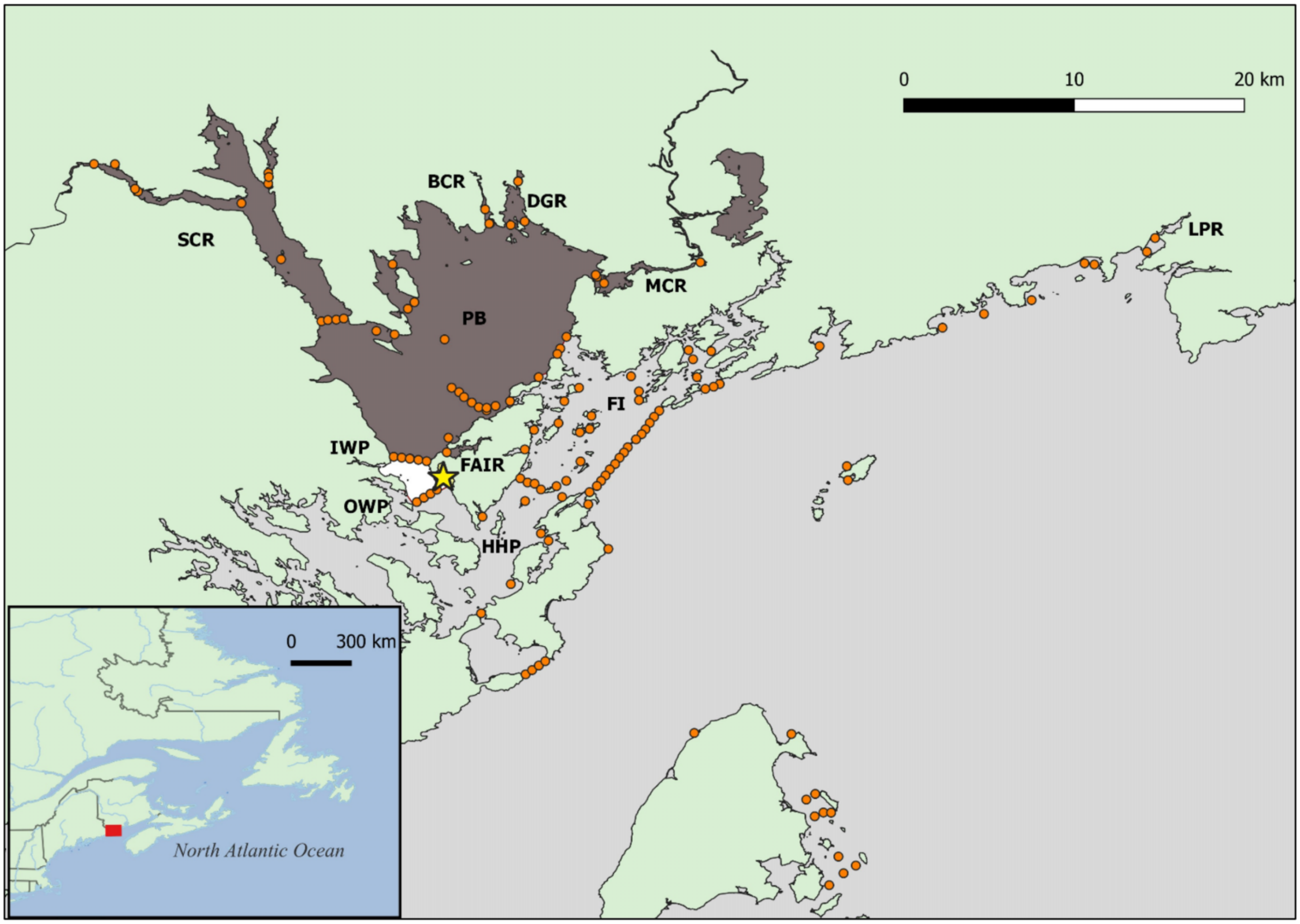
As will be discussed later on, the Fairhaven site had a fine-scale array of seven acoustic receivers (VR2W-69 kHz acoustic receivers; InnovaSea Systems, Inc., Bedford, NS, Canada), used in conjunction with a boat-based hydrophone (VR100 receiver; InnovaSea Systems, Inc., Bedford, NS, Canada), to detect fish as they were released. The region-wide acoustic array consisted of 133 acoustic receivers placed in strategic positions throughout Passamaquoddy Bay and the outer Bay of Fundy (Fig. 1). Receivers consisted of a mixture of VR2AR, VR2W, and VR2Tx receivers (InnovaSea Systems, Inc., Bedford, NS, Canada) that were deployed in advance of the release of the tagged salmon, generally between May and July of 2021. Most receivers were retrieved in late November and early December of 2021 for download, providing an approximately 4-month monitoring duration of the tagged escapees. A few of the receivers remained deployed in nearby rivers over the winter period (retrieved in May 2022) to monitor for fish entry and residency. It is important to note that all river associated receivers were located in their respective estuaries and were below the head of the tide (i.e., still under saltwater influence). Estuaries had receivers placed at both inner and outer sections such that a general direction of movement could be determined (i.e., seaward vs. upriver movements).

All raw receiver data were uploaded to the Ocean Tracking Network Data Portal and are publicly available (https://members.oceantrack.org/project?ccode=PBSM). For the purposes of the downstream analyses, individual receivers were grouped into subsets (arrays) that were within close proximity to one another. The arrays were then organized into broad geographical regions of the bay (i.e., sections; see Fig. 2). All map-based figures were made using the QGIS software package (Version 3.22.0; QGIS Development Team 2023) using a base layer derived from the National Oceanic and Atmospheric Administration's Medium Resolution Shoreline shapefile (National Oceanic and Atmospheric Administration 2000; EPSG:4269–NAD83) and Natural Earth (https://www.naturalearthdata.com/downloads/) at the 10 m resolution.

## Fish collection and tagging procedures

Farm-raised Atlantic salmon were acquired from an aquaculture site in Passamaquoddy Bay, at Fairhaven, Deer Island (44.9641, −67.0117; Fig. 1). Following land-based hatchery

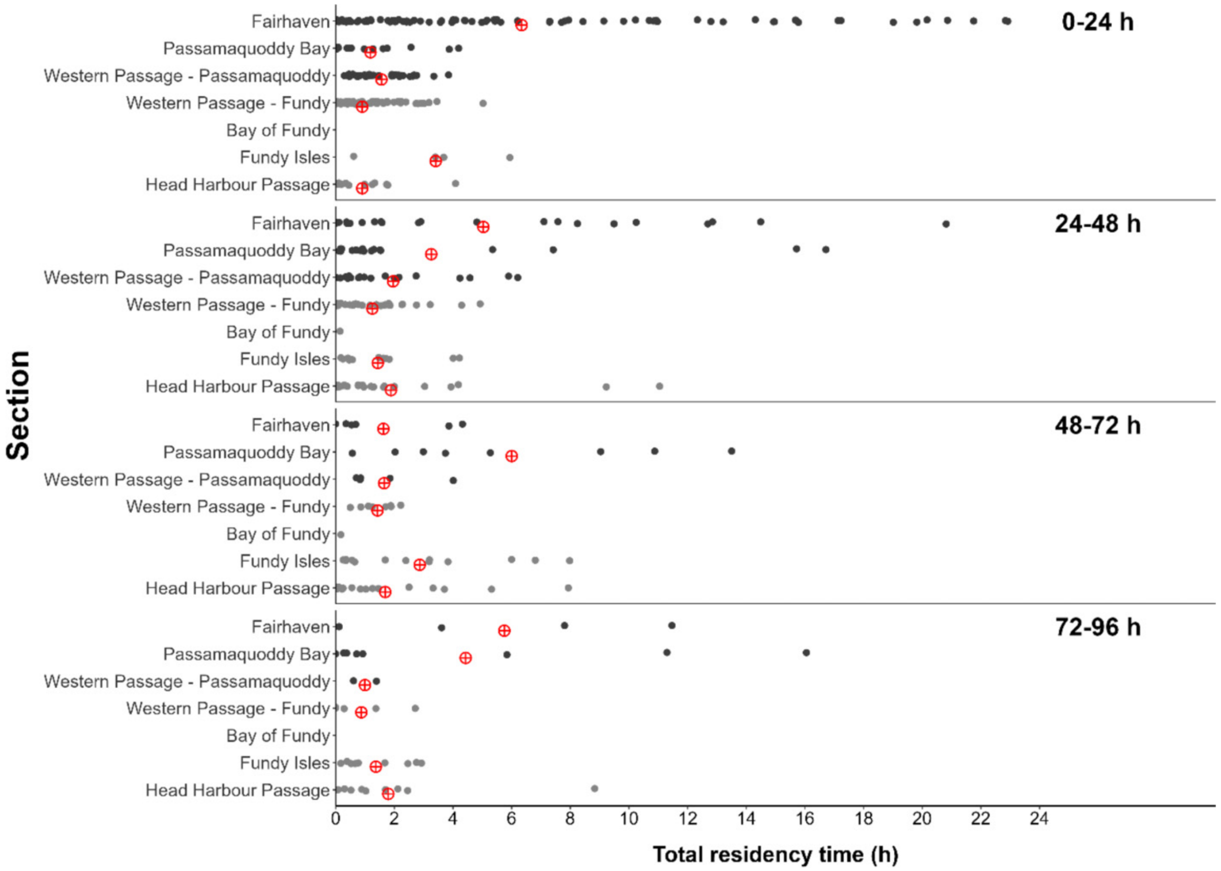
**Fig. 1.** Overview of the acoustic array in the Passamaquoddy Bay/Bay of Fundy region used in tracking the post-release behaviours of Atlantic salmon (*Salmo salar*) following a simulated escape event. The release point at the Fairhaven Aquaculture site is denoted by a yellow star shape (FAIR) while individual receivers are indicated by the orange circles. Following release, salmon can initially encounter one of two arrays, the Western Passage—Passamaquoddy (IWP) or the Western Passage—Fundy (OWP), whose bounds are denoted by the white region. Additional sections include the St Croix River (SCR), Passamaquoddy Bay (PB), Bocabec River (BCR), Digdeguash river (DGR), Magaguadavic (MDR), Fundy Isles (FI), and Head Harbour Passage (HHP). For the broad geographical regions, the sections were either in the Passamaquoddy Bay (dark grey) or the Bay of Fundy (light grey) region. The red box on the insert map represents the study region in the greater context of Eastern North America. Land masses are depicted by the pale green colour while water (insert only) is denoted by blue fill. Local map base layers were provided by the National Oceanic and Atmospheric Administration's Medium Resolution Shoreline shapefile (National Oceanic and Atmospheric Administration 2000; EPSG:4269–NAD83) for the local features of Passamaquoddy Bay area while the map inset layers being sourced from Natural Earth (https://www.naturalearthdata.com/downloads/) at the 10 m resolution. Map projections use the EPSG:4326–WGS 84 datum using a Geographic (uses latitude and longitude for coordinates) coordinate system.



grow-out at the Thomaston Corner Hatchery (Downstream of Magaguadavic Lake on the Magaguadavic River; 45.661208, −67.135549), these fish were raised from post-smolts in large, at-sea net pens (polar circle; ~33 m diameter, ~10 m depth; ~8552 $m^3$), as per industry standard. On 30 August 2021, 125 salmon were moved from a single polar circle (of 10 pens at the aquaculture site) to a smaller, sentinel net pen (9 × 3 m; 54 $m^3$ volume) for at least 20 days before tagging commenced to allow for the depuration of applied treatments prior to release (e.g., chemical sea lice pesticides). Fish were fed commercial feed pellets by the aquaculture company during this time.

In an effort to monitor the behavioural patterns and fate of salmon escaping from an aquaculture site, we elected to use acoustic telemetry (Crossin et al. 2017), and fit 99 salmon post-smolts (mean mass = 601.8 ± 118.5 g; mean total length = 370.9 ± 24.71 mm) with acoustic tags (V9TP-2x; 31 × 9 mm; 4.9 g in air; 2.8 g in water; InnovaSea Systems, Inc., Bedford, NS, Canada; Tag burden = 0.81% body weight). Genotyping of the salmon showed that males was 41.41% of the fish were male and 58.59% were female (details on the genotyping method and the associated raw data can be found in the Supplementary Materials). Tags had both temperature (−5 to 35 °C; ±0.5 °C accuracy, 0.15 °C resolution) and depth

**Fig. 2.** Total residency time of individual Atlantic salmon (*Salmo salar*) by section over the first 96 h following their release. Sections included in the Passamaquoddy Bay and Bay of Fundy regions are denoted by dark grey and light grey points, respectively. The red crosshair represents the mean value for a particular time/section. Residency times were tallied for individual fish binned into discrete 24 h blocks.



sensors (to 68 m; ±1 m accuracy, 0.3 m resolution) and were programmed to randomly emit an acoustic signal between 90 and 150 s for an average of 120 s. All surgical procedures were conducted on board a vessel (24 ft Rosborough boat, Halifax, NS, Canada) that was docked to the sentinel net pen in an effort to minimise stresses associated with handling, transport, and air exposure (Lawrence et al. 2020). Tagging procedures are in line with those used in Lawrence et al. (2023). On the day of the tagging, an individual fish was quickly transferred from the net pen into an anaesthetic water bath of tricaine methanesulfonate (100 $mg{\cdot}L^{-1}$; MS222; Syndel Canada, Nanaimo, BC, Canada). Once the fish had lost equilibrium (1–2 min), it was promptly transferred to a wetted V-trough, ventral side up, where the gills were irrigated with a weaker MS222 solution (50 $mg{\cdot}L^{-1}$). A small incision was then made on the ventral midline of the animal (~20 mm) and the tag was inserted into the coelomic cavity, and gently pushed ventrally. The incision was then sutured closed with two dissolvable stitches (3-0 coated Vicryl braided suture; Ethicon Inc., Raritan, NJ, USA). The surgery procedure lasted about 1–2 min. All tools used in the surgery, and the tag itself, were first disinfected for each fish in a diluted povidine–iodine solution (Betadine®, Avrio Health L.P., Stamford, CT, USA).

Following incision closure, the individual was moved to a recovery bath containing raw seawater, which was actively pumped over the gills. Once independent ventilation and self-righting resumed, the fish was transferred to a floating overboard holding crate (50.8 × 80.0 × 40.6 cm; ~165 L) to recover for 1 h. Tagging was spread out over 4 days to minimize tag collision. On each of the four tagging days (21, 23, 27, and 29 September 2021), five groups of fish ($N \leq 5$ per group) were tagged with each release being ~30 min between groups. Following recovery, fish were released at the centre of the aquaculture site representing $t = 0$ h of the experimental series. There was no concern for MS222 entering the food chain from released animals as all fisheries for Atlantic salmon in the Bay of Fundy are currently closed (Amiro and Jefferson 1996; DFO 2011; Fisheries and Oceans Canada 2025).

## Post-release monitoring and statistical analyses

All analyses were conducted using the R programming language (Version 4.1.1) in R Studio (Version 1.4.1717; R Core Team 2021). Raw data files and R scripts can be found in an open repository on the Ocean Tracking Network data portal (https://members.oceantrack.org/data/repository/pbsm/data-and-metadata/2021-2) and the Government of Canada Open Data portal (https://open.canada.ca/data/en/dataset/3cc1c921-152b-4b8f-81b4-ebb1b13a3f53). From the raw receiver files, tag codes assigned to experimental salmon were filtered to obtain only detections relevant to this study. Temperature and depth sensor values from the detections were then corrected using factory calibration values. The initial stages of the analysis used the raw receiver data to compile several metrics of interest to this study, namely, predation events and depth profiles.

## Predation analyses

Parameters concerning predation events constituted the first portion of our analysis. Predation events were recognized by tag temperature data and split into two main predator groups, endothermic or mesothermic, which were delineated by maximum temperature values. In the case of endothermic predators, marine mammals (e.g., seals, whales) and avians (e.g., sea birds) were representative, with a core body temperature beyond 35 °C (Note: temperature sensors were capped at 35 °C, making it difficult to distinguish birds from mammals). However, a maximum temperature value above or equal to 30 °C was used as a threshold for category recognition in the event that the tag had not equilibrated to body temperatures at the time of detection. Ambient water temperature was set at a maximum value of 15.5 °C, which is typical of surface water temperatures in Passamaquoddy Bay in early autumn (10–14 °C is the normal range for September to October at 2 and 5 m depth; see Robinson et al. 1996). For salmon preyed upon by mesothermic predators such as sharks (e.g., lamnids) and large fish (e.g., tuna) that have core body temperatures above ambient (i.e., $>\sim 14$ °C), we set the range of temperatures to be between 18 and 30 °C. We also verified that temperatures were not a result of a warmer water environment, such as a river, that may result in a false positive predation event. Fish that remained at ambient environmental temperatures (i.e., $\leq 15.5$ °C) for the duration of their monitoring period were scrutinized to discern consumption by an ectothermic predator or from tagging-related mortality. This was accomplished through comparison with concurrent depth sensor values, where abnormalities in the animals' depth profile might indicate predation. In this study, four fish appeared to remain stationary (i.e., depth not actively changing, detected at a single array), which were removed from the dataset as they likely represented tagging-related mortality (or tag loss).

Once salmon had been assigned to their respective predator category (i.e., endothermic, mesothermic, not predated), we determined overall predation rate as a percentage of the total number of tagged salmon and on a per-predator type basis. The timing of the predation event was also determined. Here, we manually identified the timepoint wherein the fish was still at ambient temperature (i.e., $\leq 15.5$ °C) and thus considered to be alive/free-swimming (i.e., last time the salmon was still considered "alive"). Following predation, the fish would have warmed in the stomach of the predator with the tag's recorded temperature exceeding 15.5 °C (i.e., 15.6–35 °C) at which point we considered the fish to have been consumed. The time difference between release and the last ambient temperature detection constituted survival time, and served as a proxy for predation event timing. In pinnipeds, cetaceans, and endothermic fishes, digestion of food appears to occur rather quickly on the order of hours with meals passing quickly through the digestive tract such that acoustic tags from ingested salmon in our study should quickly equalise to the surrounding body temperature of the predator. For example, previous work with bluefin tuna demonstrated a 1 $°\mathrm{C}\cdot\mathrm{h}^{-1}$ increase in the stomach following a meal (Carey et al. 1984) while in pinnipeds, ingestion to faecal times ranged between 2.5 and 6.25 h across several species (Helm 1984; Markussen 1993; Kuhn and Costa 2006). We also acknowledge that our values of predation timing may represent an overestimate of predation timing as lags between actual ingestion and the salmon's acoustic tag may require a few hours to rise above ambient seawater temperatures to one that is reflective of the predator's internal body temperature. Using the last ambient temperature, we were also able to relate the detection to respective receiver/section to identify where the predation event likely occurred. However, we realise that our analyses were not able to detect ectothermic predation with any fish at ambient temperature being assumed to be still alive.

Post-predation detections were filtered out from the dataset to ensure that movement patterns were reflective of the tagged salmon and not the predator. Following this, depth profiles were determined for salmon following release from the aquaculture site. Depth data were binned at discrete time intervals (0, 1, 2, 4, 6, 8, 12, 18, 24, 36, 48, 72, and 96 h post-release), bracketed by the proceeding timepoint (e.g., 0–1, 1–2, 2–4 h). For individual fish, the maximum, minimum, and average experienced depth was tabulated for each of the time bins. These values were then averaged across all tagged fish to determine mean maximum depth, mean minimum depth, and mean average depth, for each of the binned-time intervals.

## Immediate release patterns and residency analyses

Spatial and residency analyses were conducted using the R package "actel" (Version 1.2.1.9014; Flávio and Baktoft 2021). Residency timing and section movements were computed using the "residency" function with a maximum interval between discrete events of 15 min. Analyses also incorporated the section order to map fish movement between various arrays/section in the larger receiver network. A jump warning of two sections was used to identify if a fish traversed numerous arrays without detection, highlighting potential receiver detection inefficiencies, that could lead to misinterpreted findings.

The results of the residency computation were used to determine a number of relevant indices for explaining the post-release behaviour of escaped salmon. We first determined the time to leave the release site (Fairhaven), which constituted the difference from the release time to the last detection on the Fairhaven array (applicable only to fish with first receiver detections at Fairhaven). Additionally, fish that were predated upon at the Fairhaven site without ever leaving the site were removed from the analysis so as to not inflate leave times. Interestingly, four fish were not initially detected at any of the Fairhaven array receivers, but were first detected on arrays which flanked the site (i.e., Western Passage arrays).

Using these data, we also determined the direction of travel after leaving the Fairhaven site for the first time, as individuals were faced with the choice of either heading into Passamaquoddy Bay (north) or out to the Bay of Fundy (south; see Fig. 1). The initial direction of the fish was noted and then we recorded their subsequent section movements to develop rough movement profiles following release from the aquaculture site to a total of five movement steps.

Residency timing within the first 96 h following release was tabulated. Here, residency time values were binned on their duration from release on a 24, 48, 72, and 96 h basis. For each timeframe, residency time was computed both in terms of total time and a percentage value (i.e., out of 24 h) by an individual fish at a given section (e.g., Fairhaven, Passamaquoddy Bay, Western Passage—Inner, etc.). Determination of the total time involved summing the residency periods of an individual fish for each section. This value was then averaged across all fish for a given section resulting in a mean residency time by section. The percentage residency time was tabulated in a similar manner where an individual's total time was summed for a particular section and then was divided by 24 h (i.e., the monitoring period). These percent values were also averaged across all fish for a particular section. In this way, we could identify areas where the fish were spent the majority of their time following an escape event and within the first 96 h of release.

## River system analyses

We also determined if any of the escaped salmon reached any of the nearby river systems and, if so, how many frequented each system and how much time was spent there. To accomplish this, we filtered out section residency times associated with local river systems, which included the St Croix, Bocabec, Digdeguash, Magaguadavic, and Lepreau rivers. All of these systems had receiver arrays placed in the estuary with downstream and upstream locations to determine directionality of movements. As with the first 96 h residency calculations, we computed both total residency time per section and percent residency time per section for each fish. Unlike the 96 h residency percent values, river fish percent residency was computed using the total time that the fish spent active in the array system. The number of fish detected in rivers was also noted and we identified if multiple river systems were visited.

# Results

## Residency patterns (first 96 h post-release)

In the first 96 h following release, salmon spent the majority of their time associating with the Fairhaven aquaculture site for almost all time blocks (Fig. 2). The 0–24 h timeframe was where this association was the strongest with fish spending as much as 26.4% of their time budget here on average. Although, the 48–72 h timeframe was the only point where Fairhaven residency was comparable to most other sections suggesting a higher degree of dispersal of fish throughout the array during this time. This period also coincided with a high degree of residency with several of the rivers around the Passamaquoddy Bay region, supporting the higher dispersal away from the release site during this time. Interestingly, by the 72–96 h timeframe, this trend had reversed, with fish mostly associating with the Fairhaven release site again (Fig. 2).

For fish moving into the Passamaquoddy Bay area, the largest proportion of their time was spent on receiver arrays in the Passamaquoddy Bay section (Fig. 2). Here, mean total residency ranged between 1.2 and 6.0 h of time, representing upwards of 25.0% of their time budget (Fig. 2). Aside from the first 24 h following release, residency with the Western Passage—Passamaquoddy section appeared rather transitory with fish spending $\leq$ 8.1% of their time in this section. During the 0–24 h period, residency in the Western Passage—Passamaquoddy section was qualitatively comparable to the time spent in the Passamaquoddy Bay section (Fig. 2), likely resulting from a gradual dispersion of fish away from the release site.

In fish that reached the Bay of Fundy region of the array, animals were seen to be resident at a larger number of the sections (Fig. 2). During the 0–24 h period, fish spent most of their time at the Fundy Isles section, relative to other Bay of Fundy region sections. However, residency at the Fundy Isles, Head Harbour Passage, and Western Passage—Fundy sections were generally comparable across all timepoints following 0–24 h (Fig. 2). Notably, most of the fish's time in this region was spent in sections within close proximity to the release site with fish rarely entering the Bay of Fundy or Narrows (Not illustrated) sections.

## Movement patterns (first five movements post-release)

In all, 81 fish were able to leave the Fairhaven release site without immediately succumbing to predation or tagging-related mortality. Of these fish, 75 were first detected at the Fairhaven release site. These individuals remained at the release point for an average of 5.0 h before they moved off site. There was also a degree of individual variation in the time it took fish to leave the release site as the departure times ranged between 0.2 and 32.9 h. The six remaining fish that were not first identified at Fairhaven were instead first detected at the Western Passage—Passamaquoddy ($N = 3$) and Western Passage—Fundy ($N = 3$) sections. Using their arrival time at these two sections as an approximation of their departure time from the Fairhaven release site, we tabulated their mean departure time to be 3.1 h (1.5–5.9 h range).

We were also interested in identifying the direction of travel of salmon after leaving the release site. Upon release, a salmon could either choose to move further into Passamaquoddy Bay via the Western Passage—Passamaquoddy section or move out into the Bay of Fundy via the Western Passage—Fundy section. The initial decision of each fish (i.e., Bay of Fundy- or Passamaquoddy Bay-bound) was noted with fish being placed into one of two groups based on their initial direction selection. We then characterised the next three subsequent section movements (i.e., Steps 2, 3, and 4 of section movement) to identify broad patterns in spatial behaviours.

After leaving the Fairhaven release-site, only a small number of fish (*N* = 8) were observed to have moved toward Passamaquoddy Bay (i.e., first detection at Western Passage—Passamaquoddy section) as their initial movement direction (i.e., movement Step 1). Following this movement (i.e., movement Step 2), fish either returned back to Fairhaven (*N* = 2), dispersed further into Passamaquoddy Bay (*N* = 3), or moved to the Western Passage—Fundy section (*N* = 3; Fig. 3A). During the third movement step, some fish remained at Fairhaven (*N* = 2) with some being observed in the nearby Western Passage sections (*N* = 3). Two fish were observed moving into river sections (Estuaries of Bocabec and St Croix rivers) and a single fish dispersed further into the Bay of Fundy region (Fig. 3A). By the fourth movement step, most of the fish were largely in close proximity to the release point (*N* = 5).

After leaving the Fairhaven release-site, the majority of fish initially moved toward the Bay of Fundy via the Western Passage—Fundy section (*N* = 73; Movement Step 1; Fig. 3B). Most of these fish returned to Fairhaven following this (*N* = 69) with only two fish moving further into the Bay of Fundy being detected at the Head Harbour Passage section as part of the second movement step. By the third movement step, salmon were still in close proximity to the release point being detected at the Western Passage—Passamaquoddy (*N* = 1) and Western Passage—Fundy (*N* = 64) sections. During this point, two fish had moved even further out into the Bay of Fundy. This trend continued into the fourth movement step where fish mostly observed around Fairhaven (*N* = 61) with a few fish being detected further abroad in both Passamaquoddy Bay (*N* = 1) and in sections associated with the Bay of Fundy region (*N* = 5 total).

## Predation

Seventy-two salmon were confirmed as being killed by predators following release, representing a total mortality of 72.7%. Of these predated fish, 68 were consumed by endothermic (i.e., birds or mammals) and 4 by mesothermic (i.e., lamnid sharks or tuna) predators, representing a mortality of 68.7% and 4.0%, respectively. There were also a single fish (1.4%) who appeared to have suffered mortality associated with surgical procedures and another fish who appeared to have died later on but the cause is uncertain. Most fish were predated in close proximity to the Fairhaven aquaculture site (*N* = 38; Fig. 4) with predation outside of the release site being more apparent in the Bay of Fundy portions of the array network (*N* = 23) compared to the Passamaquoddy Bay sections (*N* = 9).

Mean survival time for the predated fish was 57.9 h, but values ranged between 0.5 h and 14 d. For fish consumed by endothermic or mesothermic predators, mean survival times were 56.0 (*N* = 66) and 88.4 h (*N* = 4), respectively. Here, 20.8% of predated salmon were consumed within the first 6 h following release and 63.9% by 48 h release (Fig. 5).

## Association with nearby river estuary systems

In all, 14 individual fish were found to reach one of the five river estuary systems located within our array network. Overall, fish spent an average of 4.2, 4.8, 1.1, 18.7, and 1.2 h at the St Croix, Bocabec, Digdeguash, Magaguadavic, and Lepreau River estuaries (in order of proximity to the release site), respectively. Interestingly, four fish were observed to frequent multiple rivers in the system. For example, one fish was detected at Bocabec, Digdeguash, and Magaguadavic rivers following its release at sea. Average time for a salmon to first reach a river system following release was 87.4 ± 59.3 h. Salmon appeared to remain in the lower reaches of the river estuary and, in one instance, a fish remained somewhere further upstream of the Magaguadavic River receivers for the remainder of the winter after being last detected in the estuary during the autumn. Although, we are uncertain of the exact whereabouts of the fish in-between the autumn and spring detections of this fish.

## Depth profiles

Salmon appeared to initially descend to a relatively deep depth (10.3 ± 5.5 m) within the first hour following release (Fig. 6). In subsequent timeframes, fish maintained a comparatively shallower disposition having mean depths ranging from 6.6–7.0 and 2.9–3.8 m over the 1–6 and 6–18 h periods, respectively (Fig. 6). Beyond 18 h post-release, mean depth appeared to become much more variable.

# Discussion

## Salmon dispersal patterns

Understanding the movement patterns of escaped aquaculture-reared salmon is of importance in addressing the potential environmental impacts of commercial fish aquaculture (Thorstad et al. 2008; Solem et al. 2013; Matley et al. 2022) and in developing effective guidance on fish recovery following an escape event (Skilbrei et al. 2015; Hamoutene et al. 2018; Bungay et al. 2021). Consequently, we sought to characterise post-release dispersal patterns of Atlantic salmon post-smolts to potentially identify where recovery efforts may be concentrated. In this study, released salmon appeared to be generally associated with the release site and nearby sections showing a high degree of release site fidelity. Furthermore, fish were also seen making repeated forays back onto the release site even after initially leaving it. These observations contrast with the behavioural patterns found in another simulated escape of post-smolts in this region wherein fish dispersed quickly from the release point and did not appear to exhibit high release site fidelity (Whoriskey et al. 2006). While our study was comparable to Whoriskey et al. (2006) in most respects, they differed in the season that the fish were released and their animals were slightly larger than ours, which may have contributed to the disparate behavioural response. Indeed, spring-released Atlantic salmon tend to exhibit lower site fidelity and engage in faster seaward migrations relative to autumn-released fish in other regions as well (Skilbrei 2010*a*, 2010*b*; Skilbrei and Jorgensen 2010; Skilbrei et al. 2010; Hamoutene et al. 2018). For example, Skilbrei (2010*b*) found that, at a Norwegian aquaculture facility within a fjord, 90% of the fish exited the fjord within the first day in a springtime release

**Fig. 3.** Overview of the first four movement steps of escapee Atlantic salmon (*Salmo salar*) released from the Fairhaven aquaculture site (Step 0) for fish that first moved toward the Passamaquoddy Bay (A) or Bay of Fundy regions (B). Relative numbers of fish are denoted by differing thicknesses within a step and are not done to scale. In both panels, the Fundy region (light grey) incorporates sections that were in or adjacent to the Bay of Fundy, Passamaquoddy (dark grey) includes sections that were within or immediately adjacent to the Passamaquoddy Bay area (as seen in Fig. 1), the white section represents the Western Passage arrays, and the Fairhaven release site is denoted by the yellow shading. Receivers are denoted by orange circles. Movement steps are clustered by colour. Local map base layers were provided by the National Oceanic and Atmospheric Administration's Medium Resolution Shoreline shapefile (National Oceanic and Atmospheric Administration 2000; EPSG:4269–NAD83) for the local features of Passamaquoddy Bay. Map projections use the EPSG:4326–WGS 84 datum using a Geographic (uses latitude and longitude for coordinates) coordinate system.

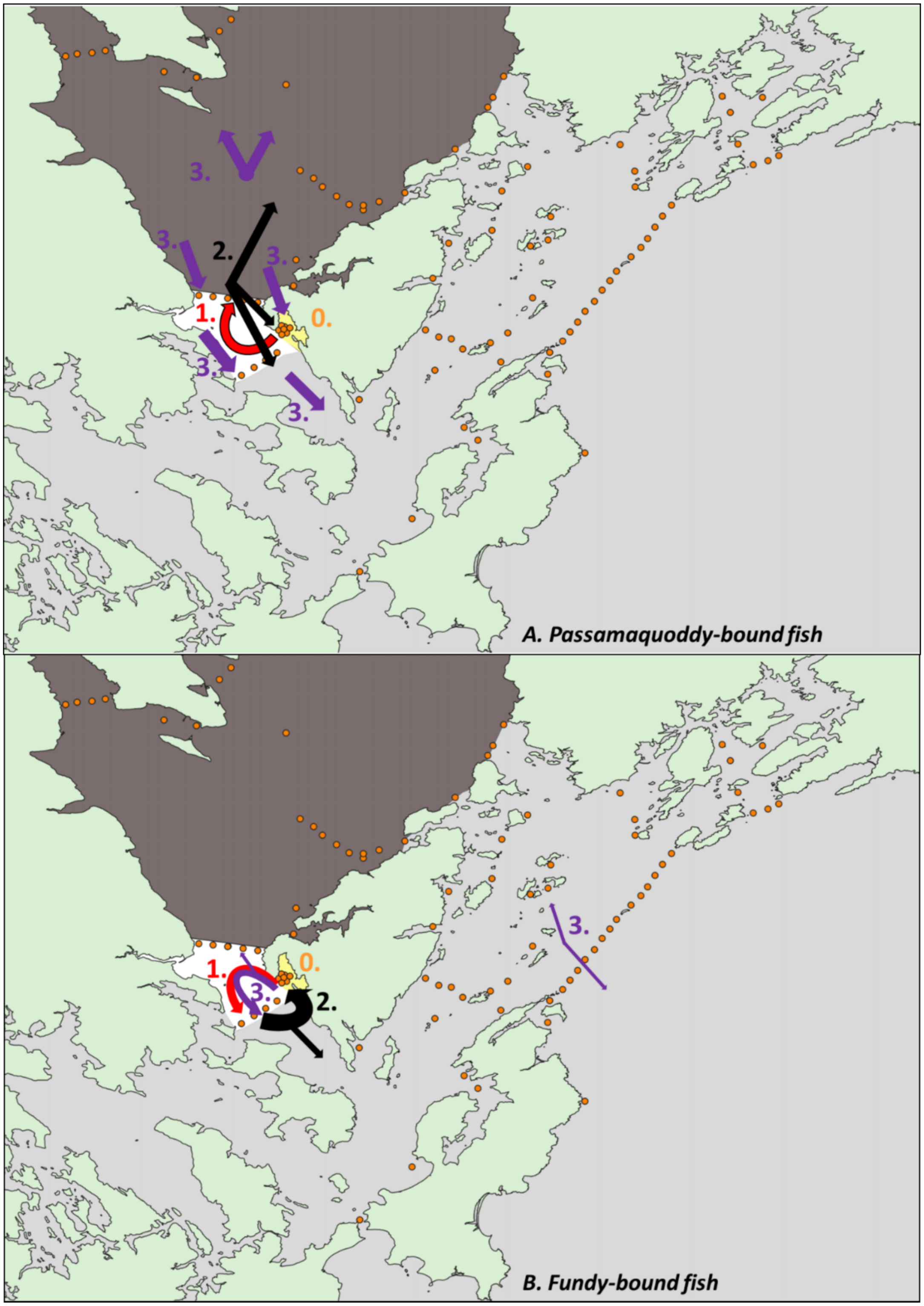
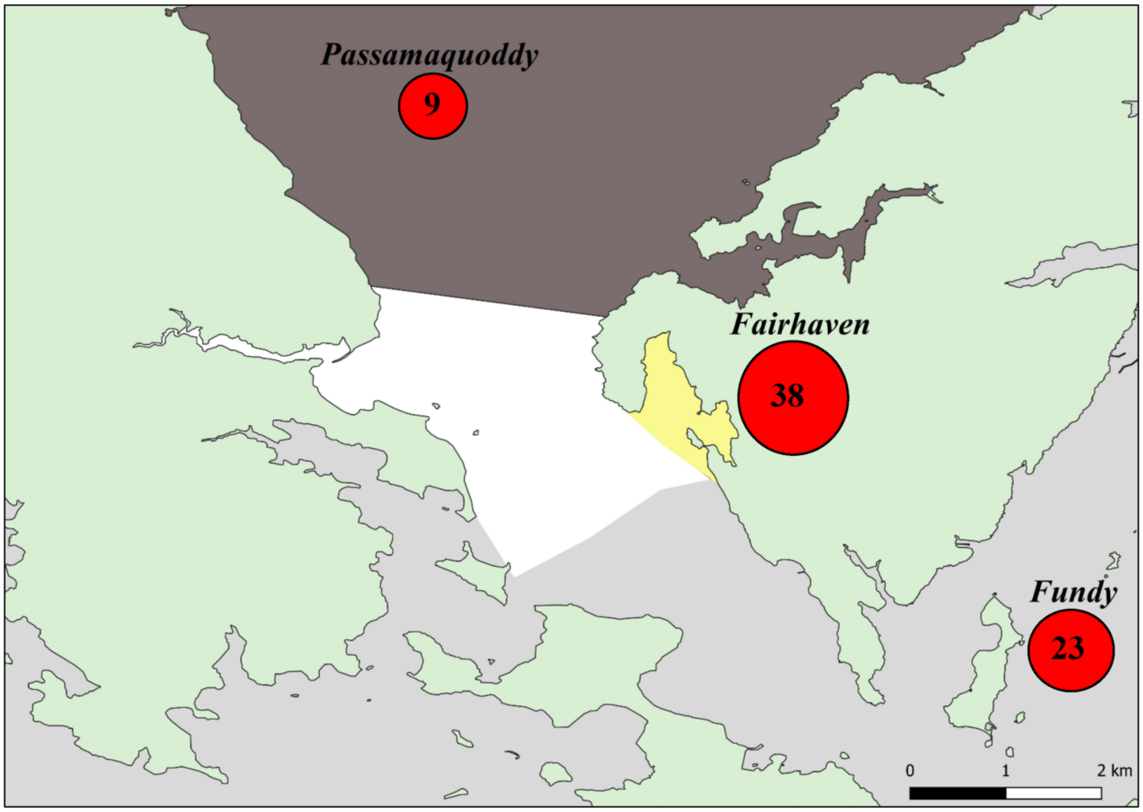


**Fig. 4.** The last region where tagged Atlantic Salmon (*Salmo salar*) were still considered alive before a predation event. The Fundy region (light grey) incorporates sections that were in or adjacent to the Bay of Fundy, Passamaquoddy (dark grey) includes sections that were within or immediately adjacent to the Passamaquoddy Bay area (as seen in Fig. 1), and the Fairhaven release site is denoted by the yellow shading. The number inside the red circles denotes the number of fish that were predated in each of these three geographical regions. Local map base layers were provided by the National Oceanic and Atmospheric Administration's Medium Resolution Shoreline shapefile (National Oceanic and Atmospheric Administration 2000; EPSG:4269–NAD83) for the local features of Passamaquoddy Bay. Map projections use the EPSG:4326–WGS 84 datum using a Geographic (uses latitude and longitude for coordinates) coordinate system.



compared to just a single fish doing so within the first week in autumn released animals. As seaward migration in the outer Bay of Fundy salmon populations occurs in the spring months, it is conceivable that the high degree of residency near the release site in our study reflects a behavioural/physiological state where fish are not engaged in seaward migrations (Furevik et al. 1990; Skilbrei 2010*b*; Chittenden et al. 2011; Hamoutene et al. 2018; Bungay et al. 2021). Thus, recovery of salmon from an escape event may be aided by seasonal effects, particularly in instances where seasonal migratory behaviours are strongly imprinted on the population. It should be noted though that smolts introduced in net pens during fall also have a tendency of exiting the release site quickly (Skilbrei 2013). Hence, other factors beyond season such as size affect the migratory behaviour of farm-raised salmon once they escape (Hamoutene et al. 2018).

While escapee salmon were generally associated with the release site, a number of fish were still detected further abroad in the acoustic array. For example, several fish were identified in the Bay of Fundy and Fundy Isle sections suggesting that large-scale movements of the fish still occurred. Indeed, one fish was also identified off the Ocean Tracking Network's Halifax Line (detected on Halifax Line receivers at locations: 44.31071, −63.34569, 44.33422, −63.37182, 44.27545, −63.3032, 44.2468, −63.26521, 44.29882, −63.33276; ~300 km great-circle distance; https://devel.oceantrack.org/) by May of 2022 following an overwinter period in the Magaguadavic River (Winter of 2022). This result is unsurprising as previous work has shown intraspecific variation in post-release dispersal patterns representing a heterogenous pool of behavioural phenotypes (Chittenden et al. 2011) and that local current dynamics may be playing a role in salmon dispersal (Whoriskey et al. 2006; Quinn et al. 2022). However, Quinn et al. (2022) found that dispersal of salmon in this region is the result of several environmental and behavioural inputs in which currents appeared to be playing a comparatively small role in shaping behavioural responses. Outer Bay of Fundy salmon generally migrate toward the waters off of Greenland (reviewed in Lacroix (2008)), which is consistent with the early migration patterns of this lone overwintering fish. However, additional fish and detections on more northward receivers would be needed to confirm this notion.

**Fig. 5.** Counts of binned survival times of Atlantic salmon (*Salmo salar*) consumed by endothermic (white bars) and mesothermic (black bars) predators at 6, 12, 24, 48, and 48+ h following release from the Fairhaven aquaculture site. The grey bar represents a running total of all fish predated at the specified timepoint with its corresponding percent total specified above each bar.

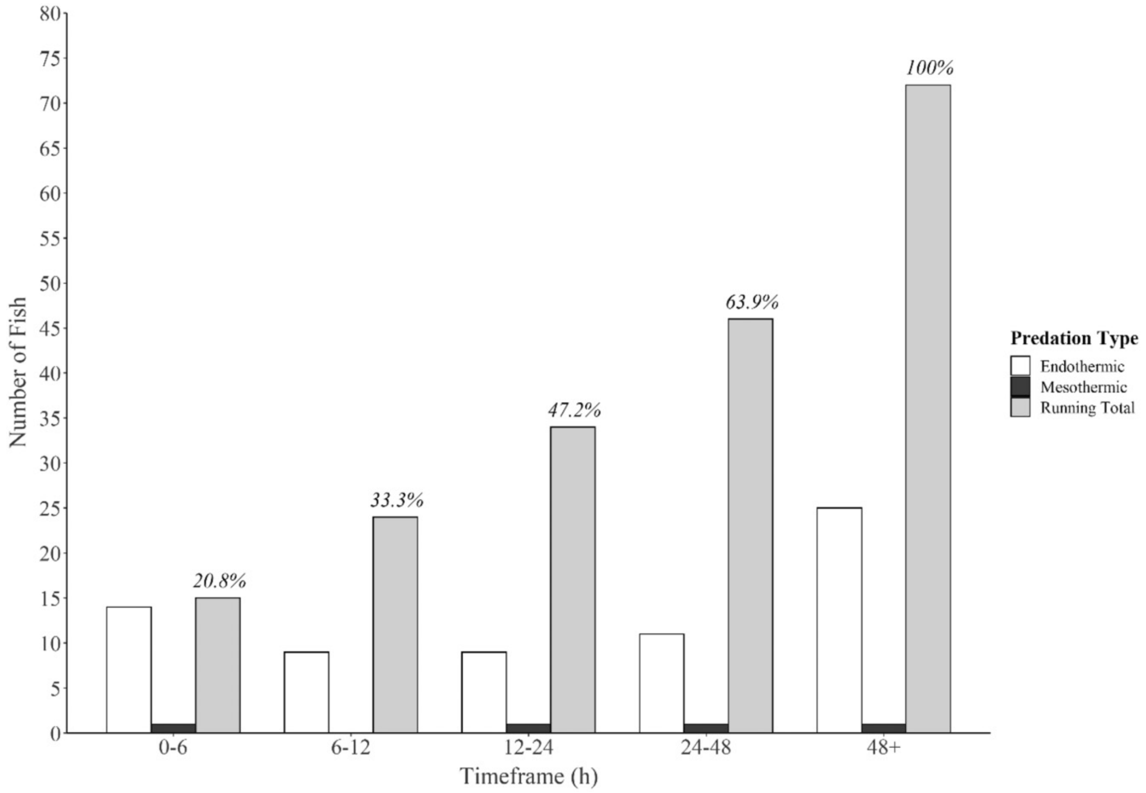
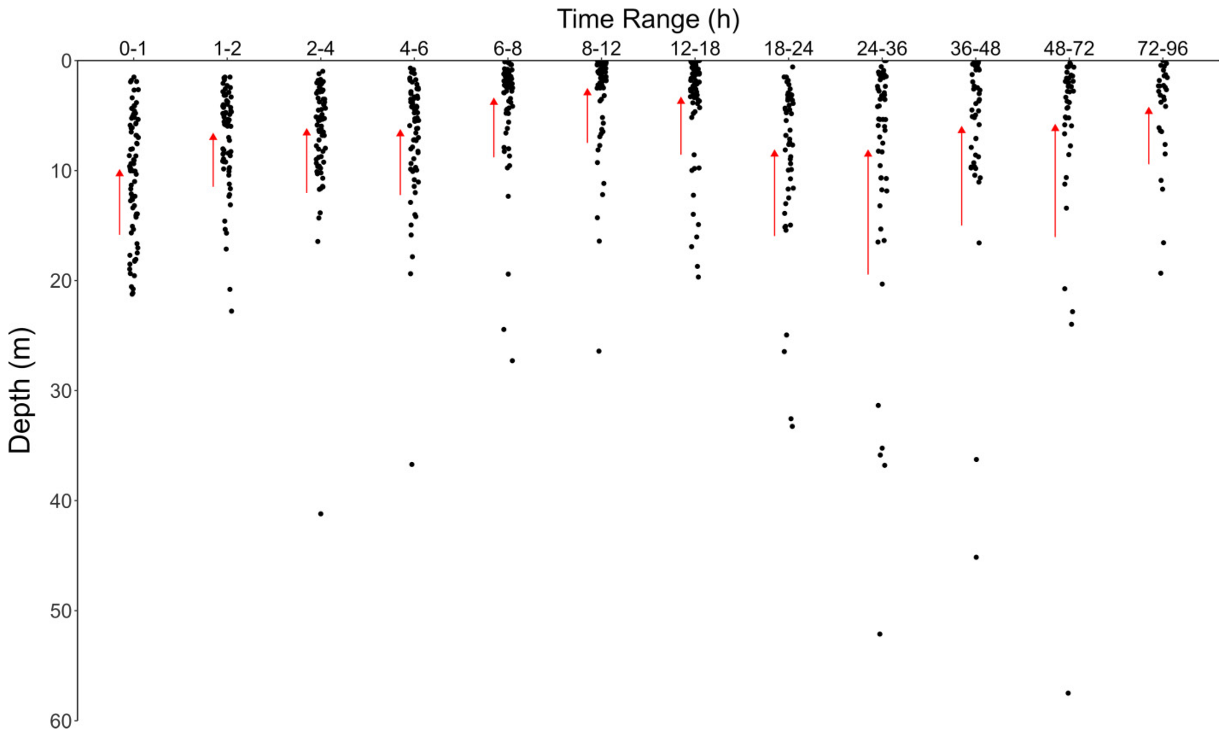


**Fig. 6.** Mean depth profiles of Atlantic salmon (*Salmo salar*) released following a simulated escape event from an aquaculture site over the first 96 h. Each black point represents an individual's max/min value for the selected timeframe. Red triangles represent the mean value for the parameter of interest (mean ± standard deviation) across all fish for the selected timeframe. In the case of mean depth values specifically (A), they represent a binned average of an individual fish per time range, which was then averaged across all individual fish.



Several of the escapee salmon also dispersed to nearby river systems in this study. This result is puzzling as all of the released salmon were post-smolts and would not have matured over the observation timescale. While we are unsure of the exact mechanism(s) driving this behaviour, the appearance of immature escapee salmon in rivers/freshwater systems has been observed in the wider literature (Carr et al. 1997; Lacroix et al. 1997; Fiske et al. 2001; Madhun et al. 2023) and in the Magaguadavic River specifically (Carr et al. 1997; Lacroix et al. 1997). The appearance of immature escapee salmon in rivers seems to be a largely North American phenomena (Thorstad et al. 2008) with fish appearing have a lower distance travelled within rivers compared to wild conspecifics, remaining in the lower reaches of the estuaries, and not returning to sea post-spawning period (c.f. wild salmon; Carr et al. 1997). These behaviours are clearly not spawning-related due to the fish being immature but may represent exploratory behaviours among bolder individuals in the population (i.e., random dispersal; Solem et al. 2013). Furthermore, we could also speculate that if food resources were not readily accessible around the aquaculture facility, fish may be seeking out alternative foraging opportunities elsewhere throughout the bay (Solem et al. 2013) as escapee salmon have been observed feeding on both wild prey items and commercial pellets from aquaculture sites (Jacobsen and Hansen 2001; Olsen and Skilbrei 2010). However, more in-depth dietary studies and personality trait-telemetry assessment would be needed to address such hypotheses.

Dispersal further abroad was likely facilitated in this environment by the strong currents that result from the large tidal flux that occurs twice daily (~5.6 m; Brooks 1992). Indeed, Whorisky et al. (2006) noted that salmon movements in Passamaquoddy Bay generally occurred along the tidal currents in the region. Consequently, intraspecific variation in behavioural patterns and local tidal conditions may affect salmon dispersal patterns following release (Quinn et al. 2022). Such conditions were beyond the scope of this work, with further modelling needed to fully address the role of tidal flows in dictating dispersal patterns of escapee salmon.

The salmon in this study showed an interesting propensity to dive deeply within the first hour of release, returning to shallower depths thereafter. Rapid dives immediately following tagging have been observed previously in both Atlantic salmon (Skilbrei et al. 2009; Skilbrei and Jørgensen 2010; Chittenden et al. 2011) and other nonsalmonid fishes (Holts and Bedford 1990; Block et al. 1992; Davis and Stanley 2002; Afonso and Hazin 2014). In all these instances, animals did return to "normal" depth profiles following the initial dive period. While the exact reasons for this behavioural pattern are unclear, it may serve as a stress recovery strategy (i.e., post-tagging; Block et al. 1992; Walker et al. 2000; Davis and Stanley 2002; Chittenden et al. 2011) or as part of a predator avoidance strategy (Skilbrei et al. 2009). Likely, in our study, this dive response represents a combination of these two processes given the seemingly high predation pressure in the area and that animals were still recovering from the stress of surgical manipulations. We suggest that in future works that fish be held for a longer period of time or use of an alternative form of anaesthesia (i.e., electroanesthesia) to minimise the effects of stress and tagging effects on the fish's behaviour. As with other works with escapee salmon (Skilbrei et al. 2009; Skilbrei 2010*b*; Skilbrei and Jørgensen 2010; Chittenden et al. 2011; Renkawitz et al. 2012), our fish tended to stay close to the surface (~5 m depth) for the first 96 h of monitoring suggesting that recapture efforts may be focused on surface waters.

## The role of predation in mitigating escape events

To date, there is limited information concerning predation rates of escapee salmon during a small leak event. Hamoutene et al. (2018) identified high rates of mortality in experimentally released farm-raised salmon (≤53%), which the authors suggest as being, in part, from predation. Furthermore, Whoriskey et al. (2006) found that there was high salmon mortality in a mock escape event that was likely attributed to seal consumption as several tags were found near seal haul outs. Here, we found that 72% of fish were consumed by a combination of endothermic and mesothermic predators within the entire observation period, indicating that predator mortality following a release event can be quite high and may limit the impact of escapees on the local environment. Though it should be noted that such small-scale release is unlikely to fully saturate predators in their ability to consume these salmon (i.e., there are more fish than the predators can eat, which is a type 3 functional response; see Holling 1959; Hunsicker et al. 2011). Importantly, seasonality is likely to play a role in predator-saturation as seal abundances in the area do decrease during the autumn (Jacobs and Terhune 2000) and some evidence does suggest a similar seasonal variation in mesothermic sharks as well (Pratt 2012; Bastien et al. 2020; Franks et al. 2021; Anderson 2024). While speculative, predation rate may be expected to be affected by the scale of the escape event, with local predators likely to be overwhelmed by the foraging bonanza created by a large-scale release of farm-raised salmon. Previously, predation of post-smolts in Passamaquoddy Bay are typically low (English et al. 2023) but these characterisations were made in early spring and may not be directly comparable to our study (e.g., autumn release). The high level of predation here was likely the result the higher degree of predator susceptibility/naivety that is characteristic of farm-raised salmonids (Fleming and Einum 1997; Johnsson et al. 2001; Jackson and Brown 2011; Solberg et al. 2020). Additionally, stress effects associated with surgical procedures reviewed in Lawrence et al. (2018, 2019) and the marine mammal's ability to hone in on tag acoustic emissions (Bowles et al. 2010; Stansbury et al. 2015; Rub and Sandford 2020) may also be factors in contributing to increased predator vulnerability of our tagged fish. Considering these two effects, our predation rate may represent a slightly higher than background estimate of predation rate, relative to untagged fish (i.e., untagged fish may be less susceptible to predation). Regardless, predation of escapee salmon still appears to be high and may prove to be beneficial in culling accidental salmon releases from aquaculture sites. Nonpredator mortality could also be ascertained in the future through releasing fish with a longer net-pen recovery duration to control for any acute health/physiological impacts that may have occurred during tag implantation.

Our acoustic tags were able to discern that predation stemmed from a combination of endothermic and mesothermic predators. Identification beyond these broad groups of predators based on body temperature was difficult within the current study but does make our estimates of overall rates of predation conservative as it likely underestimates predation (i.e., cannot identify ectothermic predators). For endothermic predators, the fact that the manufacturer's settings capped the tag's temperature logger at 35 °C precluded us from differentiating mammalian from avian predation (i.e., mammals ∼37 °C vs. birds > 38 °C; Clarke and Rothery 2008). The large number of detections and behavioural patterns in many of the consumed fish would suggest that the tag is still mostly submerged, pointing it to being eaten by a marine mammal rather than a bird. Among potential endothermic predators, we highly suspect that the two resident seal species, harbour (*Phoca vitulina*) and grey (*Halichoerus grypus*) seals, were largely responsible for salmon predation events here given that we frequently observe them near local aquaculture sites and that there are several large seal haul-outs throughout the Passamaquoddy Bay area (Kovacs et al. 1990; Dow 2005; Nelson et al. 2006). Although, harbour porpoises (*Phocoena phocoena*), common minke (*Balaenoptera acutorostrata*), fin (*Balaenoptera physalus*), and humpback whales (*Megaptera novaeangliae*) as well as several species of piscivorous seabirds such as cormorants (*Phalacrocorax* spp.), gulls (*Larus* spp.), ducks (*Mergus* spp.), and osprey (*Pandion haliaetus*) are common in the area and could also be responsible for predating upon our tagged fish.

A smaller proportion of our salmon were also consumed by what appeared to be mesothermic fishes. These fishes are capable of keeping their body temperature above ambient levels but at temperatures less than a mammal or a bird (<30 °C; Carey et al. 1971, 1981, 1984; Stevens and McLeese 1984; Goldman et al. 2004; Madigan et al. 2015; Mensinger et al. 2023). Thus, our data point to salmon potentially being consumed by porbeagle (*Lamna nasus*) and white (*Carcharodon carcharias*) sharks or bluefin tuna (*Thunnus thynnus*) as all of these fish are able to engage in endothermy to some extent (Carey and Teal 1969*a*, 1969*b*; Goldman 1997) and are found in Passamaquoddy Bay/Bay of Fundy. Future research could look to identify specific predator species associated with salmon predation at aquaculture sites to develop more informed salmon culture management.

## Recommendations for escapee salmon recovery

While measures to prevent escapes have improved since the inception of the farming industry such as the use of robust nets, antipredator nets, escape events nevertheless occur. Regulations concerning the recapture of escaped farm-raised salmon vary by country (Naylor et al. 2005; Kolavani and Mather 2025). Here, we suggest a series of suggested actions that could be implemented following an accidental loss of salmon from an aquaculture site to recover fish and minimize their interactions with wild conspecifics. Granted, we emphasize that these suggestions would likely only apply to a small-scale release of fish from an aquaculture site ($N < 100$ fish) and that they may not be applicable to larger scale releases, particularly when thousands of fish enter the environment. Salmon recovery is also likely to take on a multifaceted response, as a single approach is not likely to yield a high level success on its own. Our results suggest that expedited responses are likely to be the most important factor in dictating effective recovery efforts. Indeed, farm-raised salmon remained at the release point for an average of 5 h, indicating that there is a small window for initially responding to an escape event. To that end, this is predicated on having the knowledge that the release has occurred, which can often be difficult to ascertain in instances where there is not an obvious release event/source (e.g., unseen hole in pen, unknown structural damage, predator interaction, etc.; Jackson et al. 2015; Thorvaldsen et al. 2015). This uncertainty could make it hard to identify an escape event in the early stages thus losing crucial response time. While the 5 h that a fish may initially remain on the site represents an average value, it is further complicated by the considerable variation in the time it took a fish to first move off site ranging from 0.2 to 32.9 h. If tagging/stress effects are producing a delayed departure from the site (i.e., fish are staying a longer to physiologically recover), then this time scale would presumably be even shorter. As well, the high tidal currents in the region may facilitate expedited dispersal of fish and hamper recovery efforts (Whoriskey et al. 2006) with currents being an important factor in determining salmon dispersal after release (Hansen 2006). Dempster et al. (2018) found that in most instances, marine recapture was not an effective method in removing escapees, often had adverse effects (i.e., wild bycatch), and suggested that interception could occur in regions where concentration occurs. In all, this highlights that early identification of a leak combined with a quick response is likely to be the best means of mitigating an escape event but it is also important to realise that re-capture may not be feasible.

In the past, several methods of recovering salmon have been proposed with varying degrees of success. Prior works have tested the use of gill, trawl, and bag nets (Hansen 2006; Skilbrei and Jørgensen 2010; Skilbrei et al. 2010; Chittenden et al. 2011; Dempster et al. 2018) as well as angling, specifically in nearby river and streams (Hansen 2006; Skilbrei et al. 2010, 2015). Although, in the Bay of Fundy region, the latter is unlikely to be relevant given the current ban on all recreational fisheries for Atlantic salmon (Fisheries and Oceans Canada 2008). Experimental series looking at recovering escapee salmon have considerable variation in success ranging 0%–79% recapture rates (reviewed in Dempster et al. 2018), predation events notwithstanding. Importantly, successful recapture of salmon is improved with smaller escape events and larger fish sizes (Dempster et al. 2018) and may be a prime consideration when organising recovery effort objectives. In the case of small/juvenile fish, recapture may require interception at a counting ladder once the animals reach sexual maturity (Carr and Whoriskey 2004). Regardless, the use of commercial fishing methods (i.e., gill and bag nets) could prove to be useful in recovering released salmon, particularly gills nets which have been shown have a great deal of success in salmon recapture (Skilbrei et al. 2010), provided that salmon are large enough to be caught using this method (see Skilbrei et al. 2015) and that accidental capture of other native species could be minimised. Bagnets also have high recapture success (Chittenden et al. 2011) but are limited by the surrounding bathymetry and local geography and may not be suitable for aquaculture sites located in deeper waters away from coastal environments or in high current situations, such as Passamaquoddy Bay.

Escapee salmon here appeared to mostly occupy surface waters (≤5 m depth on average) following the initial timeframe (i.e., 6–18 h) following release such that recovery efforts may focus in the upper parts of the water column. Indeed, high degrees of surface swimming are common in escapee salmon (Skilbrei et al. 2009; Chittenden et al. 2011; Solem et al. 2013) such that these suggestions should be broadly applicable to a variety of settings and contexts. Recovery efforts could also be enhanced by establishing fish interception and monitoring programmes at fish ladders in riverine systems for fish that may disperse further afield. Such a programme has been used in Norway, Ireland, and the United Kingdom to ascertain rates of escapee fish entering riverine habitats and to inform management decisions (Walker et al. 2006; Glover et al. 2019). In New Brunswick Canada, the Atlantic Salmon Federation has been actively involved in salmon interception/monitoring programmes on the Magaguadavic River (St George, NB, Canada; Carr et al. 1997; Carr and Whoriskey 2003, 2006). As escapee salmon do appear to move into freshwater/estuarine systems (this study; Chittenden et al. 2011; Skilbrei et al. 2015; Hamoutene et al. 2018), this could help aid in recovering more fish. Together, the use of gill and bag nets placed in shallow waters in combination with monitoring programmes could act to enhance salmon recovery following a small-scale escape event.

While fish are likely to initially leave the aquaculture site in the first 5 h of liberation, it remains probable that escapee salmon remain in close proximity to their point of origin. As we observed here, the first 96 h of liberation were punctuated by a high degree of site fidelity within proximity of the release point. In the literature, this effect has been observed and is believed to have a strong seasonal basis (Furevik et al. 1990; Skilbrei 2010*b*; Chittenden et al. 2011; Hamoutene et al. 2018; Bungay et al. 2021). As such, recovery efforts in the first 96 h following release could focus in areas within close proximity to the origin point to maximise recovery success, assuming the release happens during a nonout migratory season for salmon smolts/post-smolts (e.g., autumn and winter). However, this must be balanced against the risk of accidentally ensnaring native species, including wild Atlantic salmon. In the case of the latter, this may be facilitated by including visual marking on farm-raised fish to easily sort out these animals (e.g., tags, adipose fin removal, freeze branding). While comparable data are scant, Skilbrei and Jørgensen (2010) found that after a month's time, the vast majority of their recaptured salmon (~90% of those released) were within 40 km (21.6 nautical miles) of the release point. Their area is much wider than our suggested search area (Western passage section ~2 km from release point) but still illustrates that recovery can be focused on a small region with some rate of success. If the goal is to remove escapees from the wild, capture in the marine environment may not be the best approach given the short response timeframes and stochastic nature of tides/currents in the Bay of Fundy, which is in line with Dempster et al. (2018) given the poor rates of escapee recovery. Ultimately, the duration since the escape event (>5 h) and the risk of bycatch may preclude an attempt at marine recapture of escapees.

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### Copyright

### Data availability

All raw data for this project and R scripts can be found on the Ocean Tracking Network's data portal (https://members.oceantrack.org/project?ccode=PBSM) and on the Government of Canada's Open Data portal (https://open.canada.ca/data/en/dataset/3cc1c921-152b-4b8f-81b4-ebb1b13a3f53).

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## Competing interests

Our paper has no competing interests to declare and has not been published/submitted elsewhere. Cooke Aquaculture Inc. only provided access to their site and was a source of fish. They did not contribute to data analysis nor the interpretation of the results. Our science was completely independent despite being supported by the aquaculture industry.

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# Supplementary material

Supplementary data are available with the article at https://doi.org/10.1139/cjfas-2025-0071.

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