BOTTLENECKS TO SURVIVAL

MARINE MIGRATIONS AND OVERWINTER MORTALITY OF JUVENILE CHINOOK SALMON IN THE STRAIT OF GEORGIA, 2022-2024

Prepared by Wesley Greentree, Will Duguid, Jamieson Atkinson,
Nick Bohlender, Katie Innes, Bridget Maher, Francis Juanes

2024

PACIFIC SALMON FOUNDATION

University of Victoria

BRITISH COLUMBIA CONSERVATION FOUNDATION

TABLE OF CONTENTS

Citation:

Greentree, W., Duguid, w., Atkinson, J., Bohlender, N., Innes, K., Maher, B., Juanes, F. 2024. Marine migrations and overwinter mortality of juvenile Chinook salmon in the Strait of Georgia, 2022-2024. Prepared for the Department of Fisheries and Oceans Canada (BC Salmon Restoration Innovation Fund). 36pp.

LIST OF FIGURES

ABSTRACT

Chinook salmon exhibit diverse life history strategies across freshwater rearing, ocean entry timing, marine migrations, and maturation timing. The marine migrations of Chinook salmon are poorly resolved in terms of space, time, and individual variation. In Chinook salmon populations from rivers draining into the Strait of Georgia, ocean-type juveniles spend their first summer at sea feeding and growing in the Strait. At an unresolved time after the first ocean summer, some juveniles emigrate to the continental shelf off the west coast of Vancouver Island and the Washington outer coast. Other individuals remain resident in the Strait of Georgia for most or all their marine life. Since migrants and residents likely encounter distinct feeding opportunities, predation risks, and fisheries exploitation, it is important to determine if individual physiological condition influences migration behaviour. To track marine movements and identify links with individual condition, we acoustic tagged 329 Chinook salmon from two ocean entry cohorts (2022, 2023) in their first fall and winter at sea (2022-23; 2023-24). As tags remain active until 2026, we analyzed initial movements up to the middle of the second ocean winter for the first cohort and up to the middle of the first ocean winter for the second cohort. Residency was higher than expected in the Strait of Georgia, with migrants from the first cohort only emigrating through Queen Charlotte Strait during the second ocean spring and summer. Residents remained in the Strait of Georgia until at least the second ocean winter. In the second cohort, a small proportion of September and October-tagged individuals emigrated through the Strait of Juan de Fuca during the first ocean fall. It is important to understand where salmon move in the ocean, as well as if movements are influenced by traits such as size and growth that are also linked to survival. An improved understanding of marine migrations will support ongoing efforts to determine stage-specific marine survival rates in the Strait of Georgia.

Highlights

- Juvenile Chinook salmon from east coast Vancouver Island rivers vary in the duration of their residence in the Strait of Georgia. A major knowledge gap is when and which individuals migrate away from the Strait of Georgia.
- We tracked 329 juvenile Chinook salmon with acoustic tags, over October 2022 – present. The last tag batteries will die in summer 2026.
- In winter 2023-24, we tagged 179 Chinook salmon in September 2023, October 2023, and January 2024 over 10 days.
- Overwinter residency in the Strait of Georgia was the dominant migration strategy, with emigration mostly delayed until the second ocean summer.
- Overwinter survival was higher than expected, but mortality appears to be higher in early winter. For the October 2022 release group, 40% survival from November 1 – January 15; 82% survival from January 15 – April 1 (not corrected for detection efficiency).
- Deployed and continue to maintain an array of 13 acoustic receivers in the northern and central Strait of Georgia. Kintama Research Services, under contract to Pacific Salmon Foundation, conducted annual download of the Discovery Islands and Johnstone Strait arrays.

INTRODUCTION

Migration routes and timing shape how salmon are influenced by growth opportunities and mortality sources as they rear in the ocean (Quinn, 2021). Ocean-type Chinook salmon from east coast Vancouver Island rivers spend their first summer at sea feeding in the Strait of Georgia, but individuals and stocks vary in their ocean distribution following the first ocean summer (Freshwater *et al.*, 2021; Quinn, 2021; Quinn and Losee, 2022). After the first ocean summer, some individuals leave the Strait of Georgia and migrate to the continental shelf along the outer coast of western North America (migrants; Weitkamp, 2010; Tucker *et al.*, 2011). Others may remain in the Strait of Georgia for most or all their marine rearing (residents; O'Neill and West, 2009; Chamberlin *et al.*, 2011; Arostegui *et al.*, 2017). Some individuals may transiently move multiple times between the Strait of Georgia and the continental shelf (Kagley *et al.*, 2017). These migration strategies may expose migrants and residents to different prey fields, environmental conditions, contaminants, predation risks, and fisheries exploitation rates (Quinn, 2021). For example, migrant Chinook salmon experience greater marine growth than residents (Quinn, 2021; Quinn et al. 2022), which in turn influences fecundity (Healey and Heard, 1984). Additionally, stock-specific Chinook salmon marine survival and age-at-maturity trends covary by ocean entry region (Freshwater *et al.*, 2022), further suggesting that where salmon rear in the ocean influences fitness.

Residency is well-established for Puget Sound Chinook and coho salmon, where coded wire tag recoveries suggest that one-quarter of subyearling Chinook salmon remain resident in the Salish Sea (29%, O'Neill and West 2009; 24%, Chamberlin *et al.* 2011), with yearling Chinook salmon estimated to have higher rates of residency (45%, O'Neill and West 2009). Several studies have used acoustic tags to study movements of resident Chinook and coho salmon in Puget Sound (Smith *et al.*, 2015; Arostegui et al. 2017; Kagley et al. 2017). Notably, some residents stay highly local over long periods of time (Arostegui et al. 2017) while others show a "transient" life history, remaining in Puget Sound for an extended period before outmigrating (Kagley et al. 2017).

While residency behaviour receives much less attention in the Strait of Georgia compared to Puget Sound, Healey (1976) speculated that 15% of Strait of Georgia Chinook salmon remained resident. Two studies have since acoustic tagged juvenile Chinook salmon in the Strait of Georgia, with differing results. Neville *et al.* (2015) tagged 278 first ocean summer Chinook salmon in summer 2007 and 2008, of which only eight fish were detected at receiver arrays at the exits of the Salish Sea. Acoustic tags were programmed to run out of battery four months after tagging, which may have limited detections of overwinter migrants and prevented insights into overwinter residency. In a later study, Rechisky *et al.* (2019) double tagged 80 juvenile Chinook Salmon with acoustic and PIT tags in Cowichan Bay in September 2017. Seven fish were detected at the Juan de Fuca array, although one individual was later detected on a receiver within the Salish Sea. Another eight fish were detected in the Salish Sea in mid-winter or later, after when the acoustic tags of Neville *et al.* (2015) were programmed to cease transmission. Three of 80 fish returned to spawn (PIT tags detected in the

Cowichan River); all three remained resident in the Strait of Georgia overwinter, suggesting that residency may be an important life history strategy in east coast Vancouver Island Chinook populations. Currently, microtrolling catch rates of first and second ocean winter Chinook salmon are high at some locations in the Strait of Georgia during mid-winter, further suggesting that residency is an important migration strategy (Atkinson, James, Duguid, unpublished data, 2020-24). Residency rates may vary between years or have changed over time (Beamish and Neville, 2021; Quinn and Losee, 2022).

Data on how salmon stocks are distributed spatially and through ontogeny are a key tool for salmon fisheries management in British Columbia. Therefore, we need to answer key questions about migration strategies in Strait of Georgia Chinook salmon to understand how Chinook salmon are spatiotemporally distributed in the ocean. Additionally, knowledge gaps about migration strategies need to be resolved to support the ongoing Bottlenecks to Survival Project (co-led by Pacific Salmon Foundation and British Columbia Conservation Foundation; funded by British Columbia Salmon Restoration and Innovation Fund). The Bottlenecks to Survival Project tags juvenile Chinook salmon with PIT tags in hatcheries, rivers, estuaries, and in the Strait of Georgia to estimate stage-specific survival for multiple populations. PIT tagging occurs in the Strait of Georgia from September through April, potentially spanning a period (or multiple periods) of outmigration. This raises the prospect that the proportion of different migration life-history types may change through the tagging period, with implications for estimation of overwinter survival. Resolving outmigration timing and relationships with individual traits is necessary to validate assumptions of marine survival estimates and test key hypotheses about overwinter mortality.

We are conducting an acoustic tagging study to address knowledge gaps about juvenile Chinook salmon migratory behaviour in the Strait of Georgia. Acoustic telemetry uses small transmitters (2-5 g) that emit ultrasonic pings to track fish as they move through coastal oceans. Primary objectives of this study are:

(1) Determine when migrants leave the Salish Sea – does outmigration occur in one large pulse or migrants leave throughout the first ocean winter in a continuous diffusion process? Do some individuals outmigrate after the first ocean winter (e.g., Kagley *et al.* 2017)? Do some individuals move between the Salish Sea and the continental shelf multiple times?
(2) Identify if migratory strategies vary with individual traits (e.g., relative body condition, fork length, early marine growth, infectious agents) during the early marine period. For example, is outmigration size- or growth-selective?

Acoustic tags also provide high-resolution data on fish survival, as acoustic tags have high recapture rates (e.g., Dudgeon *et al.*, 2015). Additionally, this will also provide novel insights into the movement behaviour of juvenile Chinook salmon in the Strait of Georgia; for example, data on vertical habitat use with pressure-sensor acoustic tags. Together, acoustic telemetry provides a valuable tool to understand Chinook salmon migration patterns.

METHODS

We used acoustic transmitters to assess movements and survival of juvenile Chinook salmon in their first winter at sea. These tags produce ultrasonic pings that are detected by hydrophones up to 1000 metres away, allowing detection of tagged salmon as they move throughout the coastal ocean, with batteries lasting up to 2.5 years. In total, 329 juvenile Chinook salmon were tagged over two winters (2022-23, 2023-24).

Study design

Chinook salmon were tagged with acoustic transmitters as they entered their first winter at sea (September 2023; October 2022, 2023). Additional salmon that survived and remained within the Strait of Georgia to mid-winter (January 2023, 2024) were tagged, as the fall tag group was expected to experience high rates of mortality and outmigration. Tagging across two winters allowed insights into interannual variability in migration strategies. Ocean entry cohort 2022 experienced a very cold spring as they entered the ocean, as well as the worst fall drought on record. In contrast, salmon entering the ocean in 2023 experienced relatively normal conditions. This difference is reflected in the size of juvenile Chinook in their first ocean fall, with larger fork lengths in 2023 than in 2022 (see Results).

In the first year, we tagged 95 Chinook salmon in October 2022 and 55 individuals in January 2023. A report on this first year was provided to BC Salmon Restoration and Innovation Fund at the end of fiscal year 2022-23 (Greentree *et al.*, 2023). In 2023-24, we tagged 179 Chinook salmon total – 65 in September 2023, 76 in October 2023, and 38 in January 2024. The September 2023 tagging group was added to assess if October tagging missed early fall migrants. In 2023-24, tagging occurred over ten days – four days in September, four days in October, and two days in January.

All tagging was conducted at Cape Lazo, near Comox, in the Strait of Georgia. Cape Lazo is a productive overwinter microtrolling site, with catches consistently dominated by the Qualicum-Puntledge fall Chinook salmon stock. Since both individual traits and migration strategies likely vary among populations, it was important to focus tagging on one stock, so that we could assess how individual traits influence migration strategies. Qualicum-Puntledge fall Chinook salmon are a major target stock of the Bottlenecks to Survival Project, meaning that the acoustic tagging study is well-positioned to test assumptions of the broader study's survival model (see Discussion).

Arrays of acoustic receivers operated by Ocean Tracking Network (OTN, Dalhousie University) monitor the exits of the Salish Sea (Figure 1). These arrays will detect migrants as they leave the Salish Sea, as well as detect any returning movements before acoustic tag batteries die. The OTN Northern Strait of Georgia array will provide detections of residents. To further monitor resident salmon, as well as to identify site fidelity behaviour, we deployed an array of 13 Innovasea VR2AR and VR2W acoustic receivers at the tagging site and in surrounding regions of the Strait of Georgia. As a result, tagged salmon were detected as they moved within the Strait of Georgia and

outmigrated to the continental shelf. DFO and NOAA arrays on the continental shelf provided additional monitoring coverage. To identify potential tagging-related mortality, we conducted systematic mobile surveys of the area surrounding the tagging site with a vessel-deployed acoustic receiver (Innovasea VR100) immediately after tagging (3 days in 2023-24).

In the second year of the study, 28 of 179 acoustic tags (10 in October 2023, 18 in January 2024) included a pressure sensor, which was calibrated to report the depth of tagged individuals in the acoustic ping train (down to 204 m depth). The use of pressure-sensor tags will provide useful insights into seasonal, regional, and diel variability in depth distribution. Pressure-sensor tags complement the overwinter habitat component of the Bottlenecks to Survival Project, which used microtrolling to assess the horizontal and vertical distribution of first ocean winter Chinook salmon in the Strait of Georgia (see Winter Ecology Synthesis Report).

Acoustic tags.

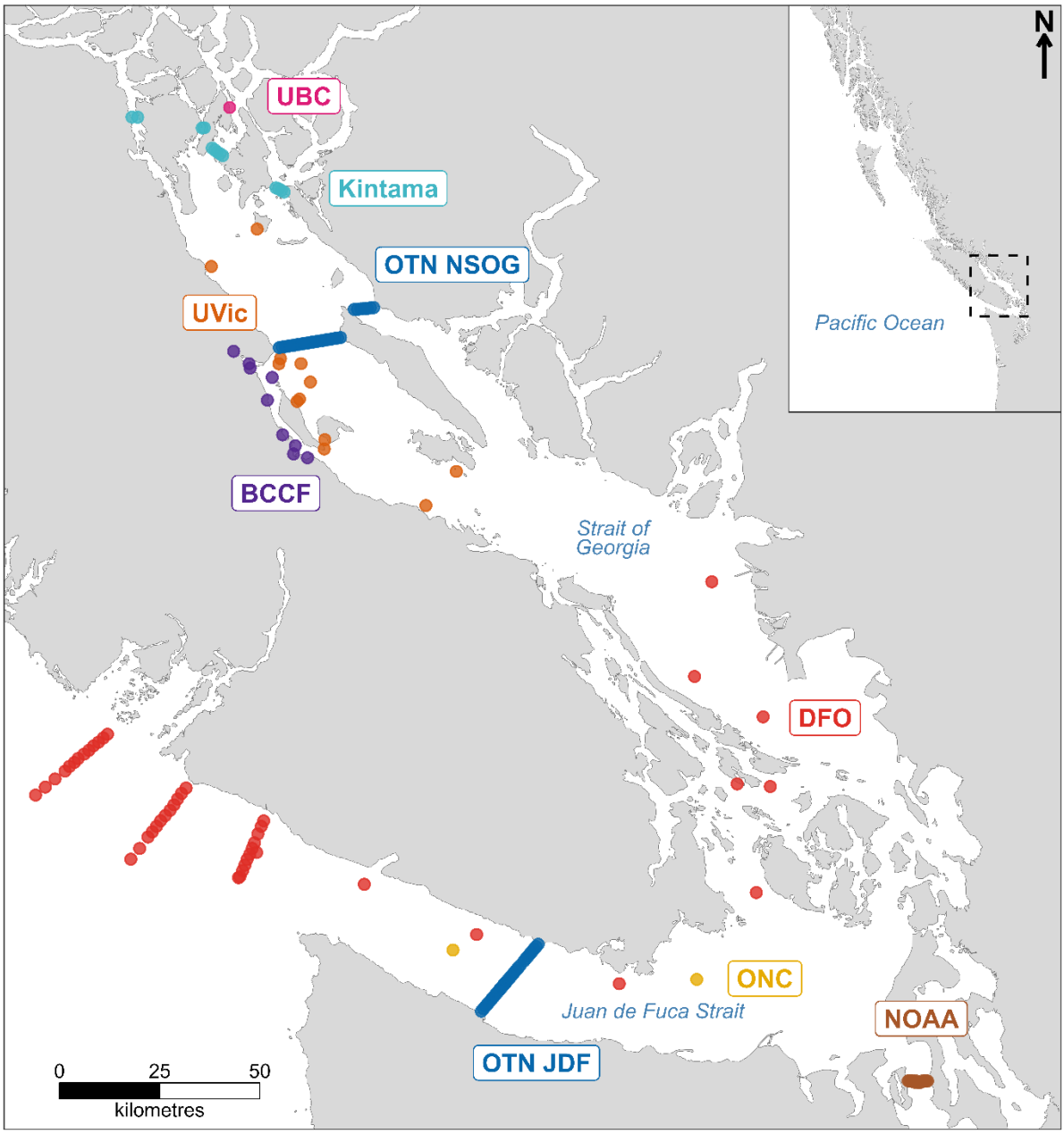


Figure 1. Acoustic receiver arrays in the Salish Sea. Queen Charlotte Strait and Johnstone Strait arrays are not shown, they cover the northern exit of the Strait of Georgia.

Tagging procedures

First ocean winter Chinook salmon were captured using microtrolling (Figure 2; Duguid and Juanes, 2017). Fish were landed directly into black buckets of aerated seawater, with minimal handling during capture and hook removal. In the first year of the study (2022-23), salmon were caught by a

separate microtrolling vessel and transferred to a second vessel where tagging occurred. Fish were anesthetized with 80 mg/L MS-222 buffered with sodium bicarbonate. While fish reached the required anesthesia depth for tagging, they were visually assessed for signs and symptoms of injury and disease and adipose fin status. Fork length and weight were measured. A gill biopsy (genomic analysis of infectious agents and stress markers) and 6-10 scales (genetic stock identification, prior growth analysis) were collected. Acoustic tags were surgically implanted using standard methods (Liedtke *et al.*, 2012), with a ~12 mm incision and three 4-0 Monocryl sutures. A passive integrated transponder (PIT; Biomark, 0.1 g) was also implanted through the same incision. Following tagging, fish were returned to an oxygenated black bucket and monitored for recovery using a qualitative four-level scale. Upon recovery to normal swimming and after 20 minutes, fish were released.

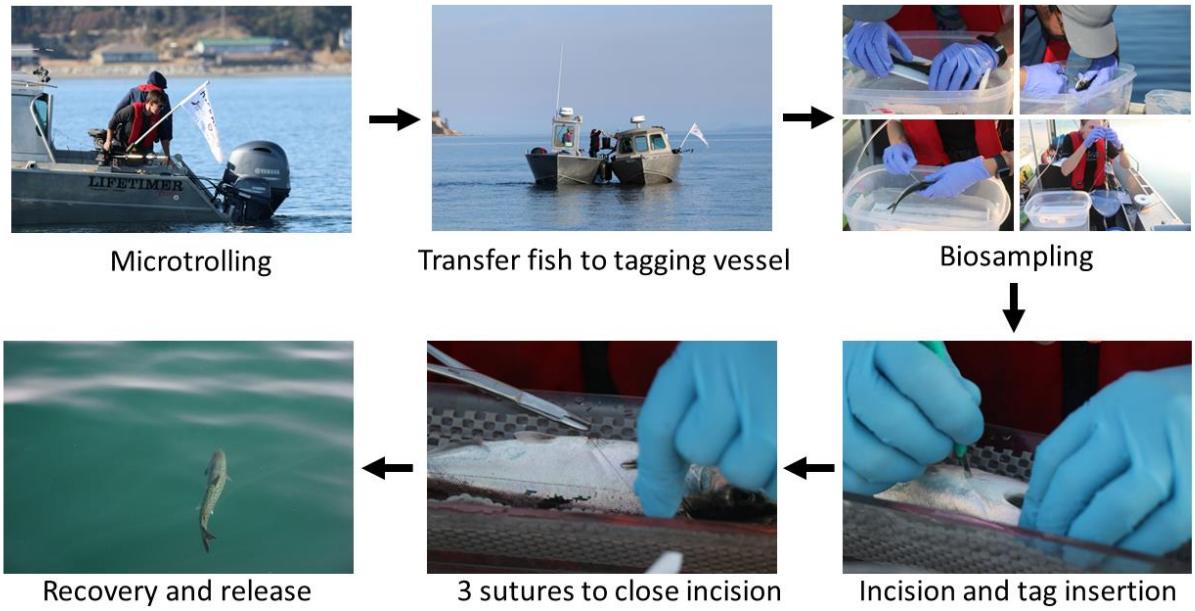


Figure 2. Process of acoustic tagging juvenile Chinook salmon, from capture by microtrolling to release back to ocean.

Acoustic tags were programmed to ping on a 150 second random delay (*i.e.*, randomly every 110-190 seconds). The 150 second delay was selected to optimize detection efficiency and tag battery life, based on simulations of tag detections during the 2017 Cowichan acoustic tagging study (Rechisky *et al.*, 2019). Juvenile Chinook salmon show less directed migrations than other Pacific salmon species (e.g., sockeye salmon, steelhead; Welch *et al.*, 2010), meaning that a longer tag delay could be used.

Different sizes of Innovasea V9 69 kHz acoustic tags were used, depending on fish size. In 2022-23, V9-1L (n = 85; 3.6 g; 569 days) and V9-2L (n = 65; 4.5 g; 912 days) tags were used in all fish. The minimum tagging size for the V9-1L tag was 72 g (5.0% tag burden). We tagged larger fish (generally larger than 125 g) with larger V9-2L tags to increase battery life. V9-1L and V9-2L tag batteries will

last until the end of the second ocean winter, with V9-2L tags lasting nearly a full year longer. Given their long battery lives, both the V9-1L and V9-2L tags will provide the long-term resolution needed to identify if there is also a transient migration strategy, where immature salmon either outmigrate late (e.g., after a year at sea; Kagley *et al. 2017*) or move between the Salish Sea and the continental shelf multiple times.

In October 2022, some captured salmon were too small (<72 g) to be tagged with V9-1L tags. Therefore, in September and October 2023, we tagged smaller individuals with V8 tags (n = 40, 2.0 g, 356 days). The V8 tags allowed tagging throughout the size range caught (minimum size: 40 g). A subset of the October 2023 (n = 10) and January 2023 (n = 18) release groups were tagged with V9P-2L pressure-sensor tags (4.9 g; 730 days), calibrated to report depth in the same ultrasonic ping train reporting the tag's unique identification code. The remainder of fish tagged in the three 2023-24 release groups were tagged with V9-1L or V9-2L tags.

Statistical analysis

A key goal of this study is to determine if individual traits like body size, condition, or early marine growth differ between migrants and residents. In this report, we assessed relationships between migration strategy and individual traits for the winter 2022-23 release groups only. detections from the Strait of Juan de Fuca and Queen Charlotte Strait arrays are not available after October 2023. Additionally, it is likely that not all migrants from the 2023-24 release groups have emigrated yet (see Results for migration timing of the winter 2022-23 release groups).

Migrants were defined as salmon detected at an array monitoring an exit of the Salish Sea, either Queen Charlotte Strait or the Strait of Juan de Fuca (Figure 1). All migrants from the winter 2022-23 release groups overwintered in the Strait of Georgia, which was not expected. Therefore, overwinter residency was not sufficient to identify an individual as a resident and residents were defined as individuals detected within the Salish Sea (including the Discovery Islands) after 26 July 2023, which was the date that the last migrant arrived at the Queen Charlotte Strait array. The "unclear" class was not detected after 26 July; i.e., classification as resident required survival past 26 July. A less-conservative definition may be appropriate. For example, defining residents as detected within the Salish Sea after 75% of migrants had been detected at Queen Charlotte Strait, or the date of the last migrant departure from Discovery Islands.

We used binomial generalized linear models to test for differences in traits between migrants (1) and residents (0), with an interaction term to fit the relationship separately for each release group. The model was only run on fish identified by genetic stock identification to the target Qualicum-Puntledge fall Chinook stock, as it is important to avoid conflating inter-individual variation with differences among populations.

The interaction term was deemed biologically necessary, but not just because some trait values increase through the winter (e.g., body length, weight). To account for trait values increasing over time, trait values could be standardized by release group (e.g., relative length of individual *i* is the standardized deviation from the mean length of release group *j*) and a single relationship estimated

among release groups. However, deviations from the mean trait value may reflect "better" or "poorer" physiological state in one period but not in another. For example, say there is a length-dependent decision window in the first October at sea, where large body size in October is linked to outmigration later in the winter (seaward migration decision windows correlated with size are well established in Atlantic salmon and steelhead; Thorpe *et al.*, 1998; Satterthwaite *et al.*, 2009). Larger fish in October that have reached a critical size may shift energy allocation from body growth to energy-dense storage lipids, while smaller fish in October may experience compensatory growth to reach the same size later in the winter as other fish that grew fast early (Beamish *et al.*, 2011). Subsequently, relative length may reflect physiological state in October but not in January.

There are several ways to assess body condition of fish, with extensive debate about which condition index is most effective or least susceptible to bias (Cone, 1989). We used an index of relative body condition through residuals of log-log body length-weight linear regression, where body condition was the log-measured weight subtracted from the log-weight predicted by the models. Positive residuals indicate fish in above-average condition.

This model will also be run with early marine growth rates (scales) and genomic markers of infection and stress (gill biopsy). Scales have been digitized and measured, but we are still assessing the most appropriate method to use scale circuli spacing as a proxy of prior growth rates. Gill biopsies will be analyzed following development of a Fit-chip marker for nutritional stress and starvation, which is currently being developed using samples collected through a laboratory challenge study (for details see Winter Ecology Synthesis Report).

Next steps in statistical analysis

There are several immediate next steps in the statistical analysis in this study. Acoustic tags provide high-resolution data on overwinter survival. A Cormack-Jolly-Seber (CJS) survival model will be developed to estimate how apparent survival and detection probability vary through the first ocean winter and beyond. The first step is to develop a CJS that estimates month-specific survival and detection probability. At this time, the monthly detection history matrix has been coded but has not been run through the model. Following development of an initial model, the application of more complicated models will be considered (e.g., multi-state mark-recapture models, models including covariates like fork length).

Since the CJS model has not yet been run, for this report we assessed survival using period-specific estimates of minimum survival. Minimum survival estimates simply reflect the number of tags alive at the end of a period relative to the number of tags alive at the start of the period. They did not account for detection efficiency, meaning that it is likely some tagged fish assumed to be dead by these estimates were instead alive but not detected.

The survival assessment focused on winter 2022-23, for which all detection data have been received. We used two periods of similar duration to compare survival between the early (1 November – 15 January, 75 days) and late winter (15 January – 1 April, 76 days). Survival was visualized with Kaplan-Meier survival curves, which showed the depletion of alive tags over time. We qualitatively identified

stanzas with different rates of mortality and emigration, and overlaid these periods on the survival curves.

Dynamic data visualization

R scripts to produce dynamic maps of the movement tracks of tagged salmon have been developed and continue to be refined. Animated movement tracks for the October 2022, January 2023, September 2023, and October 2023 release groups are available at wesleygreentree.github.io/animations. These maps support interpretation and communication of the results of this study.

Figure 3. Screenshot for 2 August 2023 of the dynamic map of movement tracks of the January 2023 release group. Movement tracks were interpolated to remain in the water. Only points for tagged fish still alive on 2 August are shown, while paths from all fish are shown on the map.

RESULTS

Size and stock composition of acoustic tagged fish

Fork length at tagging varied between the two ocean entry cohorts. The October 2022 tag group (median: 197 mm) was smaller than the October 2023 group (median: 215 mm). In fact, median fork length was higher in September 2023 (median: 200 mm) than in October 2023. Fork length was similar in the January 2023 (median: 261 mm) and January 2024 (median: 262 mm) tag groups.

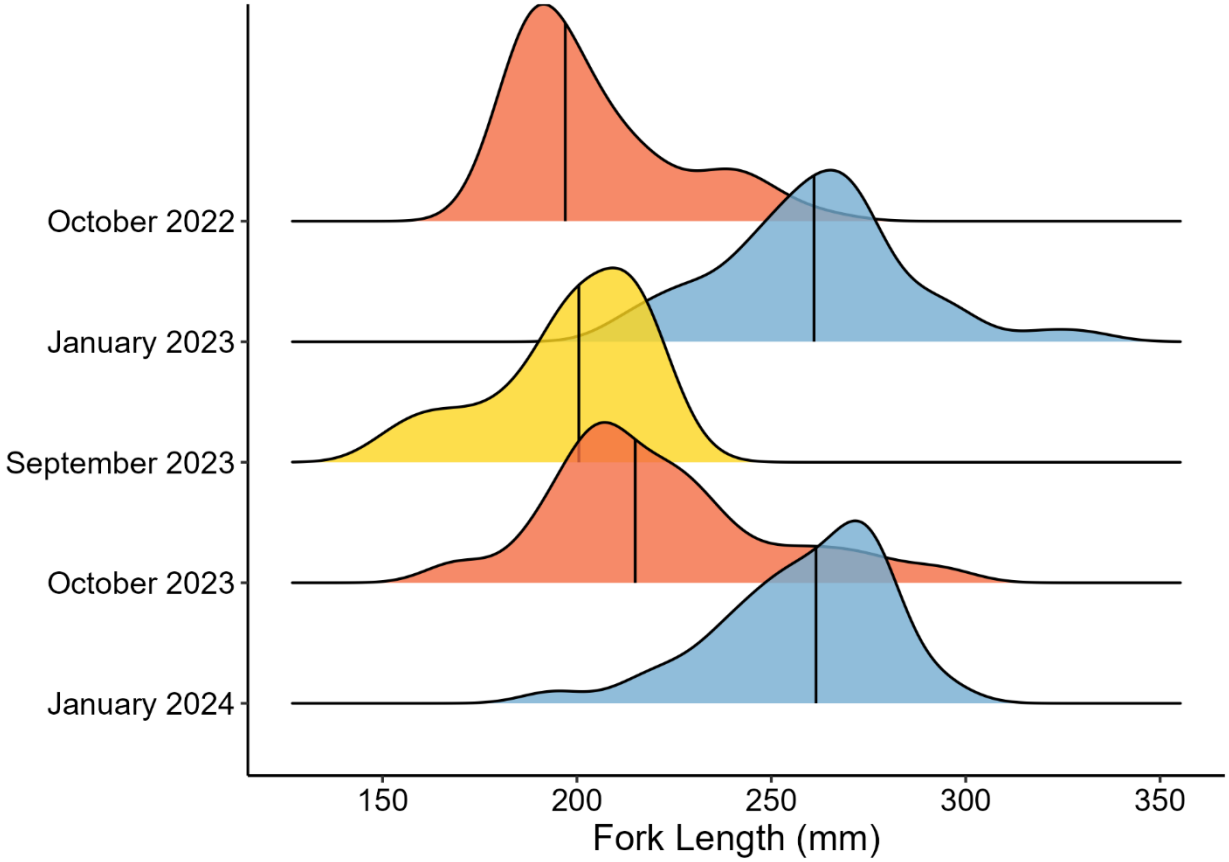


Figure 4. Fish were larger in fall 2023 than fall 2022, but similar in January 2023 and 2024. Fork length (mm) and weight (g) distributions of each tag group, with the median indicated by the vertical line. Individuals rejected for tagging not included.

Genetic stock identification is available for winter 2022-23 release groups. In October 2022, 89 of 95 (93.7%) tagged fish were from the Qualicum-Puntledge fall stock. In January 2023, 49 of 55 (89.1%) tagged fish were from the Qualicum-Puntledge fall stock. Quinsam River (n = 4), Homathko River (n = 3), Nanaimo River fall (n = 2), Soos Creek (n = 2), Puntledge River summer-run (n = 2), Harrison River (n = 2), and Shuswap River-Lower (n = 1) stocks were also identified by genetic stock

identification. Genetic samples from the winter 2023-2024 release groups will be submitted to the DFO Molecular Genetics Lab in summer 2024.

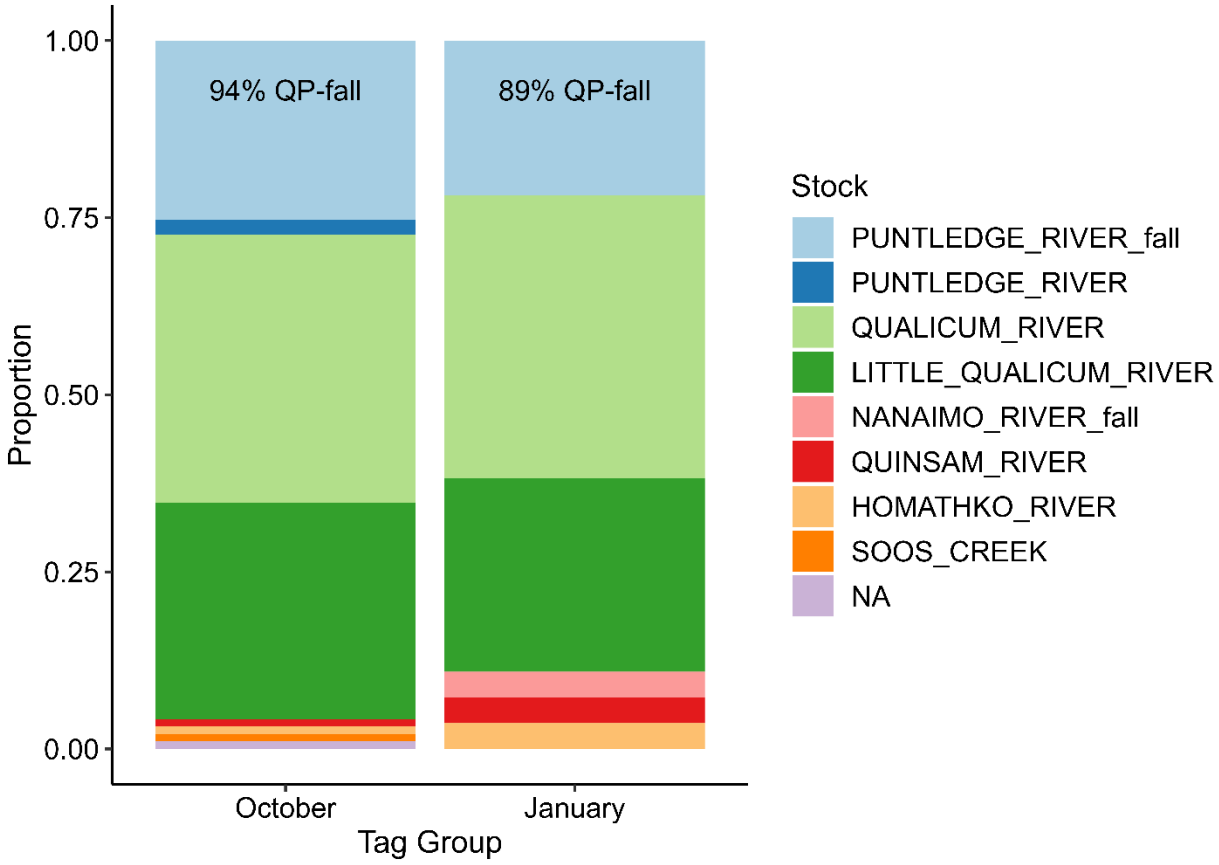


Figure 5. Genetic stock identification of the October 2022 and January 2023 release groups, using the most probable stock for each individual rather than the mixture of stock probabilities outputted by the GSI model.

Movements and migration

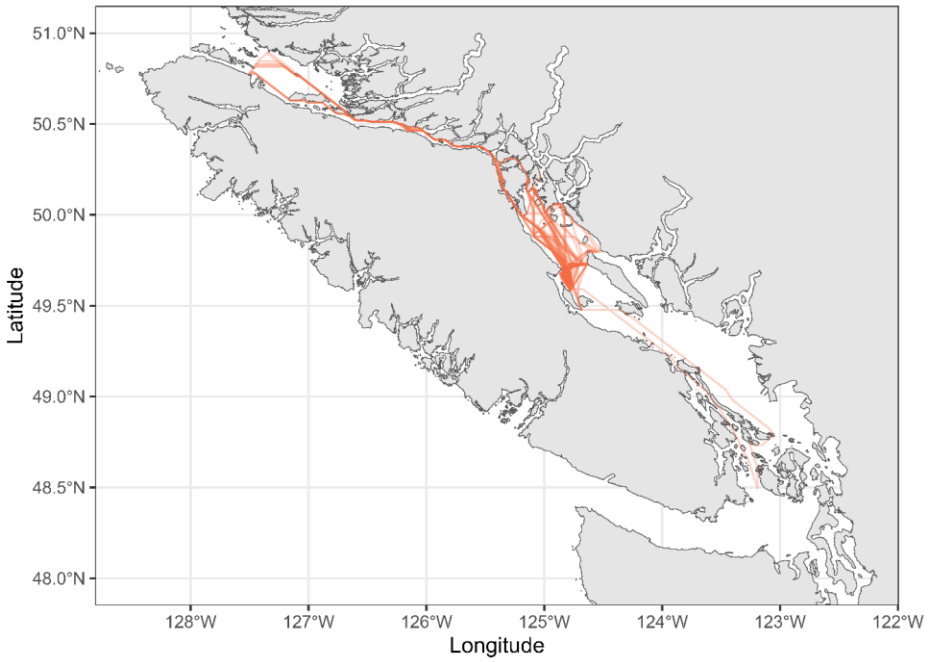
In winter 2022-23, all tagged Chinook overwintered in the Strait of Georgia, typically remaining close to Comox throughout the first ocean winter (Figures 4A, 4B, S1, S2). Movements to the Discovery Islands, Salmon Point, and southern Strait of Georgia occurred during the winter, but were uncommon. Tags A69-1604-30534 and A69-1604-30580 arrived in Johnstone Strait on 26 February and 29 March 2023 respectively, representing the earliest movements out of the Strait of Georgia. In their second ocean spring and summer, salmon moved more widely throughout the northern Strait of Georgia. Between April and July 2023, 27 individuals (11 of 95 tagged in October 2022, 16 of 55 tagged in January 2023) emigrated through Queen Charlotte Strait. For the October 2022 release

group, six of 95 were detected as residents in the Strait of Georgia in August 2023 or later, composed of three Puntledge River fall, two Qualicum River, and one Little Qualicum River individuals. 13 of 55 January 2023 tags remained resident in the Strait for this period, composed of seven Little Qualicum River, five Qualicum River, and one Puntledge River fall individuals.

The 27 migrants consisted of 11 Big Qualicum River, nine Puntledge River fall, three Little Qualicum River, three Homathko River (notable that all Homathko tags survived and outmigrated), and one Quinsam River individuals. Outmigration was typically rapid from the Discovery Islands to Queen Charlotte Strait (Figure 10), although one tag (A69-1604-30534) milled around the Johnstone Strait array for an extended period (26 February – 22 April 2023). Three individuals from the January 2023 tag group were detected by DFO and NOAA arrays off the west coast of Vancouver Island in summer 2023 (earliest arrival 29 July, last departure 3 November). Tag A69-1604-5348 left the Queen Charlotte Strait array on 5 July 2023, was detected off Barkley Sound from 29 July to 3 November, then returned to Johnstone Strait on 13 January 2024.

For both winter 2022-23 release groups, summer migrants were longer (Figure 11). In the October 2022 release group, residents had higher condition (both median and mean; Figure 12). January 2023 migrants had higher mean condition but lower median condition than January 2023 residents, suggesting differences are not meaningful (Figure 12). However, binomial generalized linear models testing for a tag group-specific relationship between fork length or condition and migration strategy were not significant ($p > 0.05$).

A. October 2022



B. January 2023

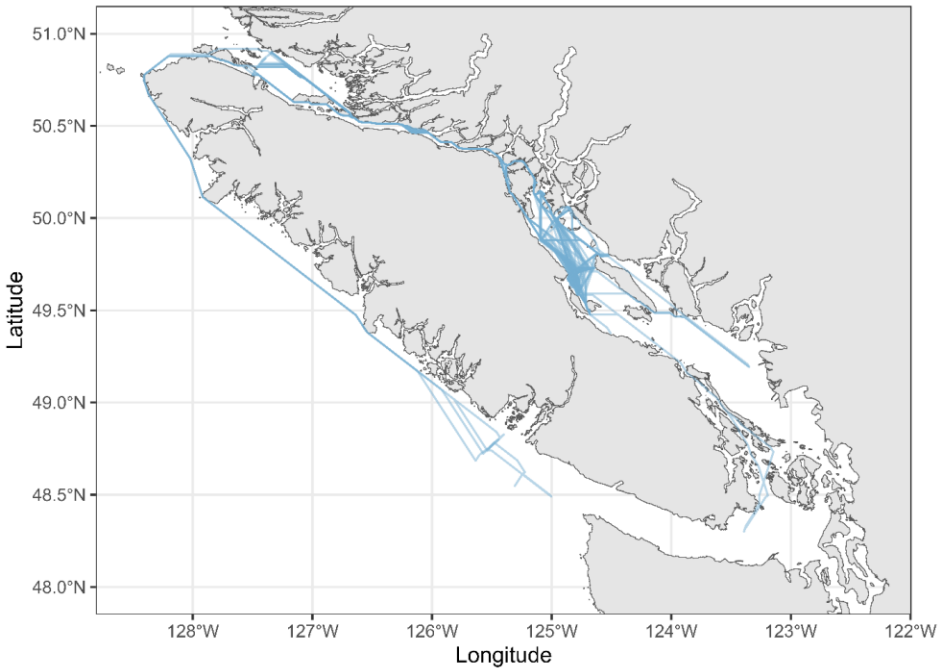


Figure 6. Movement tracks of acoustic tagged juvenile salmon from winter 2022-23, with a separate panel for each release group. Tracks between detections are interpolated to remain in water, rather than crossing over land.

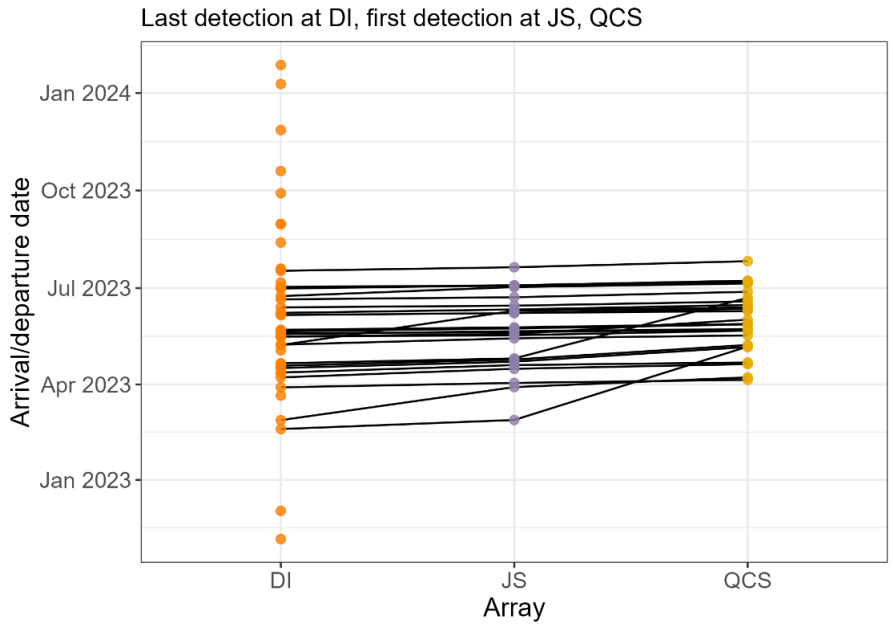


Figure 7. Time of arrival at arrays on the outmigration route through Queen Charlotte Strait. Both cohorts are included. However, no individuals tagged in winter 2023-24 were detected north of the Discovery Islands.

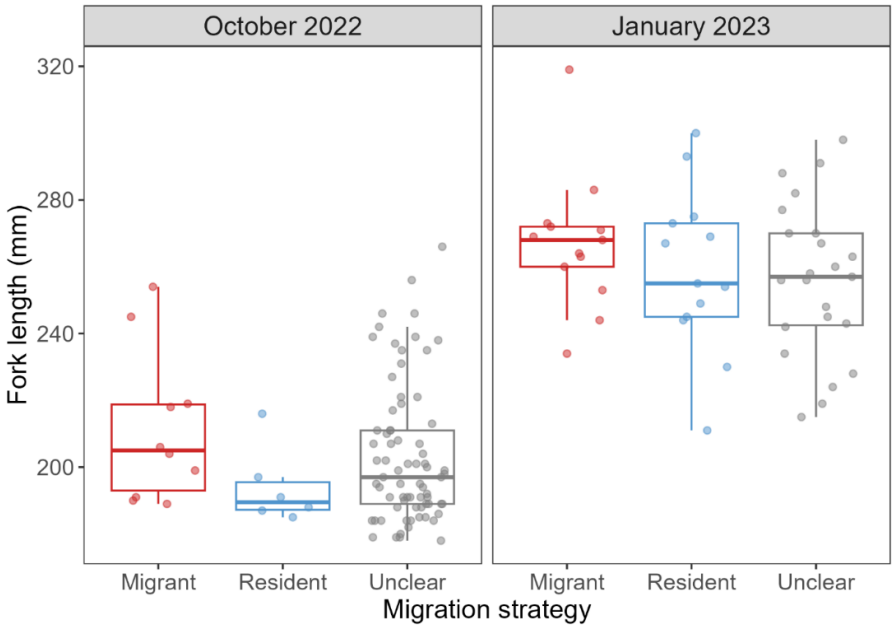


Figure 8. Fork length, by migration strategy, for Qualicum-Puntledge fall Chinook from October 2022 and January 2023 tag groups. The Unclear migration strategy represents fish that were not detected after July 26, 2023, which was the date that the last summer migrant arrived at Queen Charlotte Strait.

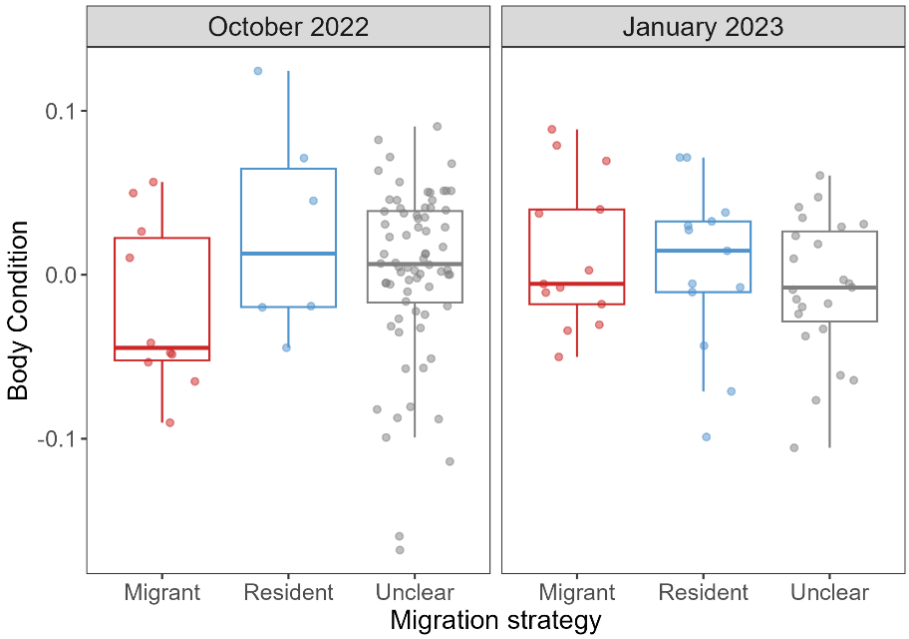
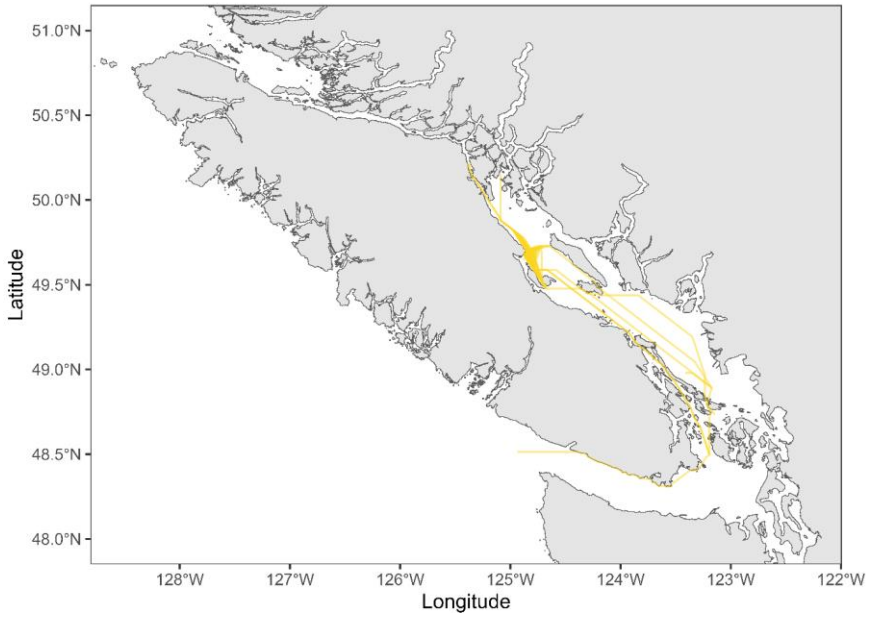


Figure 9. Condition (measured as the residual of a ln(fork length)-ln(weight) linear regression), by migration strategy, for Qualicum-Puntledge fall Chinook from October 2022 and January 2023 tag groups. The Unclear migration strategy represents fish that were not detected after July 26, 2023, which was the date that the last summer migrant arrived at Queen Charlotte Strait.

Not all salmon tagged in fall 2023 overwintered in the Strait of Georgia. One individual tagged in September (A69-1604-19219) and two tagged in October (A69-9002-13541, A69-9002-13547) emigrated through the Strait of Juan de Fuca. These tags were detected by Fisheries and Oceans Canada receivers in Juan de Fuca and Swiftsure Bank; this array design is expected to have low detection efficiency. The gate-style Juan de Fuca array data are not yet available, meaning fall migrant numbers may be higher.

Like in the previous winter, most tagged salmon from September 2023 (Figures 5A, S3), October 2023 (Figures 5B, S4), and January 2024 (Figure S5) remained highly resident to the Comox tagging site. Some fish tagged in September moved more widely throughout the northern Strait of Georgia (Figure 7; Salmon Point, Lambert Channel). Most acoustic receivers deployed for winter 2023-24 have not yet been recovered, meaning that data on wider movements of the October 2023 (Figure 8) and January 2024 release groups (Figure 9) are not yet available. As a result, models assessing relationships between migration strategies and individual traits have not yet been run for winter 2023-24 tags.

A. September 2023



B. October 2023

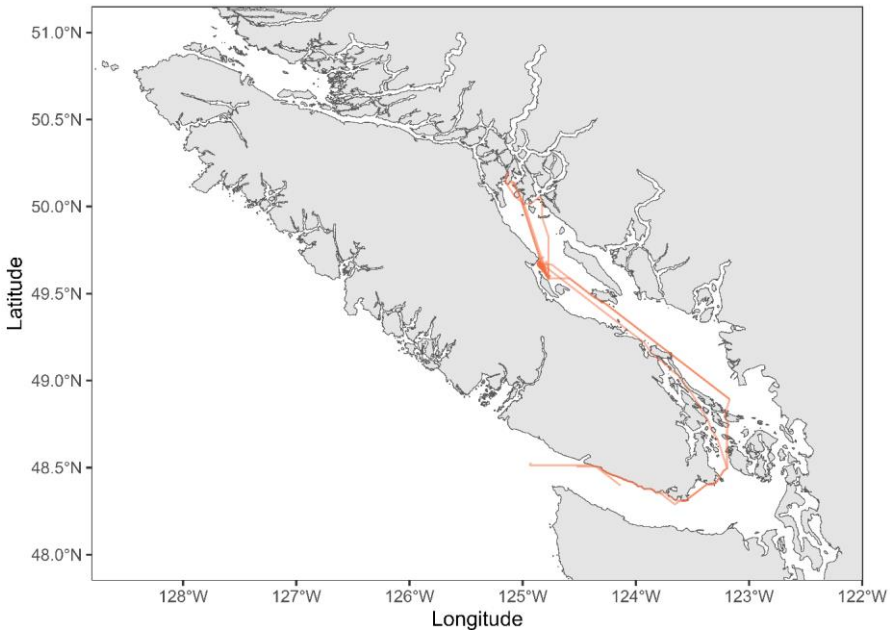


Figure 10. Movement tracks of acoustic tagged juvenile salmon from winter 2022-23, with a separate panel for each release group. Tracks between detections are interpolated to remain in water, rather than crossing over land. Widespread detections for the January 2024 release group are not yet available. Detections at Salmon Point received on 17 May 2024 are not included, due to long computer run times required to interpolate movement tracks between detection locations.

Survival

Detection data throughout the winter are only available for the first winter (2022-23). Survival was higher in early winter than late winter (Figure 11). In early winter, 28 of 70 (40%) October 2022-tagged salmon detected alive on 1 November 2022 survived to 15 January 2023 or later. In contrast, 23 of 28 (82%) of October 2022-tagged salmon still alive on 15 January 2023 survived to 1 April 2023. Late winter was similarly high for the January 2023 release group, with 40 of 55 (73%) January 2023-tagged salmon surviving to 1 April 2023 or later.

Most detection data are not yet available for winter 2023-24. Of the September 2023 release group, 56% (25/45) of tagged fish detected alive on 1 November 2023 were detected on 15 January 2024 or later. For the October 2023 release group, 62% (36/58) of tagged fish detected alive on 1 November 2023 were detected on 15 January 2024 or later. Both fall 2023 tag groups experienced higher survival during early winter than in the previous year (Figure 12), even though data from most acoustic receivers were unavailable for winter 2023-24 at the time of this report. These minimum survival estimates are expected to increase when more receiver data are available. Fall 2023 tags were not yet assessed for stationary tags detected by mobile tracking.

Two tags from winter 2022-23 returned as jacks in 2023. Tag A69-1604-5316 from October 2022 returned to the Puntledge River on 18 September 2023. One individual tagged in January 2023 (A69-1604-30578) returned to the Little Qualicum River to spawn as a jack on 27 September 2023. In summer 2024, VR2W acoustic receivers will be deployed in the estuaries or lower reaches of the Puntledge, Big Qualicum, and Little Qualicum rivers to detect tagged individuals returning to spawn. PIT arrays in these systems (PSF/BCCF Bottlenecks to Survival) will also monitor for returning fish, since fish were implanted with both an acoustic and PIT tag.

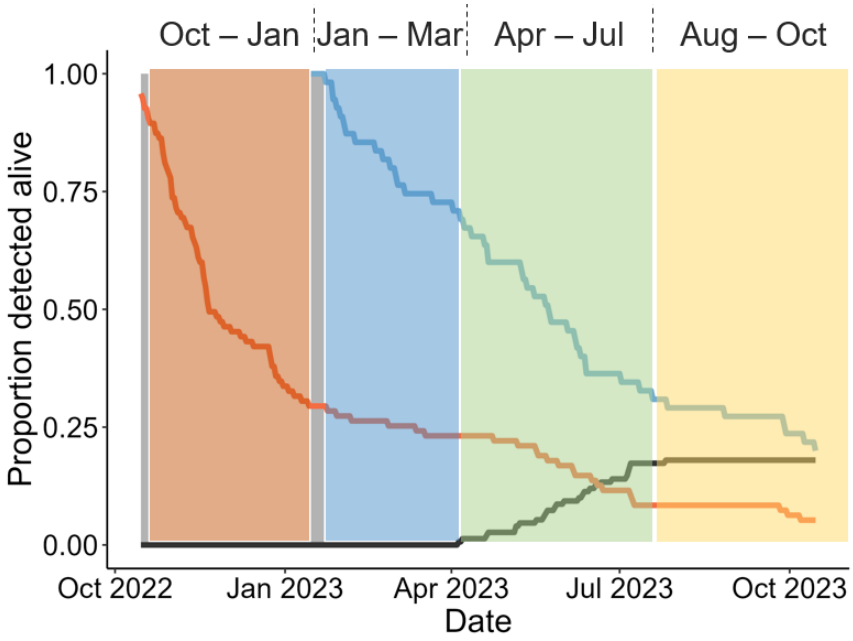


Figure 11. Kaplan-Meier survival curves for juvenile Chinook tagged in winter 2022-23, until 15 October 2023 (one year after the first tags were released). The year is divided into four stanzas with varying mortality and movements. October – January: high apparent mortality, all tags remained resident. January – March: low to moderate apparent mortality, all tags remained resident (though one tag was detected in Johnstone Strait in this period).

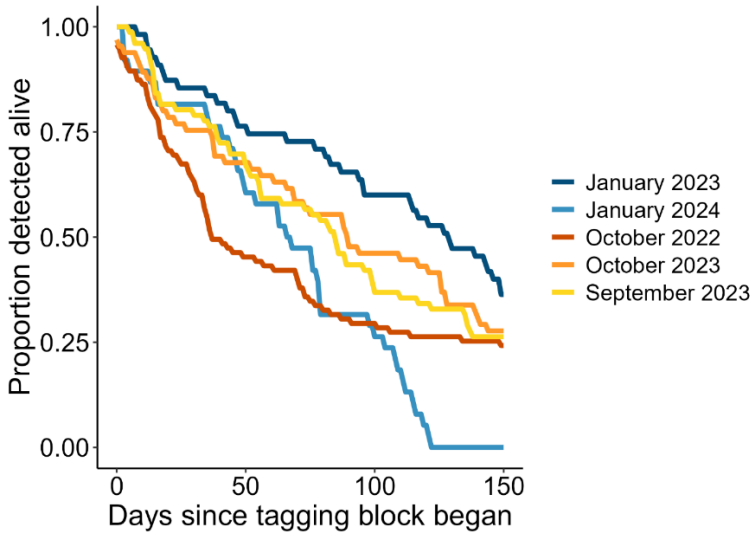


Figure 12. Survival was higher in fall 2023 than in fall 2022. Preliminary Kaplan-Meier curves for all release groups until 150 days after the tagging block began. Data are lacking for the winter 2022-23 release groups, particularly the January 2024 group (*i.e.*, 150 days after mid-January 2024 has not passed at the time of the submission of this report).

Vertical habitat use

Most detection data from winter 2023-24 is not currently available, meaning that inference of Chinook salmon vertical habitat is currently limited. Still, we currently have access to 34,514 detections of the 28 depth tags. Diel, regional, and seasonal trends in water column depth are not currently evident (e.g., see variable diel patterns in Figure 8).

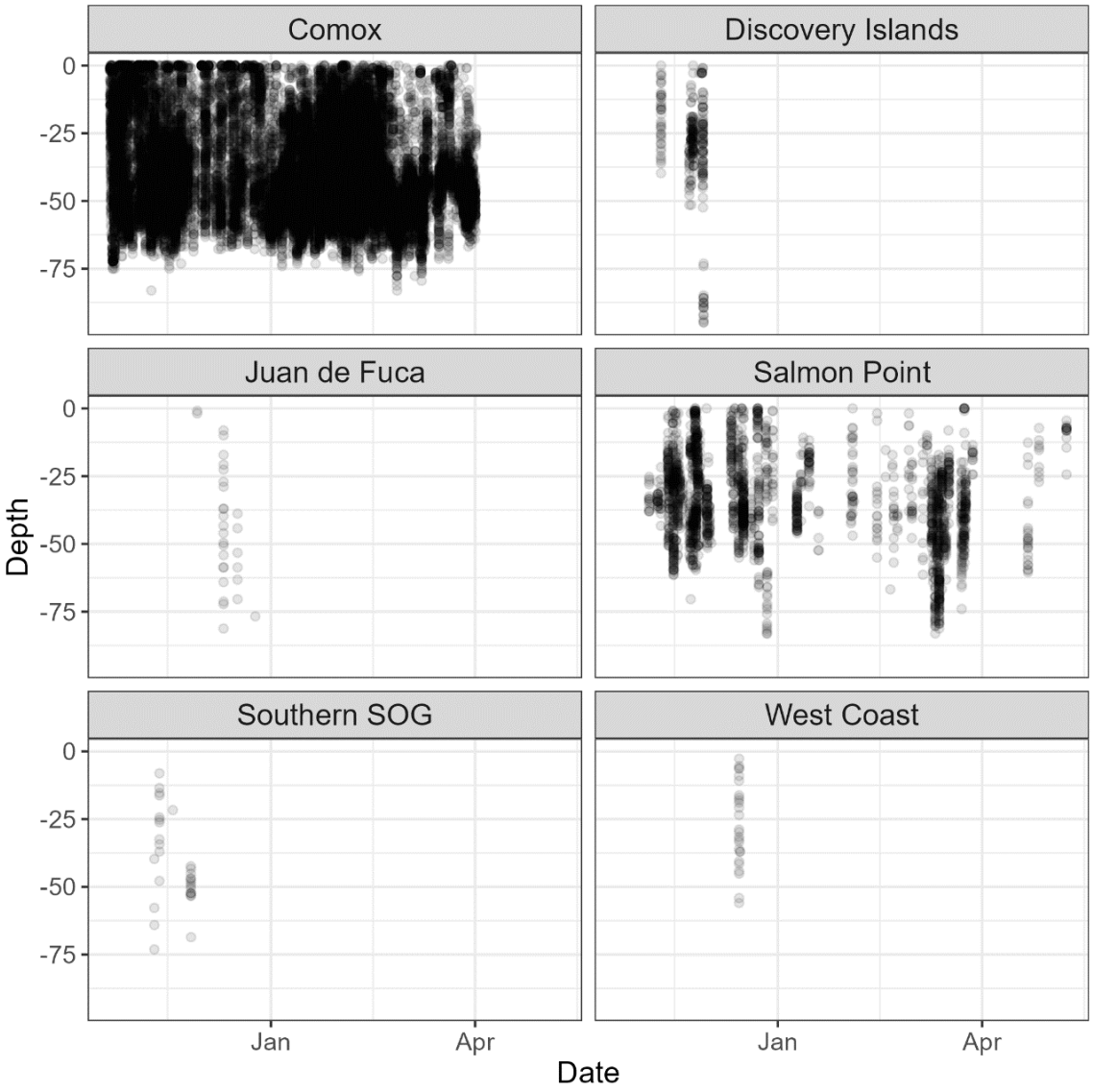


Figure 13. Depth (metres) at detection of 28 Chinook salmon tagged with pressure-sensor acoustic tags in winter 2023-24, split by region. Most detection data are not yet available for this period. Even at Comox, detections are not yet available for most of the receivers monitoring the region.

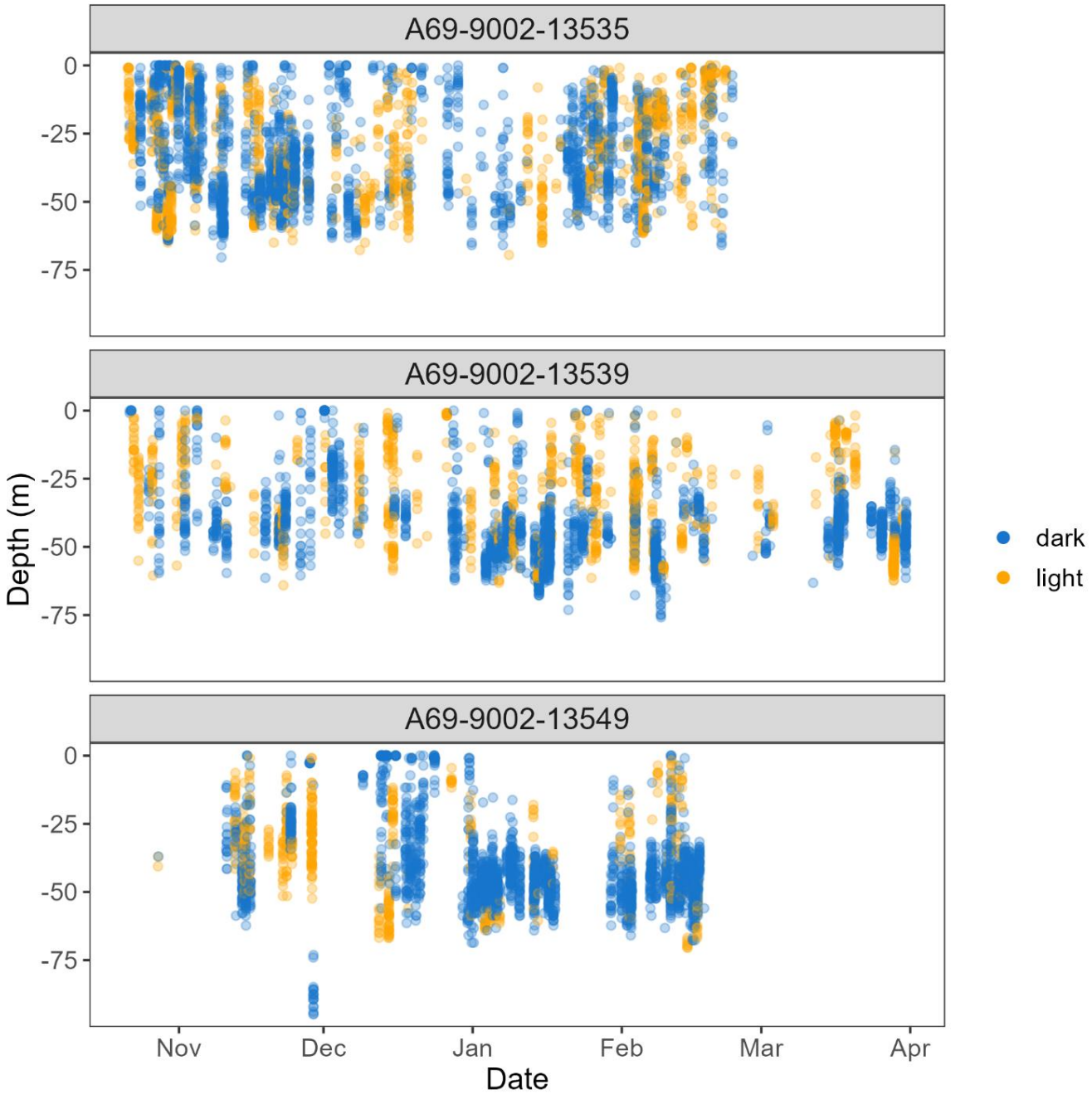


Figure 14. Depth (metres) at detection for three tags, for light and dark diel periods. Detections after civil twilight and before sunrise were classified as "dark," while detections during the day were detected as "light." The three tags were the tags with the highest number of detections (all >2500 detections).

DISCUSSION

We tagged 329 Chinook salmon during their first fall and winter at sea, with salmon tracked as long as to the beginning of the third ocean spring (tag A69-1604-5272). Tracked movements emphasize the importance of overwinter residency in the Strait of Georgia for Qualicum-Puntledge fall Chinook salmon. Limited detections are currently available for the winter 2023-24 release groups. Tags will continue to ping until summer 2026, providing a long time series of juvenile and subadult Chinook salmon movements within and away from the Strait of Georgia.

Overwinter residency in the Strait of Georgia

Juvenile Chinook salmon that were tagged in the fall (September, October) and mid-winter (January) mostly remained resident in the Strait of Georgia throughout the winter. Though there was previous evidence that residency is an important strategy of ocean-type Chinook salmon stocks entering the Strait of Georgia (e.g., high microtrolling catches of first and second ocean winter Chinook in the Strait of Georgia; Atkinson, James, Duguid, unpublished data), we did not expect nearly all tagged salmon to reside in the Strait of Georgia through the first ocean winter.

During the first ocean winter, many residents were highly localized to Cape Lazo, where they were tagged. It is an interesting question why salmon exhibited strong fidelity to this site. One hypothesis is that during the winter, juvenile Chinook salmon prefer habitats that reduce predation risk rather than those with high prey availability or quality. Interestingly, in both years, many tagged fish appeared to leave Cape Lazo in late February or early March, coinciding with the timing of the Pacific herring fishery and increased sea lion abundance. The September 2023 group may provide insight into fall dispersal and overwinter site selection, as this release group may have preceded the timing of this "decision" to remain resident to a single site over winter.

For the October 2022 and January 2023 release groups, emigration to the outer coast was only observed after the first ocean winter, with tags detected at the Queen Charlotte Strait array between early April and late July. In this first year, all migrants followed the "transient" strategy demonstrated by Kagley *et al.* (2017) of emigration only following extended residency in the Salish Sea. All emigrations during the second ocean spring and summer (data only available for first year) were observed through the northern exit of the Strait of Georgia. In contrast, fall emigrations (data available for both years, but fall emigration only in fall 2023) were only observed through the southern exit through the Strait of Juan de Fuca. Migrants were non-significantly larger than residents. Similarly, Chamberlin *et al.* (2011) found that CWT release groups with larger mean size were more likely to be residents.

Survival was higher in late winter than early winter, suggesting that mortality mechanisms may be stronger in early winter. However, detection histories still need to be run through a mark-recapture CJS model to properly disentangle differential survival and dispersal mechanisms. For example, localization to the Cape Lazo array was likely more common in late winter, increasing the likelihood

that tags alive in late winter were detected. Despite most detections not being available for 2023-24, survival was higher for the September and October 2023 release groups than October 2022. The September and October 2023 release groups were both larger than the October 2022 release group. Chinook salmon that entered the ocean in 2022 experienced a harsh spring and an extended fall drought in British Columbia, likely leading to the observed small body sizes. This may suggest a cohort-level link between body size and migration strategies.

Testing assumptions of the Bottlenecks Project

The Bottlenecks to Survival Project captures and PIT tags thousands of Chinook salmon in their first ocean fall and winter in the Strait of Georgia. Sampling is limited to the Strait of Georgia, However, the PIT survival study assumes that the overwinter tagging period is representative of all migration strategies. In winter 2022-23, all tagged salmon remained resident in the Salish Sea through the first ocean winter, suggesting that overwinter PIT tagging of Qualicum-Puntledge Chinook salmon was representative of Qualicum-Puntledge Chinook salmon that were present in the Strait of Georgia in the fall.

Three fish tagged in fall 2023 were detected emigrating through the Strait of Georgia in the fall, on a sparse array deployed by DFO. Detections from the OTN Juan de Fuca array which monitors the entire Strait of Juan de Fuca as a movement gate (Figure 1) are not yet available, meaning that fall migrant numbers may be higher. To test if the assumption that migrants and residents are similar (*i.e.*, no size-selective emigration), we will compare individual traits like body size and early marine growth between residents and migrants tagged in winter 2023-24 when sufficient detection data are available.

Acoustic tagging in winters 2022-23 and 2023-24 highlighted that a meaningful contingent of the Qualicum-Puntledge fall Chinook salmon stock remains resident in the Strait of Georgia through their first ocean winter. There was a large pulse of second ocean year migrants through Queen Charlotte Strait in spring and summer 2023. Survival was higher in early winter, particularly in fall 2023. Acoustic tags remain active as long as summer 2026 and will continue to develop a time series of juvenile and subadult Chinook salmon movements within and away from the Strait of Georgia. An improved understanding of juvenile Chinook salmon marine migrations is important for studies testing important questions about overwinter mortality.

ACKNOWLEDGEMENTS

This study was funded in part by the British Columbia Salmon Restoration and Innovation Fund (Fisheries and Oceans Canada, Province of British Columbia), as part of the Bottlenecks to Survival Project. Vessel time for the initial year of tagging was funded through the Winter Ecology component of BCSRIF 2019-2040 (see Winter Ecology Synthesis Report) with tags and extensive additional support provided in kind by DFO Science and Stock Assessment. Primary funding for the second year of tagging and ongoing receiver array maintenance is being provided through BCSRIF 2022-456. Lucia Ferreira (LGL Ltd.) was the tagger in October 2022 and trained WG and KI in tagging methods. We thank Jake Dingwall (PSF), Nicole Christiansen (PSF), Paulina Salinas Ruiz (PSF), Chloe Kraemer (UVic), and Avril Hann (UVic) for joining tagging field days. Tags were detected by receivers deployed by Ocean Tracking Network, Fisheries and Oceans Canada, Kintama Research Services, Hornby Island Diving, Underwater Harvesters Association, British Columbia Conservation Foundation, NOAA Northwest Fisheries Science Centre, Ocean Networks Canada, and the University of British Columbia. We are grateful for the extensive work done to deploy and maintain these arrays. WG received graduate student support from Mitacs Accelerate, Pacific Salmon Foundation, NSERC, and the University of Victoria.

REFERENCES

Arostegui, M.C., J.M. Smith, A.N. Kagley, D. Spilsbury-Pucci, K.L. Fresh, and T.P. Quinn. 2017. Spatially clustered movement patterns and segregation of subadult Chinook salmon within the Salish Sea. Mar. Coast. Fish. 9, 1-12.

Beamish, R.J., R.M. Sweeting, K.L. Lange, and C.M. Neville. 2011. Changes in the population ecology of hatchery and wild coho salmon in the Strait of Georgia. Trans. Am. Fish. Soc. 137, 503-520.

Beamish, R., and C. Neville. 2021. The natural regulation and relevance of wild and hatchery coho salmon production in the Strait of Geogia. Fisheries 46, 539-551.

Chamberlin, J. W., T.E. Essington., J.W. Ferguson, and T.P. Quinn. 2011. The influence of

hatchery rearing practices on salmon migratory behaviour: is the tendency of Chinook Salmon to

remain within Puget Sound affected by size and date of release? Trans. Am. Fish. Soc. 140, 1398-1408.

Cone, R.S. 1989. The need to reconsider the use of condition indices in fishery science. Trans. Am. Fish. Soc. 118, 510-514.

Dudgeon, C.L., K.H. Pollock, J.M. Braccini, J.M. Semmens, and A. Barnett. 2015. Integrating acoustic telemetry into mark-recapture models to improve the precision of apparent survival and abundance estimates. Oecologica 178, 761-772.

Duguid, W.D.P., and Juanes, F. 2017. Microtrolling: an economical method to nonlethally sample and tag juvenile Pacific salmon at sea. Trans. Am. Fish. Soc. 146, 359-369.

Liedtke, T.L., J.W. Beeman, and L.P. Gee. 2012. A standard operating procedure for the surgical implantation of transmitters in juvenile salmonids. United States Geological Survey, Open-File Report 2012-1267.

Greentree, W. W. Duguid, K. Innes, J. Atkinson, and F. Juanes, 2023. Preliminary movements patterns of acoustic tagged juvenile Chinook salmon in the northern Strait of Georgia, winter 2022/23. Report to British Columbia Salmon Restoration and Innovation Fund.

Freshwater, C., S.C. Anderson, T.D. Beacham, W. Luedke, C. Wor, and J. King. 2021. An integrated model of seasonal changes in stock composition and abundance with an application to Chinook salmon. PeerJ 9, e11163.

Freshwater, C., C.K. Parken, S. Tucker, A. Velez-Espino, and J. King. 2022. Nonstationary patterns in demographic traits covary with Chinook salmon marine distributions. Can. J. Fish. Aquat. Sci. 79, 1860-1878.

Healey, M.C. 1976. Herring in the diets of Pacific salmon in the Georgia Strait. Fish. Res. Bd. Can. MS Rep. No. 1382.

Healey, M.C., and W.R. Heard. 1984. Inter- and intra-population variation in the fecundity of Chinook

salmon (Oncorhynchus tshawytscha) and its relevance to life history theory. Can. J. Fish. Aquat. Sci. 476, 476-483.

Kagley, A.N., J.M. Smith, K.L. Fresh, K.E. Frick, and T.P. Quinn. 2017. Residency, partial migration, and late egress of subadult Chinook salmon (Oncorhynchus tshawytscha) and coho salmon (O. kisutch) in Puget Sound, Washington. Fish. Bull. 115, 544-555.

Neville, C.M., R.J. Beamish, and C.M. Chittenden. 2015. Poor survival of acoustically-tagged juvenile Chinook salmon in the Strait of Georgia, British Columbia, Canada. Trans. Am. Fish. Soc. 144, 25-33.

O'Neill, S.M., and J.E. West. 2009. Marine distribution, life history traits, and the accumulation of polychlorinated biphenyls in Chinook salmon from Puget Sound, Washington. Trans. Am. Fish. Soc. 138, 616-632.

Quinn, T.P. 2021. Differential migration in Pacific salmon and trout: patterns and hypotheses. Anim. Migr. 8, 1-18.

Quinn, T.P., and J.P. Losee. 2022. Diverse and changing use of the Salish Sea by Pacific salmon, trout, and char. Can. J. Fish. Aquat. Sci. 79, 1003-1021.

Rechisky, E.L., A.D. Porter, D.W. Welch, and W. Duguid. 2019. Mortality, movements, and migration timing of age-0 Cowichan Chinook salmon tagged in the southern Gulf Islands in fall 2017. Final report to the Pacific Salmon Foundation and the Salish Sea Marine Survival Project.

Satterthwaite, W.H., M.P. Beakes, E.M. Collins, D.R. Swank, J.E. Merz, R.G. Titus, S.M. Sogard, and M. Mangel. 2009. Steelhead life history on California's Central Coast: insights from a state-dependent model. Trans. Am. Fish. Soc. 138, 532-548.

Smith, J.M. K.L. Fresh, A.N. Kagley, and T.P. Quinn. 2015. Ultrasonic telemetry reveals seasonal variation in depth distribution and diel vertical migrations of sub-adult Chinook and coho salmon in Puget Sound. Mar. Ecol. Prog. Ser. 532, 227-242.

Thorpe, J.E., M. Mangel, N.B. Metcalfe, F.A. Huntingford. 1998. Modelling the proximate basis of salmonid life-history variation, with application to Atlantic salmon, Salmo salar L. Evol. Eco. 12, 581-599.

Tucker, S., Trudel, M., Welch, D.W., Candy, J.R., Morris, J.F.T., Thiess, M.E., Wallace, C.E., and Beacham, T.D. Life history and seasonal stock-specific ocean migration of juvenile Chinook salmon. Trans. Am. Fish. Soc. 140, 1101-1119.

Weitkamp, L.A. 2011. Marine distributions of Chinook salmon from the west coast of North America determined by coded wire tag recoveries. Trans. Am. Fish. Soc. 139, 147-170.

Welch, D.W., M.C. Melnychuk, J.C. Payne, E.L. Rechisky, A.D. Porter, G.D. Jackson, B.R. Ward, S. P. Vincent, C.C. Wood, and J. Semmens. 2011. In situ measurement of coastal ocean movements and survival of juvenile Pacific salmon. Proc. Nat. Acad. Sci. USA. 21, 8709-8713.

APPENDIX

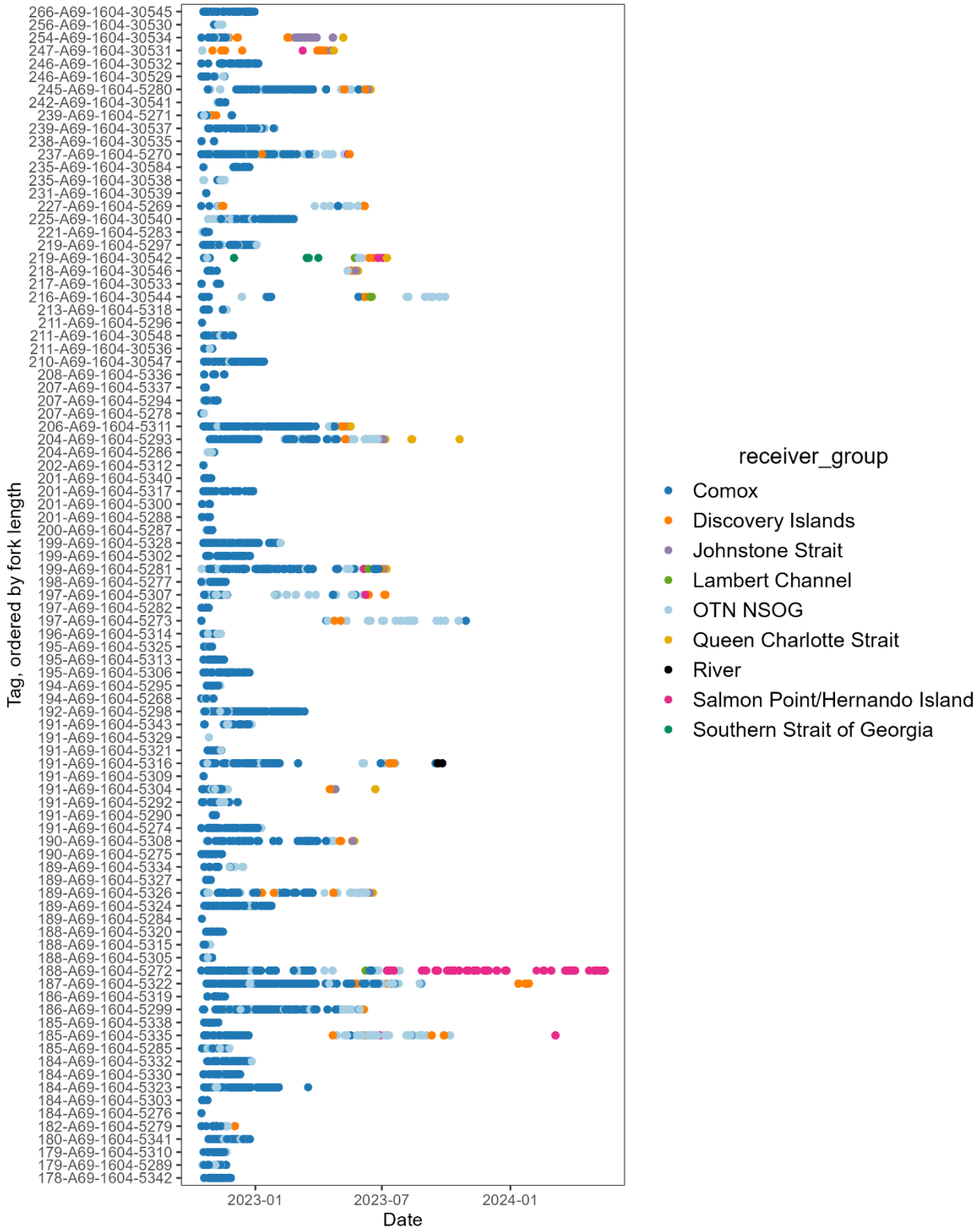


Figure A1. October 2022 abacus plot.

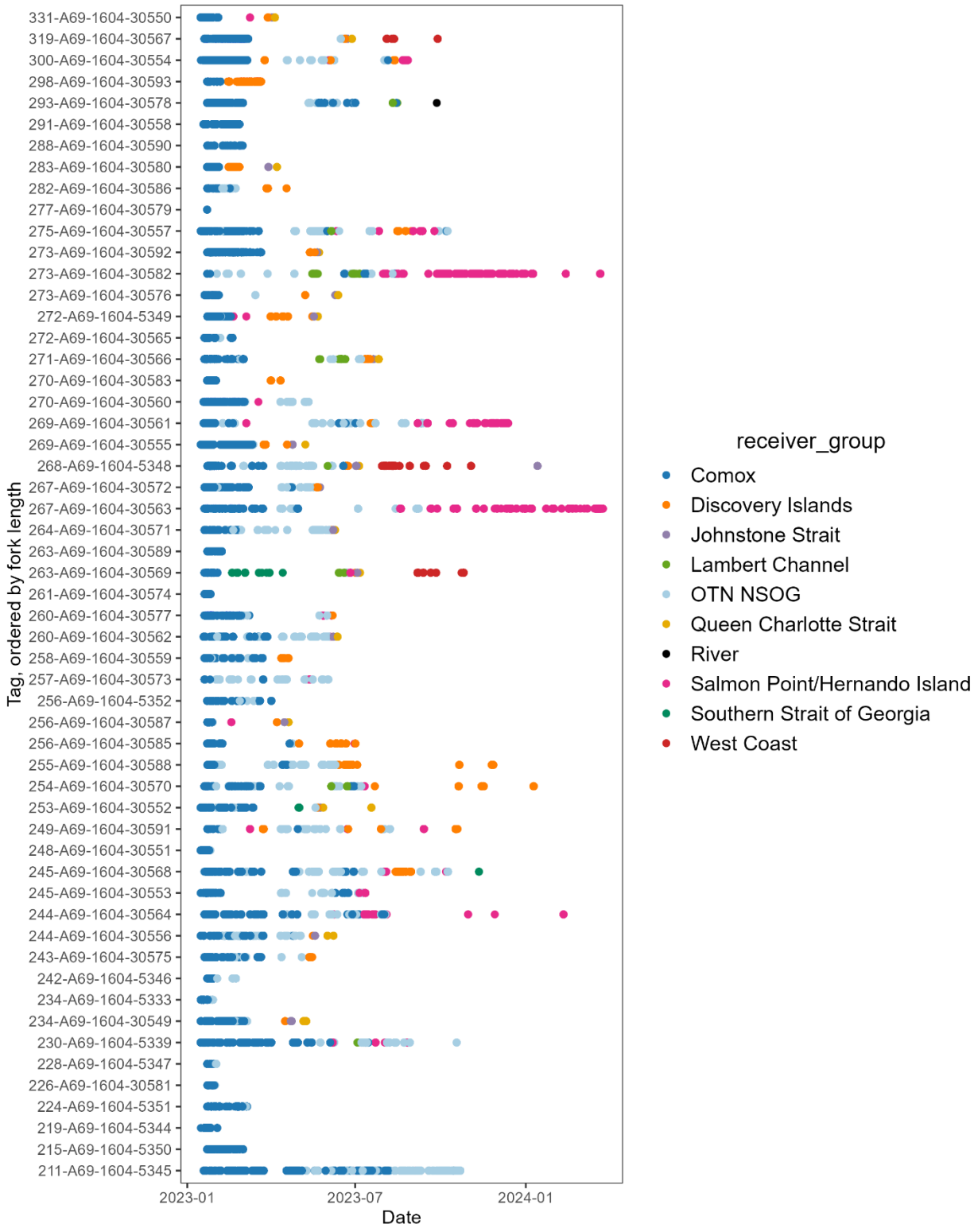


Figure A2. January 2023 abacus plot

Figure A3. September 2023 abacus plot.

Figure A4. October 2023 abacus plot.

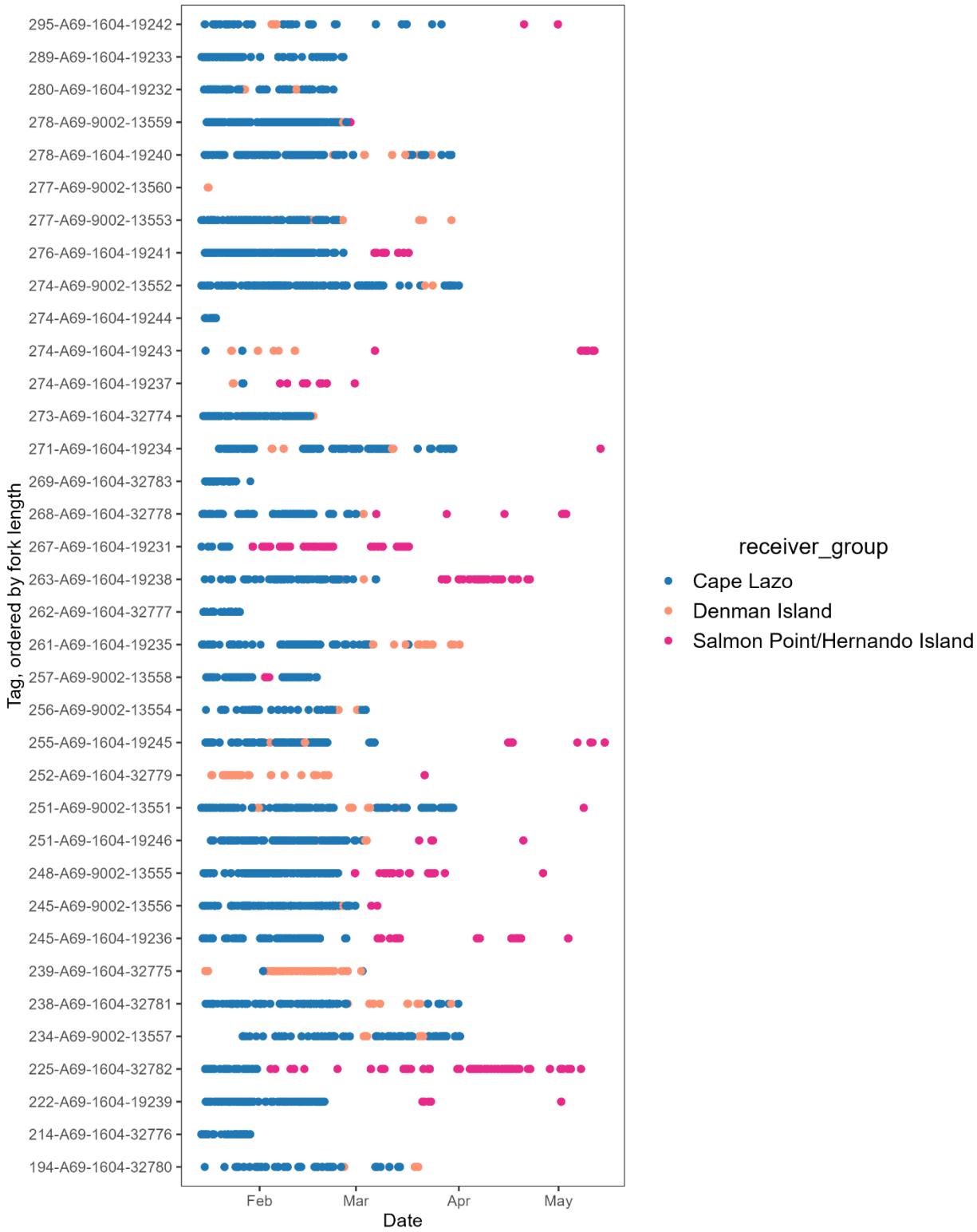


Figure A5. January 2024 abacus.

PACIFIC SALMON FOUNDATION

BRITISH COLUMBIA CONSERVATION FOUNDATION

University of Victoria

Fisheries and Oceans Canada | Pêches et Océans Canada

Funding for this project is provided by the BC Salmon Restoration and Innovation Fund, a contribution program funded jointly between Fisheries and Oceans Canada and the Province of BC.