

MANAGEMENT BRIEF

Exposure Time of Wild, Juvenile Sockeye Salmon to Open-Net-Pen Atlantic Salmon Farms in British Columbia, Canada

Erin L. Rechisky*  and Aswea D. Porter 

Kintama Research Services, 4737 Vista View Crescent, Nanaimo, British Columbia V9V 1N8, Canada

Stephen D. Johnston

Pacific Salmon Ecology and Conservation Laboratory, Department of Forest and Conservation Sciences, University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada

Christine F. Stevenson 

Pacific Salmon Ecology and Conservation Laboratory, Department of Forest and Conservation Sciences, University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada; and Fisheries and Oceans Canada, 401 Burrard Street, Suite 200, Vancouver, British Columbia V6C 3L6, Canada

Scott G. Hinch

Pacific Salmon Ecology and Conservation Laboratory, Department of Forest and Conservation Sciences, University of British Columbia, 2424 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada

Brian P. V. Hunt 

Institute for the Oceans and Fisheries, University of British Columbia, 2202 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada; Department of Earth, Ocean, and Atmospheric Sciences, University of British Columbia, 2207 Main Mall, Vancouver, British Columbia V6T 1Z4, Canada; and Hakai Institute, Post Office Box 25039, Campbell River, British Columbia V9W 0B7, Canada

David W. Welch 

Kintama Research Services, 4737 Vista View Crescent, Nanaimo, British Columbia V9V 1N8, Canada

Abstract

The role that open-net-pen farms for Atlantic Salmon *Salmo salar* play in the global decline of stocks of wild salmonids (*Salmo* spp. and *Oncorhynchus* spp.) is contentious; Canada's west coast is no exception. We identified the proportion of acoustic-tagged juvenile Sockeye Salmon *Oncorhynchus nerka* migrating through the main migration routes of the Discovery Islands region of British Columbia and measured both residence time in a major waterway hosting several Atlantic Salmon farms and exposure times to individual farms. One-third of tagged fish migrated through this channel, with median residence times of 32.6 h in 2017 and 46.0 h in

2018. The median time near individual farms was 4.4 min in 2017 when farms were fallow and 10.9 min in 2018 when farms were stocked. The increase in 2018 was probably not caused by farm activity because the proportion of total time spent in the channel was the same across years. Sockeye Salmon used all major migration pathways, but the lack of farms and rapid migration speeds in the westernmost passage offers the lowest potential exposure to fish farms. These are the first individual-level data available to inform assessments of the transmission risk of infectious agents from farms to wild salmonids.

*Corresponding author: erin.rechisky@kintama.com
 Received July 17, 2020; accepted December 19, 2020

Aquaculture of Atlantic Salmon *Salmo salar* is one of the most profitable and technologically advanced fish production industries globally (FAO 2020). Currently about 98% of global salmonid production comes from open-net-pen systems in nearshore marine environments (DFO 2019). Open-net-pen systems are considered a high-risk aquaculture method because the potential flow of disease, parasites, and chemicals from the pens to wild fish may reduce survival (Ford and Myers 2008). In the Atlantic Ocean, hybridization of wild Atlantic Salmon with escaped farmed salmonids may lead to reduced reproductive success (Glover et al. 2017).

There are approximately 20 open-net-pen Atlantic Salmon farm tenures in the Discovery Islands region of British Columbia, which is a major corridor used by juvenile Pacific salmon *Oncorhynchus* spp. migrating from rivers to the south (Figure 1). About half of these farms may be active in any given year (<http://www.dfo-mpo.gc.ca/aquaculture/bc-aquaculture-cb-eng.html>). Although many infectious agents are naturally occurring in British Columbia salmonids (Jia et al. 2020), Atlantic Salmon farms have been identified as a potential contributor to the decline of Fraser River salmonid stocks through increased transfer of sea lice, bacteria, and viruses (Price et al. 2010; Kent 2011; Godwin et al. 2017). Short time series, however, have limited the statistical power to detect relationships between salmonid survival and pathogen or parasite variables (Connors 2011; Korman 2011).

A federal commission of inquiry into the decline of Sockeye Salmon *Oncorhynchus nerka* recommended that open-net-pen aquaculture lying on the migration routes of juvenile Sockeye Salmon be shut down by September 2020 “if, by that date, DFO (Fisheries and Oceans Canada) cannot confidently say the risk of serious harm [to salmon] is minimal” and that “DFO should explicitly consider proximity to migrating Fraser River sockeye when siting salmon farms” (Cohen 2012). Three first-order knowledge gaps must be filled to address these recommendations: (1) identifying the major migration routes through the Discovery Islands, (2) determining the proportion of the population that uses routes where salmon farms are sited, and (3) measuring the time spent near salmon farms. Together these metrics determine the degree of exposure to farms and can help inform risk analyses and assessment for Fraser River Sockeye Salmon and other stocks. Although sampling programs and previous tracking studies have demonstrated that Sockeye Salmon migrate via routes known to include salmon farms (Neville et al. 2016; Johnson et al. 2019; Stevenson et al. 2019) and travel rates have been reported on a broader scale (Clark et al. 2016; Rechisky et al. 2018), precise information on residence and exposure time near farms is lacking.

Fraser River Sockeye Salmon enter the Strait of Georgia in spring (April and May) and generally migrate north

upon ocean entry reaching the Discovery Islands in May and June (Groot and Margolis 1991; Welch et al. 2009; Neville et al. 2016; Johnson et al. 2019). The exception is Harrison River Sockeye Salmon that enter the Strait of Georgia later, remain in the strait longer than the other stocks, and then use Juan de Fuca Strait or the Discovery Islands to exit the Strait of Georgia; the proportion and exit timing of the Harrison River population is currently unknown (Beacham et al. 2014). Stevenson et al. (2019) provided evidence that acoustic-tagged juvenile Sockeye Salmon from Chilko Lake were widespread throughout the Discovery Islands during their migration. We explore this topic further by focusing on migration at a finer scale.

The objectives of our study were to identify migration routes of acoustic-tagged juvenile Sockeye Salmon through the Discovery Islands, to measure residence time in the Discovery Islands and in Okisollo Channel (a major waterway with several farms in the Discovery Islands), and to estimate the degree of exposure (time) to Atlantic Salmon farms to help quantify the risk from potential infectious agents. In 2017, the first year of this study, all fish farms in the core study area (Hoskyn and Okisollo channels) were fallow (i.e., farms were not stocked); however, in 2018 most farms in this area were active. In 2018 we also expanded the geographic scope of the acoustic receiver array to refine our understanding of the migration route use of tagged salmonids, and we increased the number of farms equipped with receivers. These provide the first direct measurements of juvenile Sockeye Salmon movement speeds in the vicinity of open-net-pen Atlantic Salmon farms in the Discovery Islands region, which are necessary for understanding the potential interaction between migrating salmonids and salmon farms in British Columbia. Ideally these data could be coupled with existing circulation models for the Discovery Islands (Foreman et al. 2012) to explore the vulnerability of wild Sockeye Salmon to waterborne infectious agents originating from salmon farms, as suggested in Foreman (2015).

METHODS

Smolt collection and tagging.—In 2017, juvenile Sockeye Salmon were captured in Chilko Lake, British Columbia (“lake-tagged” fish), in the Fraser River basin and in Okisollo Channel in the Discovery Islands (“marine-tagged” fish; Figure 1; Table 1). Lake-tagged juveniles were collected from the Fisheries and Oceans Canada enumeration fence as they migrated out of Chilko Lake, surgically implanted with acoustic transmitters, and released back to the river the evening after tagging. The distance to the Discovery Islands is ~850 km. The juvenile migration ran from approximately April 18 to May 16, 2017 (T. Cone, Fisheries and Oceans Canada, personal communication) and tagging occurred from April 24 to May 3, which

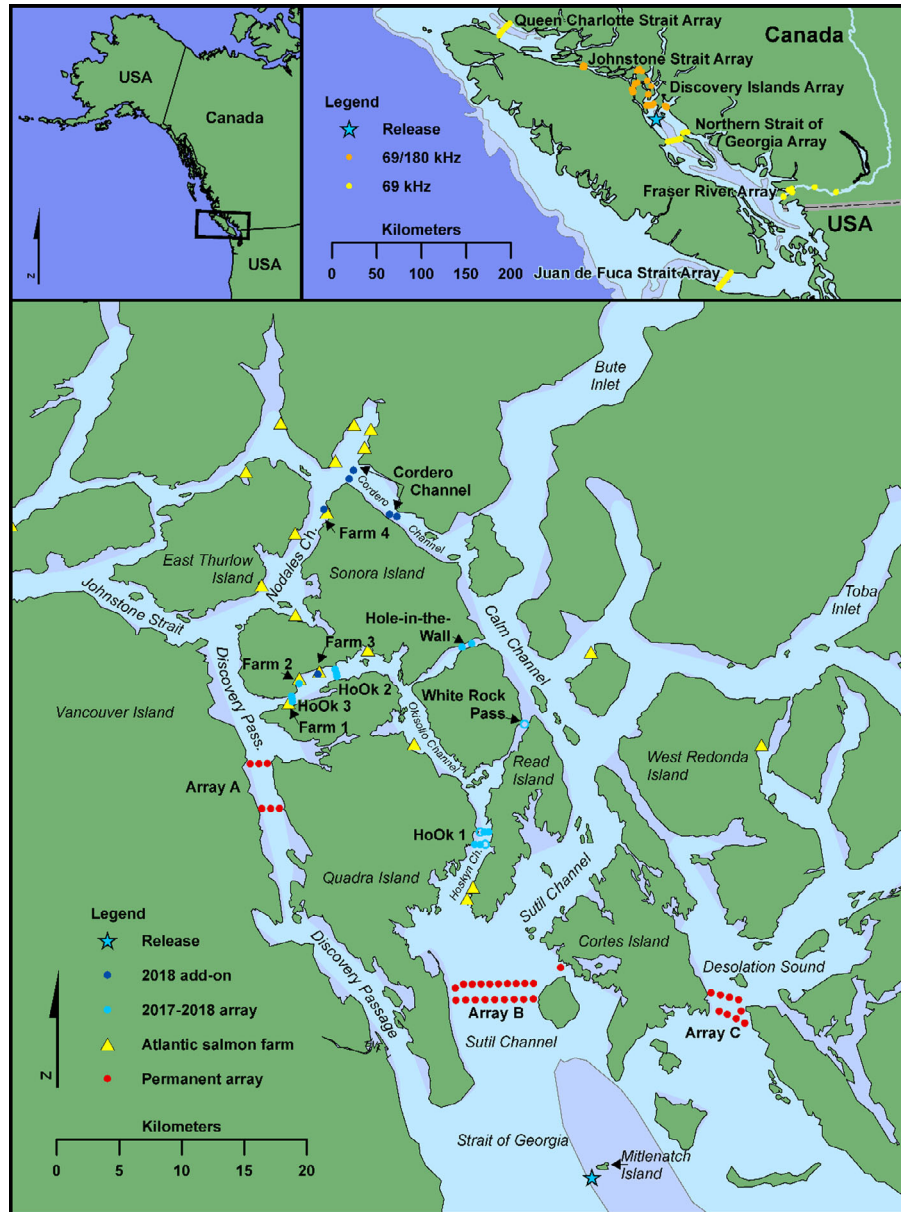


FIGURE 1. Map of the acoustic array in 2017 and 2018. Not shown are a few individual receivers also capable of detecting 180-kHz tags on the northern Strait of Georgia and Juan de Fuca Strait arrays, which were not used in this study. Open circles indicate receivers lost in 2017; all receivers were successfully recovered in 2018. The Chilko Lake release site in the Fraser River basin is not shown. Abbreviations are as follows: HoOk = Hoskyn–Okisollo Channel.

overlapped with the peak migration and ~67% of the total outmigration. In Okisollo Channel, migrating juveniles were captured using a small seine net, surgically implanted with an acoustic transmitter, transported south ~53 km, and released into the northern Strait of Georgia. Fish collection occurred from June 9 to June 21; tagging coincided with the peak CPUE and the latter part of the juvenile Sockeye Salmon migration through the Discovery Islands

(Johnson et al. 2019). The fish were implanted with Inno-vasea (previously VEMCO; Bedford, Nova Scotia) V7-2L transmitters (69 kHz, 7 mm in diameter, 18 mm in length, 1.6 g in air, random transmission interval between 20 and 40 s, estimated tag life 79 d) or V4-1H transmitters (180 kHz, 3.6 mm in height, 5.7 mm in width, 11 mm in length, 0.42 g in air, random transmission interval between 15 and 35 s, estimated tag life 38, 43, or 46 d depending on length

of a programmed “off” period during downstream migration).

In 2018, juveniles were captured only in Okisollo Channel following the methods used the previous year. Fish collection occurred May 24 to June 22, which was 2 weeks earlier than in 2017 but again coincided with the peak CPUE (May 23) and the latter part of the juvenile Sockeye Salmon migration (see Johnson et al. 2019 for migration timing). They were implanted with V7-2L transmitters (as in 2017 except with a random transmission interval of 18–24 s and estimated tag life 60 d) or V5-1H transmitters (180 kHz, 4.3 mm in height, 5.6 mm in width, 12.7 mm in length, 0.65 g in air, random transmission interval of 10–14 s, estimated tag life of 41 d). We reduced the transmission interval in 2018 because it was not necessary to conserve battery power given the reduced size of the study area that year. Sample sizes at release in Chilko Lake and in the Discovery Islands, fish sizes, and tag burdens are summarized in Table 1. Details of the tagging procedure are described elsewhere (Clark et al. 2016; Rechisky et al. 2018; Stevenson et al. 2019).

In 2017, genetic stock identification was used to determine that the majority of fish captured in Okisollo Channel originated from Chilko Lake (88% of sample with stock probability >60%). In 2018, biological samples were not collected in order to reduce handling, so stock origin was not determined.

Acoustic array.—In 2015, we deployed long-term receiver arrays near the entrance to the Discovery Islands in Discovery Passage (array A), Sutil Channel (array B), and Desolation Sound (array C) and 69 km north of array A in Johnstone Strait to assess migration route and travel time through the Discovery Islands (Figure 1). These receivers remained in place throughout the study. In 2017, we deployed three short-term receiver arrays: one in a central

subroute of the Discovery Islands (Hoskyn Channel, leading to Okisollo Channel; HoOk 1–3) and the others in two small pathways connecting major subroutes (White Rock Pass and Hole-in-the-Wall). We also deployed single receiver moorings within two fallowed Atlantic Salmon farm tenures in Okisollo Channel: Brent Island farm (farm 1) and Venture Point farm (farm 2). A tenure is aquatic Crown land leased to the salmon farming corporations by the province of British Columbia for the purpose of anchoring the surface and subsurface infrastructure. Farm 1 also formed a component of the HoOk 3 array described above. In 2018, we redeployed receivers at all 2017 locations, added an additional short-term array in the easternmost subroute (Cordero Channel), and deployed single receiver moorings within two additional farm tenures: Sonora Island farm (in Okisollo Channel; farm 3) and Sonora Point farm (in Nodales Channel; farm 4). Tenure receivers were placed about 90–200 m from the net-pens. Fish detection range was assumed to be ~80 m for 180-kHz tags and ~300 m for 69-kHz tags (Rechisky et al. 2020). All receiver moorings were successfully recovered in both years except for White Rock Passage in 2017. Prior to analysis, we screened all data for false detections (see Rechisky et al. 2018).

Migration routes.—We used the temporal sequence of detections to identify migration routes. The main routes describe how fish entered the Discovery Islands region through the passages monitored by arrays A through C (Figure 1). We used the last detection on these arrays to define their route (e.g., if a fish was detected on array B and then array A, its route was assigned as array A). The subroutes describe how the fish continued northward migration via (1) Hoskyn and Okisollo channels or (2) Calm and Cordero channels to the east before eventually reaching Johnstone Strait (if they survived). Fish that

TABLE 1. Tagging summary of wild Sockeye Salmon smolts. Groups were either tagged and released at the mouth of Chilko Lake (Fraser River basin) and allowed to freely migrate ~850 km to the study site or captured and tagged in the marine waters of Okisollo Channel and released in the northern Strait of Georgia. Age indicates the number of years spent in freshwater prior to the onset of seaward migration. Acoustic tags were either V4-1H transmitters (180 kHz, 3.6 mm high, 5.7 mm wide, 11 mm long, 0.42 g in air), V7-2L transmitters (69 kHz, 7 mm in diameter, 18 mm long, 1.6 g in air), or V5-1H transmitters (180 kHz, 4.3 mm high, 5.6 mm wide, 12.7 mm long, 0.65 g in air). The tag burden is the tag mass as a percent of the fish mass.

Year	Group	Tag type	N released	Release dates	Median FL in mm (range)	Tag burden (range)	N detected in Discovery Islands
2017	Chilko Lake, age 1	V4	155	Apr 24–May 4	86.0 (79–95)	8.4 (7.0–10.5)	35
	Chilko Lake, age 2	V4	76	Apr 24–May 3	128.5 (121–137)	2.6 (2.2–2.8)	22
	Chilko Lake, age 2	V7	75	Apr 24–May 3	128.0 (122–140)	9.9 (7.3–10.7)	17
	Marine	V4	58	Jun 19–21	122.5 (103–140)	2.3 (1.6–4.2)	15
2018	Marine	V5	100	May 25–Jun 22	125.0 (105–140)	3.6 (2.6–6.3)	76
	Marine	V7	50	May 25–Jun 22	143.5 (131–190)	5.7 (2.0–7.7)	40

entered the Discovery Islands over array A in Discovery Passage were assumed to have continued north in that channel. In 2017, there were no receivers deployed in Cordero Channel so we assigned that route to fish that crossed array B or array C and then were not detected in other channels in the Discovery Islands area (i.e., we assigned fish that were not detected to the only route without detectors). This was not a concern in 2018 when receivers were deployed in Cordero Channel. A number of individuals also used White Rock Passage and Hole-in-the-Wall waterways to transition between Hoskyn Channel and Calm Channel (the channel leading to Cordero Channel; see Figure 1). Fish that reached Johnstone Strait without prior detection were assigned a migration route of “unknown.” Finally, a large number of marine-tagged fish that crossed array B (directly north of their release site) were not detected again (51%). We assume that these fish died somewhere between array B and the Cordero Channel arrays (route = Calm-Cord [mort]), presumably as a result of handling and tagging or predation. Some other minor assumptions were necessary because detection efficiency through the array was not perfect, but these affected only a few individuals (see Supplement 1 in the online version of this article). For the route use analyses, fish were grouped by treatment, i.e., lake-tagged fish (in 2017) and marine-tagged fish (2017 and 2018). We calculated uncertainty as the standard error of a proportion:

$$SE = \sqrt{\frac{p(1-p)}{N}}.$$

Residence time.—We calculated overall residence time in the Discovery Islands as the first detection on arrays A, B, or C to the last detection on the northern (Johnstone Strait) array. We also calculated residence time between the HoOk arrays. First, we calculated the time interval between the first detection on HoOk 1 and the last detection on the HoOk 2 (~20 km; Figure 1). There are two fish farm tenures in that segment: both were fallow in 2017 and one was stocked in 2018 (neither was instrumented with acoustic receivers). Second, we calculated the time interval between HoOk 2 and HoOk 3 (4 km). There are three fish farm tenures in this short segment: all were fallow in 2017 (two were instrumented with acoustic receivers) and all were stocked in 2018 (all were instrumented with acoustic receivers). Finally, we calculated the time interval between HoOk 1 and HoOk 3 to quantify the overall residence time in this major migratory route with potential exposure to five fish farms in 24 km. Whereas route use was grouped by treatment type, the residence and exposure time analyses were grouped by year.

Exposure to individual Atlantic Salmon farms.—We calculated exposure time to individual Atlantic Salmon farms as the interval between the first and last detections of each

fish at each instrumented farm tenure within a passage event. A new passage event was defined if there was a 15-min silent interval between successive detections. When multiple passage events occurred, they were summed for each individual at each farm site. Fish detected only once near a farm tenure ($n=4$ in 2017; $n=7$ in 2018) were assigned an exposure time equivalent to the minimum tag transmission interval (10 to 20 s depending on tag type). Tag types were pooled to calculate summary statistics because there was no difference in exposure time by tag type in 2018 (Wilcoxon rank-sum test: $P \geq 0.11$ for individual farm tenures; not tested in 2017 because only two 69-kHz tags were detected at each tenure). Farms used in exposure calculations were fallow in 2017 and stocked in 2018.

Effect of farm stocking.—To assess whether residence time and exposure time were related to farm status (stocked with Atlantic Salmon versus not stocked), we evaluated the proportion of time in Okisollo Channel (HoOk 2 to HoOk 3) relative to the broader residence time between the Hoskyn (HoOk 1) and Johnstone Strait arrays in each year. Relative residence times account for interannual variation in absolute residence times that might stem from differences in study design and environmental conditions between the years rather than from farm status (e.g., fish length, Sockeye Salmon population, handling). As there are three farms between HoOk 2 and HoOk 3, travel time through this area (4 km) could be considered a broader estimate of cumulative exposure than simply summing the times spent in close proximity to each farm. Using the residence time in Okisollo Channel rather than the exposure time near individual salmon farms also minimizes the effect of differences in transmitter detection range on the comparison (the 69-kHz tags have a greater detection range [~300 m] than the 180-kHz tags [~80 m]).

We hypothesized that fish would spend a greater proportion of their overall migration in Okisollo Channel if they were attracted to active salmon farms due to the release of commercial pellets or because the farm may act as a fish-aggregating device (Dempster et al. 2010; Callier et al. 2018). Because sample sizes were small and travel time data were right-skewed, we used a bootstrap procedure to test if the proportion of time in Okisollo Channel differed by year (i.e., by the farm’s operational status). Only three marine-tagged fish were detected at all sites in 2017 and were excluded from the bootstrap simulation. Specifically, for both years and both segments, we resampled the travel time estimates 1,000 times with replacement, each time drawing a random sample of the same size as the original (using R; R Core Team 2019). We then calculated the median travel time for each sample, matched these medians for the two segments by sample number, and calculated the proportion of time spent in Okisollo Channel.

RESULTS

Main Routes through the Discovery Islands

Of the three major channels, the central route (Sutil Channel) was most often used by tagged Sockeye Salmon (Figure 2). Forty-six percent of lake-tagged Sockeye Salmon ($SE = 5.5\%$) were detected on array B in Sutil Channel, followed by array A to the west (Discovery Passage: 27%, $SE = 4.9\%$; but see Supplement 3 in the online version of this article and Discussion below for information on transmitter expiry for age-1 fish in 2017) and array C to the east (Desolation Sound: 17%, $SE = 4.2\%$). The route of 10% of the lake-tagged Sockeye Salmon was unknown because they were detected on the Johnstone Strait array to the north but on none of the southern arrays. The majority (60%, $SE = 4.1\%$) of marine-tagged Sockeye Salmon also migrated via Sutil Channel directly north of release, with most of the remainder using Discovery Passage (25%, $SE = 3.6\%$). Only 7% ($SE = 2.2\%$) used Desolation Sound, and the route of 8% was unknown. A dynamic animation of the juvenile Sockeye Salmon movements is available at <http://kintama.com/visualizations/>.

Subroutes through the Discovery Islands

Lake-tagged Sockeye Salmon used a variety of subroutes, which we summarize in Figure 2. Overall, one-third of lake-tagged fish migrated through Okisollo Channel (33%, $SE = 5.2\%$) and nearly one-third (28%, $SE = 5.0\%$) used Calm–Cordero Channel; the remainder were unknown or they used Discovery Passage so they did not encounter subroutes (see Main Routes through the Discovery Islands above). Several fish moved from Calm–Cordero Channel to Okisollo Channel via Hole-in-the-Wall. Of the marine-tagged Sockeye Salmon, 18% ($SE = 3.2\%$) migrated through Okisollo Channel and 50% ($SE = 4.2\%$) entered or used Calm–Cordero Channel; the remainder were unknown or they used Discovery Passage so they did not encounter subroutes (Figure 2).

Sockeye Salmon Arrival and Residence Time in the Discovery Islands

Lake-tagged Sockeye Salmon reached the Discovery Islands arrays from May 19 to July 1, 2017, and reached Johnstone Strait from May 31 to July 3, 2017 (see Table 1 for release dates and Figure 3 for distances). Of those detected on Johnstone Strait, 50% were detected by June 12 and 95% were detected by July 1. Arrival times for 2018 are not reported because fish were captured in Okisollo Channel and transported to the northern Strait of Georgia (i.e., first detection time on the Discovery Islands arrays following release is not indicative of natural arrival timing; see Methods for tagging dates relative to run timing).

The shortest, most direct, and likely the quickest route was via Discovery Passage. From array A to Johnstone Strait (70 km), median residence time was 1.7 d in 2017 and 2.8 d in 2018 (Figure 3A). Note, however, that array A is located in the northern section of Discovery Passage, so this residence time does not include an approximate 20-km section to the south. Migration routes to the east were longer and residence times increased. From array B to Johnstone Strait via all possible routes (~105 km), median residence time was 4.7 d in 2017 and 6.9 d in 2018. The longest route was via Desolation Sound (120 km), which also had several blind channels and inlets; from array C, Sockeye Salmon took 8.8 d (2017) and 11.6 d (2018) to reach Johnstone Strait. Aggregating over all migration routes, overall residence time in the Discovery Islands was generally longer in 2018 than in 2017 but with substantial overlap of the confidence intervals (median in 2017 = 4.9 d, interquartile range = 3.0–7.4 d; median in 2018 = 6.1 d, interquartile range = 4.1–8.5 d; not shown in Figure 3).

Residence Time in Hoskyn and Okisollo Channels

The median residence time spent in Hoskyn and Okisollo channels (HoOk 1 to HoOk 3) was 32.6 and 46.0 h in 2017 and 2018, respectively (Figure 3B; Table 1 in Supplement 2 in the online version of this article). From HoOk 1 to HoOk 2 (20 km), residence time was 28.6 h in 2017 and 38.8 h in 2018. From HoOk 2 to HoOk 3 (a 4-km reach with three farms), median residence time was 5.9 h in 2017 and 7.3 h in 2018.

Exposure to Individual Atlantic Salmon Farms and Effect of Farm Stocking

In 2017, of the fish that successfully migrated through Okisollo Channel, 42% were detected at one of the two instrumented farms and 35% were detected at both farms (total 77%). In 2018, all successful migrants were detected near at least one of three farms. Of these, 13% were detected at only one of the three instrumented farms, 55% were detected at two farms, and 32% were detected at all three farms.

The median time near an individual salmon farm in Okisollo Channel was 4.4 min in 2017 (4.2 min at farm 1, 4.5 min at farm 2) and 10.9 min in 2018 (10.9 min at farm 1, 12.2 min at farm 2, 8.4 min at farm 3) (Figure 3C; Table 2 in Supplement 2). Tagged fish were detected near the Nodales Channel farm (farm 4) for a median time of 15.5 min in 2018. Although the time near farms was longer in 2018, in both years Sockeye Salmon spent a median of 7.1% of their total travel time (from HoOk 1 to Johnstone Strait) in Okisollo Channel (Figure 3D). The distributions of the bootstrapped proportions by year overlapped extensively, indicating that the relative proportion of time spent near farms was similar regardless of status.

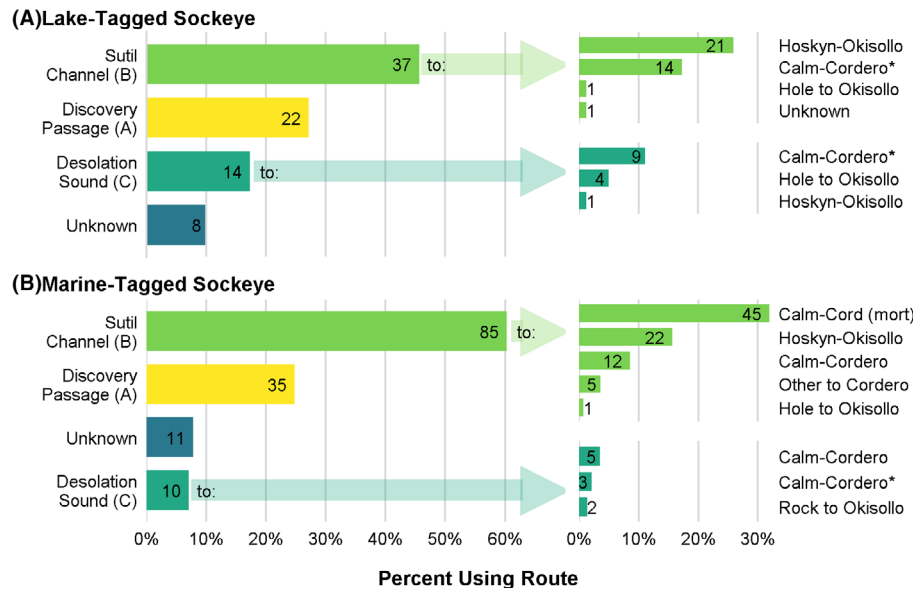


FIGURE 2. Main routes and subroutes through the Discovery Islands for (A) lake-tagged Sockeye Salmon and (B) marine-tagged Sockeye Salmon in 2017 and 2018 combined. There are no subroutes beyond Discovery Passage. Unknown fish were only detected on the Johnstone Strait array, so the prior migration route is uncertain. The numbers in the bars indicate the sample size. Abbreviations are as follows: Rock = White Rock Pass; Hole = Hole-in-the-Wall; Calm-Cordero* = smolts that were not detected on the HoOk arrays after crossing array B or array C and migrated into or through Calm and then Cordero channels where no receivers were deployed in that year; Calm-Cord (mort) = fish assumed to have entered Calm Channel but died; Other to Cordero = fish detected on Cordero that were first detected elsewhere (Hoskyn to Cordero, $n = 1$ route unknown; Hoskyn to Hole to Cordero, $n = 3$; Hoskyn to Rock to Cordero, $n = 1$).

DISCUSSION

The role of fish farms in contributing to the decline of wild salmonid stocks in an era of large-scale climate change is both controversial and challenging to rigorously test. An important step towards understanding wild-farmed fish interactions is determining the degree of exposure to farms that wild fish experience, which requires establishing both the travel routes and travel times of wild fish. Here we demonstrate that it is possible to develop rigorous metrics of exposure time directly in the wild for free-ranging fish, and we quantify the use of specific migration routes and the residence time of juvenile Sockeye Salmon in the Discovery Islands.

We found that lake-tagged Sockeye Salmon primarily entered the Discovery Islands region via Sutil Channel (46%; Figure 1). Given current farm tenure locations, fish taking this route have the highest potential for encountering salmon farms; fish may pass up to five salmon farms in Hoskyn and Okisollo channels and up to five in and beyond Cordero Channel, depending on the route taken. Few lake-tagged Sockeye Salmon entered Desolation Sound (one-sixth); however, the majority of these then migrated through Cordero Channel, where they could have encountered two to five farms. The remaining 27% used Discovery Passage, where Atlantic Salmon farms are absent.

Stevenson et al. (2019) also found that juvenile Chilk Lake Sockeye Salmon primarily migrated through the

western and central pathways in 2016 (arrays A and B, respectively). In our study, however, a smaller proportion of lake-tagged fish was detected on array A in Discovery Passage in 2017, which could be attributed to variability between years but also may be related to transmitter expiry. That is, Discovery Passage usage may have been somewhat underestimated in 2017 for lake-tagged age-1 Sockeye Salmon because the batteries in these small transmitters were nearing depletion (see Supplement 3). Age-1 juveniles reached the more distant array A an average of 6 d after age-1 juveniles reached array C, which may have reduced the detection of juveniles on array A. Overall, both studies demonstrate that the western and central routes appear to be used more often by juvenile Sockeye Salmon.

The majority of marine-tagged Sockeye Salmon migrated through Sutil Channel, but this group may not be truly indicative of major route use because they were initially captured in Okisollo Channel and then transported for release into the Strait of Georgia almost due south of array B in Sutil Channel. There were several advantages to capturing fish in Okisollo Channel rather than capturing and tagging fish in Chilk Lake. By tagging ocean-caught fish, the sample size on the Discovery Islands array was higher because loss of tagged fish to predation in freshwater was avoided, while mixed-stock tagging of ocean-caught juveniles expanded the scope of the

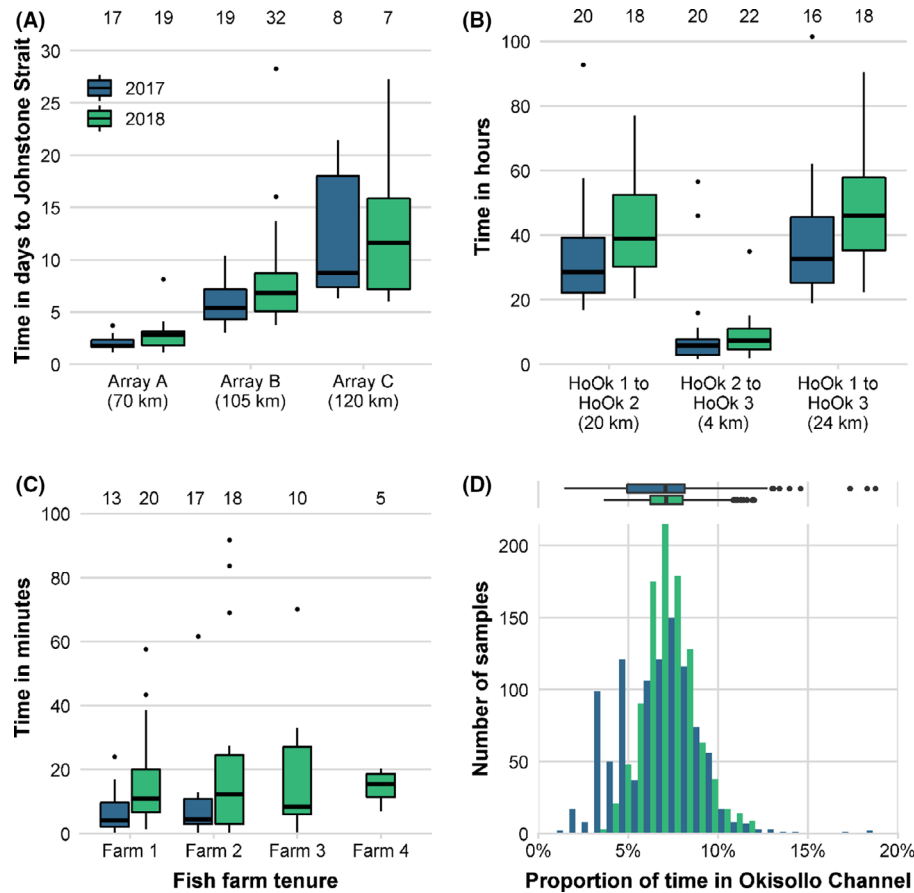


FIGURE 3. Travel time of wild Sockeye Salmon juveniles through (A) the Discovery Islands and (B) between Hoskyn and Okisollo (HoOk) arrays, (C) the exposure time to individual Atlantic Salmon farms, and (D) the proportion of time spent in Okisollo Channel relative to the time to migrate from the Hoskyn Channel array (HoOk 1) to the Johnstone Strait array. The central lines in each box show the median, the box dimensions show the interquartile range (central 50% of data points), the whiskers bracket 1.5 times the interquartile range, and the closed circles identify outliers.

study beyond solely Chilko Lake Sockeye Salmon. In addition, fish had an opportunity to grow for several additional weeks prior to tagging, allowing for the use of larger, more powerful, and longer-lived transmitters and reducing tag burdens for the larger fish. Smaller fish still received the smaller transmitters, but because the release location was nearer to the detection arrays, tag life was not an issue in 2018. Because the method of tagging and (particularly) release may have influenced subsequent route choice, the marine-tagged group was primarily used to inform residence and exposure time analyses.

Our results showed that tagged Sockeye Salmon, primarily from Chilko Lake, migrated through the Discovery Islands from late May to early July, which is consistent with survey data (Neville et al. 2016; Johnson et al. 2019); however, the residence time of individual juveniles was much shorter, indicating that migration is rapid and directional. No fish were detected migrating south in 2017, and only six were detected on a southern array (northern Strait of Georgia) after release in 2018. Most (75%) Sockeye

Salmon exited the northern end of the Discovery Islands within 7.4 d (2017) or 8.5 d (2018) after passing the detection arrays monitoring the southern entrance, despite encountering the strongest tidal currents in North America. Differences in the amplitude of the tides at the specific time the studies were carried out in 2017 and 2018 could potentially influence residence times; however, we calculated tidal amplitude as a proxy for the strength of tidal currents in the 24 h surrounding the detection of each fish and found no consistent difference between years (see Supplement 4 in the online version of this article).

Our measured residence times translate into travel rates (calculated using the most direct pathway between two arrays) of 29 and 25 km/d in 2017 and 2018, respectively, consistent with previous Sockeye Salmon tracking studies over a broader area that included the Discovery Islands (Clark et al. 2016). Within the Discovery Islands, we found that travel rates through Discovery Passage from array A to Johnstone Strait (38.0 km/d in 2017, 24.5 km/d in 2018) were approximately double those for the other

routes to Johnstone Strait (22.3 km/d in 2017, 15.2 km/d in 2018 from array B to Johnstone Strait; 14.0 km/d in 2017, 10.5 km/d in 2018 from array C to Johnstone Strait). Discovery Passage is the most direct route (offering fewer passageways to explore or forage on the way north) and has exceptionally strong tidal currents that could potentially aid northward migration if the smolts can take advantage of them. For example, tidal currents in Seymour Narrows located ~10 km south of array A can reach 7.5 m/s. It is plausible that juvenile salmonids use selective tidal stream transport to take advantage of favorable tides during their migration through the Discovery Islands. Selective tidal stream transport is commonly observed in migratory juvenile fish (Forward and Tankersley 2001), and the behavior has been documented in adult Sockeye Salmon in the Fraser River estuary (Levy and Cadenhead 1995). Although the oscillatory tidal currents are strong throughout the region, the extreme current in Seymour Narrows may provide an extra boost in speed relative to the other migration pathways through the Discovery Islands if the smolts can take advantage of the tidal currents. However, net flows in the region are actually quite slow, on the order of ~10 cm/s (<1 km/d; Foreman et al. 2012), so use of selective tidal stream transport requires that the fish employ a method of getting out of the tidal currents at those times when they are unfavorable; otherwise the net contribution of the tides will likely be negligible.

The degree of risk from potential farm pathogens is a function of both exposure (migration route) and the duration of exposure (time), as well as the actual presence of disease agents. Discovery Passage, because of its lack of farms and rapid migration speeds, offers the lowest potential exposure. Conversely, slower migration rates and numerous fish farms in Okisollo Channel and the Cordero Channel area offer the highest potential exposure in the region.

For fish that migrated into Okisollo Channel, median residence time was 5.9 h in 2017 and 7.3 h in 2018. Nearly all migrated through this 4-km region within 10 h (Figure 3B). The time spent within the detection range (~80–300 m) of individual farms was <10 min in 2017 and <25 min in 2018. While exposure to the farms increased in 2018, the increase did not appear to be caused by attraction to the stocked farms. In both years, tagged Sockeye Salmon spent a median of 7.1% of their total travel time (from HoOk 1 to Johnstone Strait) in Okisollo Channel (Figure 3D). Thus, it appears that migration speeds were slightly slower in 2018 overall but independent of the operational status of the farms. The longer residence times also did not seem to be caused by differences in tidal current strength, as discussed above; natural interannual variability or perhaps the change in capture-and-release methodology may therefore be responsible.

Although fish in salmon farms are known to host infectious agents and parasites, particularly sea lice (family Caligidae; Price et al. 2011; Miller et al. 2014), and although there are significant negative correlations between wild salmonid survival and farmed salmonid production (Ford and Myers 2008; Connors 2011), there remains debate in the literature regarding the actual pathogenicity of some Atlantic Salmon-borne infectious agents (Di Cicco et al. 2018; Zhang et al. 2019). Several biological studies have suggested potential harm from fish farms (see Morton and Routledge 2016), while others have found that there is insufficient evidence to conclude that negative impacts on wild salmonids are occurring due to disease transfer from salmon farms (Seafood Watch 2017).

Fisheries and Oceans Canada has conducted numerous risk assessments subsequent to the publication of the Cohen Report (Cohen 2012), including assessments of the risk to Fraser River Sockeye Salmon from piscine orthoreovirus (PRV) and infectious hematopoietic necrosis virus (IHNV) transfer from Atlantic Salmon farms (e.g., Mimeault et al. 2017, 2019). The assessment on PRV concluded that farming “poses minimal risk to Fraser River Sockeye Salmon abundance and diversity under the current farm practices.” This conclusion was partly supported by a laboratory challenge study where no Sockeye Salmon were infected with PRV after cohabitation with PRV-infected Atlantic Salmon for 2 weeks but all were infected by week 12 (Garver et al. 2016). Thus, Sockeye Salmon are susceptible to PRV-infection by Atlantic Salmon, but the short exposure times we observed (minutes near individual farms and hours in Hoskyn and Okisollo channels) reduce the likelihood that Fraser River Sockeye Salmon would become infected with PRV released from Atlantic Salmon farms (Table 12 in Mimeault et al. 2019).

The IHNV assessment, which predates our study, did not consider exposure time at individual salmon farms because the data did not exist. For the Discovery Islands area, they concluded that it is “likely” that at least one juvenile Fraser River Sockeye Salmon would encounter and swim through an infected Atlantic Salmon net-pen and that it is “very likely” that at least one juvenile Fraser River Sockeye Salmon would encounter and swim through the dispersed viral plume of an infected Atlantic Salmon farm given the temporal and spatial overlap of juvenile Fraser River Sockeye Salmon and reported IHNV index cases in Atlantic Salmon farms in the Discovery Islands (Mimeault et al. 2017). Our data support these conclusions and provide evidence that Sockeye Salmon likely swim through near-farm plumes, especially when we consider the limited range of the 180-kHz transmitters. Note, however, that Atlantic Salmon in the Discovery Islands have been vaccinated for IHNV since 2015 (Long et al. 2017; Mimeault et al. 2017).

Quantifying pathogen-related mortality in wild salmonids is inherently challenging because of the difficulty of measuring both fish health and ensuing mortality. Although the survival of fish tracked in this study was estimated in the three major Discovery Islands migration pathways (Johnston 2020), the study was not designed to test the effect of farm exposure on subsequent salmonid survival. We recommend that future investigations expand on our work by following the fate of groups of fish with known levels of exposure to fish farms to explicitly assess whether exposure actually reduces survival—and by how much (the important policy issues). More rigorous assessment of the impact of pathogens will be facilitated by new molecular diagnostic technologies that can inform the assessment of viral disease development in tagged fish (Miller et al. 2017).

In conclusion, the major migration routes and length of residence near (exposure to) farms are required to assess the risk posed by open-net-pen salmon farms to wild salmonid stocks. We have reported exposure time on three scales so that harm from infectious agents can be assessed given the behavior of a potentially infectious agent: near farms (within hundreds of meters; minutes), in Okisollo Channel (hours), and in the Discovery Islands (days). Ocean circulation and particle tracking models were previously used to evaluate the potential spread of IHNV from an Atlantic Salmon farm to neighboring farms in the Discovery Islands (Garver et al. 2013; Foreman et al. 2015). These studies show that the potential salmon farm viral footprint is strongly affected by circulation dynamics and environmental factors (e.g., UV radiation), and that these factors need to be taken into account when considering effective exposure duration and intensity. Telemetry data on migration routes and fish travel time can potentially be incorporated into these models to better assess risk and as a means to assess the cumulative impact of infectious agents from salmon farms on survival.

ACKNOWLEDGMENTS

We thank B. Riddell and the Pacific Salmon Foundation, Fisheries and Ocean Canada, the Aquaculture Association of Canada, and the BC Salmon Farmers Association for funding; Cermaq Canada and Mowi Canada West for allowing us to place acoustic receivers within their farm tenures; the Ocean Tracking Network for long-term use of the “permanent” acoustic receivers; and the Molecular Genetics Lab at the Pacific Biological Station (Fisheries and Oceans Canada) for genetic stock identification of tagged fish. All tagging was conducted by University of British Columbia students and staff (A. Lotto, S. Healy, A. Kanigan, and N. Furey), array operations were managed by P. Winchell (Kintama), and marine-caught fish were captured in collaboration with the

Hakai Institute (B. Johnson, C. Janusson, and J. Gan). Procedures related to the capture, handling, transport, and tagging of salmonids were approved by the University of British Columbia Animal Care Committee (AUP #A19-0193). S. Johnston was supported by the Tula-Mitacs Canada Grant IT09911 through internships FR20319 and FR23027. D. Welch is president and owner of Kintama Research Services, an environmental consultancy that designed and operates the main elements of the acoustic telemetry array described in this article. This is Publication Number 52 from the Salish Sea Marine Survival Project (marinesurvivalproject.com). There is no conflict of interest declared in this article.

ORCID

Erin L. Rechisky  <https://orcid.org/0000-0002-2811-8399>

Aswea D. Porter  <https://orcid.org/0000-0002-1258-8265>

Christine F. Stevenson  <https://orcid.org/0000-0002-8838-9895>

Brian P. V. Hunt  <https://orcid.org/0000-0003-4718-4962>

David W. Welch  <https://orcid.org/0000-0001-8851-5436>

REFERENCES

- Beacham, T. D., R. J. Beamish, J. R. Candy, C. Wallace, S. Tucker, J. H. Moss, and M. Trudel. 2014. Stock-specific migration pathways of juvenile Sockeye Salmon in British Columbia waters and in the Gulf of Alaska. *Transactions of the American Fisheries Society* 143:1386–1403.
- Callier, M. D., C. J. Byron, D. A. Bengtson, P. J. Cranford, S. F. Cross, U. Focken, H. M. Jansen, P. Kamermans, A. Kiessling, T. Landry, F. O’Beirn, E. Petersson, R. B. Rheault, Ø. Strand, K. Sundell, T. Svåsand, G. H. Wikfors, and C. W. McKindsey. 2018. Attraction and repulsion of mobile wild organisms to finfish and shellfish aquaculture: a review. *Reviews in Aquaculture* 10:924–949.
- Clark, T. D., N. B. Furey, E. L. Rechisky, M. K. Gale, K. M. Jeffries, A. D. Porter, M. T. Casselman, A. G. Lotto, D. A. Patterson, S. J. Cooke, A. P. Farrell, D. W. Welch, and S. G. Hinch. 2016. Tracking wild Sockeye Salmon smolts to the ocean reveals distinct regions of nocturnal movement and high mortality. *Ecological Applications* 26:959–978.
- Cohen, B. I. 2012. Commission of inquiry into the decline of Sockeye Salmon in the Fraser River (Canada): the uncertain future of Fraser River Sockeye. Public Works and Government Services Canada, Ottawa.
- Connors, B. M. 2011. Examination of relationships between salmon aquaculture and Sockeye Salmon population dynamics. Library and Archives Canada, Cohen Commission Technical Report 5B, Ottawa.
- Dempster, T., P. Sanchez-Jerez, I. Uglem, and P. Bjørn. 2010. Species-specific patterns of aggregation of wild fish around fish farms. *Estuarine, Coastal and Shelf Science* 86:271–275.
- DFO (Fisheries and Oceans Canada). 2019. State of salmon aquaculture technologies, 2019. DFO, Ottawa.
- Di Cicco, E., H. W. Ferguson, K. H. Kaukinen, A. D. Schulze, S. Li, A. Tabata, O. P. Gunther, G. Mordecai, C. A. Suttle, and K. M. Miller. 2018. The same strain of *Piscine orthoreovirus* (PRV-1) is involved in the development of different, but related, diseases in Atlantic and Pacific salmon in British Columbia. *Facets* 3:599–641.

- FAO (Food and Agriculture Organization of the United Nations). 2020. The state of world fisheries and aquaculture 2020. Sustainability in action. FAO, Rome.
- Ford, J. S., and R. A. Myers. 2008. A global assessment of salmon aquaculture impacts on wild salmonids. *PLOS (Public Library of Science) Biology* [online serial] 6(2):e33.
- Foreman, M. G. G., M. Guo, K. A. Garver, D. Stucchi, P. Chandler, D. Wan, J. Morrison, and D. Tuele. 2015. Modelling infectious hematopoietic necrosis virus dispersion from marine salmon farms in the Discovery Islands, British Columbia, Canada. *PLOS (Public Library of Science) ONE* [online serial] 10(6):e0130951.
- Foreman, M. G. G., D. J. Stucchi, K. A. Garver, D. Tuele, J. Isaac, T. Grime, M. Guo, and J. Morrison. 2012. A circulation model for the Discovery Islands, British Columbia. *Atmosphere-Ocean* 50:301–316.
- Forward, R., and R. Tankersley. 2001. Selective tidal-stream transport of marine animals. *Oceanography and Marine Biology* 39:305–353.
- Garver, K. A., A. A. M. Mahony, D. Stucchi, J. Richard, C. Van Woensel, and M. Foreman. 2013. Estimation of parameters influencing waterborne transmission of infectious hematopoietic necrosis virus (IHNV) in Atlantic Salmon (*Salmo salar*). *PLOS (Public Library of Science) ONE* [online serial] 8(12):e82296.
- Glover, K. A., M. F. Solberg, P. McGinnity, K. Hindar, E. Verspoor, M. W. Coulson, M. M. Hansen, H. Araki, Ø. Skaala, and T. Svåsand. 2017. Half a century of genetic interaction between farmed and wild Atlantic Salmon: status of knowledge and unanswered questions. *Fish and Fisheries* 18:890–927.
- Godwin, S. C., L. M. Dill, M. Krkosek, M. H. H. Price, and J. D. Reynolds. 2017. Reduced growth in wild juvenile Sockeye Salmon *Oncorhynchus nerka* infected with sea lice. *Journal of Fish Biology* 91:41–57.
- Groot, C., and L. Margolis. 1991. Pacific Salmon life histories. UBC Press, Vancouver.
- Jia, B., M. K. V. C. Delphino, B. Awosile, T. Hewison, P. Whittaker, D. Morrison, M. Kamaitis, A. Siah, B. Milligan, S. C. Johnson, and I. A. Gardner. 2020. Review of infectious agent occurrence in wild salmonids in British Columbia, Canada. *Journal of Fish Diseases* 43:153–175.
- Johnson, B. T., J. C. L. Gan, S. C. Godwin, M. Krkosek, and B. P. V. Hunt. 2019. Juvenile salmon migration observations in the Discovery Islands and Johnstone Strait in British Columbia. North Pacific Anadromous Fish Commission, NPAFC Document 1838, Vancouver.
- Johnston, S. D. 2020. Survival and migration characteristics of juvenile Sockeye Salmon (*Oncorhynchus nerka*) smolts through complex near-shore coastal migration corridors. University of British Columbia, Vancouver.
- Kent, M. L. 2011. Infectious diseases and potential impacts on survival of Fraser River Sockeye Salmon. Library and Archives Canada, Cohen Commission Technical Report 1, Ottawa.
- Korman, J. 2011. Summary of information for evaluating impacts of salmon farms on survival of Fraser River Sockeye Salmon. Library and Archives Canada, Cohen Commission Technical Report 5A, Ottawa.
- Levy, D. A., and A. D. Cadenhead. 1995. Selective tidal stream transport of adult Sockeye Salmon (*Oncorhynchus nerka*) in the Fraser River estuary. *Canadian Journal of Fisheries and Aquatic Sciences* 52:1–12.
- Long, A., J. Richard, L. Hawley, S. E. LaPatra, and K. A. Garver. 2017. Transmission potential of infectious hematopoietic necrosis virus in APEX-IHN[®]-vaccinated Atlantic Salmon. *Diseases of Aquatic Organisms* 122:213–221.
- Miller, K. M., O. P. Guenther, S. Li, K. H. Kaukinen, and T. J. Ming. 2017. Molecular indices of viral disease development in wild migrating salmon. *Conservation Physiology* [online serial] 5(1):cox036.
- Miller, K. M., A. Teffer, S. Tucker, S. Li, A. D. Schulze, M. Trudel, F. Juanes, A. Tabata, K. H. Kaukinen, N. G. Ginther, T. J. Ming, S. J. Cooke, J. M. Hipfner, D. A. Patterson, and S. G. Hinch. 2014. Infectious disease, shifting climates, and opportunistic predators: cumulative factors potentially impacting wild salmon declines. *Evolutionary Applications* 7:812–855.
- Mimeault, C., M. P. Polinski, K. A. Garver, S. R. M. Jones, S. C. Johnson, F. Boily, G. Malcolm, K. Holt, I. J. Burgetz, and G. J. Parsons. 2019. Assessment of the risk to Fraser River Sockeye Salmon due to piscine orthoreovirus (PRV) transfer from Atlantic Salmon farms in the Discovery Islands area, British Columbia. Canadian Science Advisory Secretariat Research Document 2019/036.
- Mimeault, C., J. Wade, M. G. G. Foreman, P. C. Chandler, P. Aubry, K. A. Garver, S. C. H. Grant, C. A. Holt, S. Jones, S. C. Johnson, M. Trudel, I. J. Burgetz, and J. Parsons. 2017. Assessment of the risk to Fraser River Sockeye Salmon from infectious hematopoietic necrosis virus (IHNV) on Atlantic Salmon farms in the Discovery Islands, BC. Canadian Science Advisory Secretariat Research Document 2017/075.
- Morton, A., and R. Routledge. 2016. Risk and precaution: salmon farming. *Marine Policy* 74:205–212.
- Neville, C. M., S. C. Johnson, T. D. Beacham, T. Whitehouse, J. Tadey, and M. Trudel. 2016. Initial estimates from an integrated study examining the residence period and migrating timing of juvenile Sockeye Salmon from the Fraser River through coastal waters of British Columbia. *North Pacific Anadromous Fish Commission* 6:45–60.
- Price, M. H. H., A. Morton, and J. D. Reynolds. 2010. Evidence of farm-induced parasite infestations on wild juvenile salmon in multiple regions of coastal British Columbia, Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 67:1925–1932.
- Price, M. H. H., S. L. Proboyszcz, R. D. Routledge, A. S. Gottesfeld, C. Orr, and J. D. Reynolds. 2011. Sea louse infection of juvenile Sockeye Salmon in relation to marine salmon farms on Canada's west coast. *PLOS (Public Library of Science) ONE* [online serial] 6(2):e16851.
- R Core Team. 2019. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna. Available: <http://www.R-project.org>. (February 2020).
- Rechisky, E. L., A. D. Porter, T. D. Clark, N. B. Furey, M. K. Gale, S. G. Hinch, and D. W. Welch. 2018. Quantifying survival of age-2 Chilko Lake Sockeye Salmon during the first 50 days of migration. *Canadian Journal of Fisheries and Aquatic Sciences* 76:136–152.
- Rechisky, E. L., A. D. Porter, P. M. Winchell, and D. W. Welch. 2020. Performance of a high-frequency (180 kHz) acoustic array for tracking juvenile Pacific salmon in the coastal ocean. *Animal Biotelemetry* [online serial] 8:article 19.
- Seafood Watch. 2017. Seafood Watch science report on Atlantic Salmon *Salmo salar* in British Columbia, Canada, marine net-pens. Monterey Bay Aquarium, Monterey.
- Stevenson, C. F., S. G. Hinch, A. D. Porter, E. L. Rechisky, D. W. Welch, S. J. Healy, A. G. Lotto, and N. B. Furey. 2019. The influence of smolt age on freshwater and early marine behavior and survival of migrating juvenile Sockeye Salmon. *Transactions of the American Fisheries Society* 148:636–651.
- Welch, D. W., M. C. Melnychuk, E. R. Rechisky, A. D. Porter, M. C. Jacobs, A. Ladouceur, R. S. McKinley, and G. D. Jackson. 2009. Freshwater and marine migration and survival of endangered Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*) smolts using POST, a large-scale acoustic telemetry array. *Canadian Journal of Fisheries and Aquatic Sciences* 66:736–750.
- Zhang, Y., M. P. Polinski, P. R. Morrison, C. J. Brauner, A. P. Farrell, and K. A. Garver. 2019. High-load reovirus infections do not imply physiological impairment in salmon. *Frontiers in Physiology* 10:114.

SUPPORTING INFORMATION

Additional supplemental material may be found online in the Supporting Information section at the end of the article.