Final Report on the Comparative Marine Survival of Seymour River Steelhead and Testing the Performance of 180 kHz Small Acoustic Tags in the Salish Sea, 2015

Report to the Pacific Salmon Foundation and the Salish Sea Marine Survival Project

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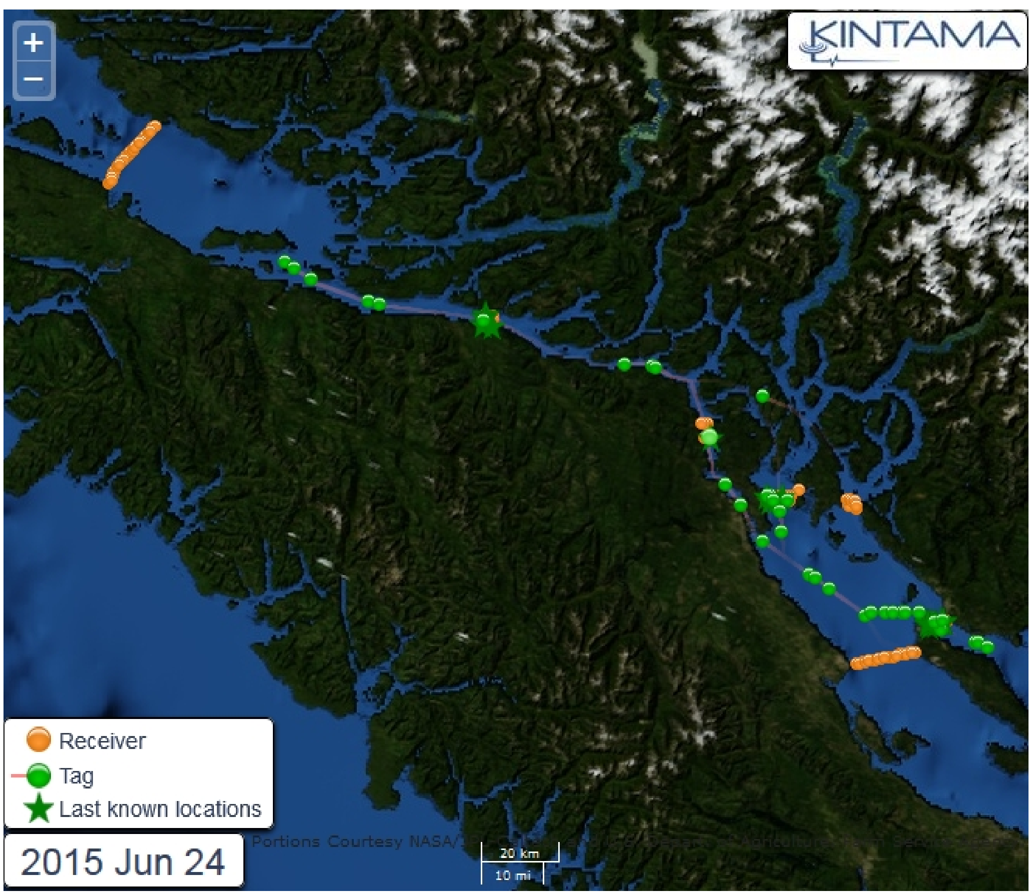

Screen capture image of the animation of Seymour River steelhead movements in 2015. The animation is available from Kintama's website: http://kintama.com/visualizations

Final Report on the Comparative Marine Survival of Seymour River Steelhead and Testing the Performance of 180 kHz Small Acoustic Tags in the Salish Sea, 2015

Salish Sea Marine Survival Project

marinesurvivalproject.com

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Executive Summary

Acoustic telemetry is a key research tool that can be used to determine when and where salmon smolts die in the Salish Sea, but transmitter size has limited past studies to studying larger smolts. Smaller transmitters have been recently developed, but they transmit on a different frequency (180 kHz) than can be detected by receivers deployed in the Salish Sea as part of the original POST array (69 kHz). Additionally, their smaller size means that battery life and acoustic output are reduced, limiting the range that they can potentially be detected and the duration studies can be conducted. This trade-off has major cost implications for future research programs.

To enable tracking of smaller smolts through the major salmon migratory route in the northern Salish Sea, the Pacific Salmon Foundation secured ~$0.5 million worth of dual-frequency acoustic telemetry equipment from the Ocean Tracking Network (OTN), and the Salish Sea Marine Survival Project (SSMSP) provided Kintama with funding to design the geometry of two new sub-arrays using this equipment and then deploy them in the Discovery Islands (DI) and Johnstone Strait (JS) in the spring of 2015[1]. The receivers (VR4s) that make up these sub-arrays are capable of detecting VEMCO's 69 kHz transmitters (e.g., V7, V9) as well as their new smaller 180 kHz transmitters (e.g., V4, V5). Since the smaller transmitters have a reduced detection range, and since sub-arrays used to detect them have never been tested in the ocean, Kintama and the PSF felt it was important to conduct a pilot study prior to implementing use of this smaller tag for studying early marine survival.

Kintama designed the pilot study to test the performance of the new array design at detecting the V4 tags. We double-tagged 50 Seymour River Hatchery steelhead smolts with V4-1H and V9-1H tags and then tracked them through the array. The V9 tags have higher acoustic power and were expected to have excellent (near-perfect) detection efficiency which could be used as a baseline to determine the detection efficiency of a given sub-array geometry using the smaller V4 tag. The V9 tags in conjunction with the newly deployed sub-arrays also allowed us to assess survival on a finer scale than previously possible in the northern Salish Sea.

An additional component of this study (mostly funded internally by Kintama) but using the same tagged fish, was to evaluate the performance of VEMCO acoustic receivers which were retro-fitted with a Kintama-designed and manufactured solid-state acoustic amplifier. We tested the performance of the

[1] Array design and deployment was completed under a separate Kintama-PSF agreement.

amplified receivers by deploying a test array in Malaspina Strait (east of Texada Island in the Northern Strait of Georgia) prior to the release of the double-tagged smolts.

Our objectives in 2015 were the following:

- a[2]- Evaluate the detection efficiency of the 180 kHz tags on new dual frequency sub-arrays
- b- Provide survival data for Seymour River Hatchery steelhead in 2015
- c- Evaluate the improved performance of retro-fitting VEMCO acoustic receivers with a solid-state acoustic amplifier

The detection efficiency of the V9 tags on the new sub-array in the Discovery Islands was 100%. This perfect detection rate allowed us to directly compare the estimated number of V4 ID codes with the number of V9 ID codes recorded on the sub-array. We estimated the number of V4 ID codes because V4 tags are short-lived relative to V9 tags and some V4 tags had stopped transmitting prior to reaching the sub-arrays. If all tag batteries had been actively transmitting, we estimate that detection efficiency of the V4 transmitters on the Discovery Islands sub-array would be 76% (SE=9%; Figure 9; Table 3). Corrected daily cumulative estimates from the first day fish were detected to the day when tags were >50% active ranged between 61% (SE=15%) and 79% (SE=9%; Figure 10). The new sub-array deployed in Johnstone Strait also had a 100% detection rate of the V9 tags; however, we were unable to assess the detection rate of the V4 tags on this sub-array because few fish reached this site before the estimated date V4 tag expiry. Since the geometry of the DI and JS sub-arrays is similar, it is reasonable to expect they would have similar performance. Based on the performance of the DI sub-array, it is now feasible to conduct salmon survival studies using V4 acoustic tags (and other 180 kHz tags) in the marine waters of the northern Salish Sea with reasonable efficiency using the new array geometry.

[2] In our original proposal and 2015 progress reports, objectives a and b are in reverse order and are slightly different. We initially presented survival estimation as the first objective because OTN receivers had not yet been negotiated, and we planned to release the tagged Seymour steelhead smolts at the conventional release location in West Vancouver. The study design changed when the OTN receivers became available, when the UBC (Hinch Lab) tagging operations were moved to the Seymour River Hatchery (because high water levels in Chilko Lake made it impossible to catch outmigrating two-year-old Chilko sockeye), and when there was a delay in the manufacture of the prototype molds for the receiver amplifiers. The deployment of the new sub-arrays and the delay in the deployment of the amplified sub-array prompted us to transport tagged smolts to Malaspina Strait to increase the number of fish surviving to migrate over these sub-arrays. Therefore, our primary objective shifted to testing the performance of the new sub-arrays at detecting 180 kHz tags. We present steelhead smolt survival from Malaspina Strait, but survival estimates for the same population from the conventional release site are available from the SSMSP funded Hinch study.

Survival of Seymour River steelhead through the 270 km region between release in Malaspina Strait and northern Queen Charlotte Strait was 28% (SE=6%) adding to the survival time series collected for this stock (2006-2009; see Discussion). The two new sub-arrays allowed us to divide this large area into three distinct marine environments (the northern Strait of Georgia, the Discovery Islands and Johnstone Strait, and the Broughton Archipelago and Queen Charlotte Strait). Survival in each these three areas ranged between 61-76%. Within the Discovery Islands we were able to estimate survival from each of the three possible migratory routes to the Johnstone Strait sub-array. Most fish took the direct Discovery Passage route (67%), followed by Sutil Channel (30%). Survival to the Johnstone Strait sub-array was 100% for the smolts that used Discovery Passage but only 22% (SE=14%) for the smolts that used Sutil Channel. Just one individual was detected migrating through Desolation Sound, but this fish did survive to reach Johnstone Strait. This is the first report on juvenile salmon survival on a finer geographic scale through an important migration area where we have seen elevated mortality in prior studies, and had identified as a potential mortality hotspot. An animation of the movements of the Seymour River steelhead smolts released in 2015 is available on our website (http://kintama.com/visualizations/).

We evaluated the detection rate of amplified and standard 69 and 180 kHz receivers on the Malaspina Strait sub-array and found no improvement in the detection efficiency of the prototype amplified receivers.

In sum, the performance of the V4 tags with the DI sub-array was sufficient to provide scientifically useful confidence intervals on the resulting survival estimates. As always, some trade-offs are necessary. In the current case, the geometry of the original POST sub-arrays was modified and the capital cost of each new sub-array more than doubled as a result. However, this increase permits the tracking of smolts as small as ~10 cm long (resulting in a tag burden of ~5% of body weight or less) which opens up the possibility of extending large-scale acoustic tracking studies to a wider range of wild sockeye, coho, Chinook, and steelhead populations. Additionally, the extension of the tracking array in the Salish Sea increases the geographic resolution of survival estimates in this area and permits the refinement and development of formal hypothesis tests in future, as well as the identification of potential mortality hotspots.

1. Introduction

The productivity and abundance of many salmonid and steelhead populations declined sharply in the inland marine waters of southern British Columbia and northern Washington State beginning in the late 1980s and early 1990s (SSMSP 2014a; SSMSP 2014b; Beauchamp et al. 2012; English et al. 2008). The reasons for these losses are unknown, but there is evidence that mortality is highest in the early-marine environment (Moore et al. 2015, Neville et al. 2015). In response, the Salish Sea Marine Survival Project (SSMSP) was created as an international research program in 2013 with the primary objective to identify the most important factors affecting the survival of juvenile salmon and steelhead in the Salish Sea.

Given the prime objective of the SSMSP, acoustic telemetry is a key research tool (e.g. Berejikian et al. 2016, Melnychuk et al. 2014, Moore et al. 2015, Welch et al. 2011). Although acoustic tag-based survival studies cannot show why mortality occurs (i.e., identify the agents of mortality), they can identify regions where mortality is potentially elevated ("mortality hotspots") and establish the relative rate of decline in survival with migration time or distance for different regions thought to be important to determining overall survival. Additionally, telemetry can be used to move from observational/correlational type studies to the testing of specific hypotheses (e.g., comparing the survival of an experimental group exposed to an alleged area of high mortality to a control group) which is another goal of the SSMSP.

In the inland waters of southern British Columbia, the Pacific Ocean Shelf Tracking (POST) acoustic telemetry array has been in place since 2004 to monitor the movements of tagged animals in the marine waters between Vancouver Island and mainland BC (Figure 1 in yellow). The existing POST array, which is now maintained by the Ocean Tracking Network (OTN), is based on a design Kintama originally developed for use with low acoustic-powered VEMCO V9-6L acoustic tags (69 kHz, 145 dB) which was the only smolt-sized tag available at the time. This tag was detected with ~85-90% efficiency on individual receiver lines (termed sub-arrays) forming the POST array (Strait of Georgia [NSOG], Juan+ de Fuca Strait [JDF], and Queen Charlotte Strait [QCS]), and multiple surgical trails indicated that it could be reasonably implanted in smolts ≥140 mm in fork length (FL).

In 2007, VEMCO introduced the V7 acoustic tag, which transmitted on the same 69 kHz frequency as the V9 tag. V7 tags are physically smaller and can be implanted into smolts ≥125~130 mm fork length (Chittenden et al. 2009, Balfry et al. 2011a, Porter et al. 2012a, Collins et al. 2013, Morrison et al. 2013). The trade-off in using smaller tags is that they have a weaker acoustic signal at source (136 dB) than the V9 tags which results in fewer tagged smolts being detected and wider confidence intervals on estimates of survival, migration speed, and residence time. However, the accuracy of the results has generally been deemed satisfactory when using release groups of a few hundred smolts per year to achieve baseline estimates.

Nevertheless, the minimum smolt size limits of 125~130 mm (V7) or 140 mm FL (V9) excludes a substantial proportion of the overall salmon smolt size spectrum, and may therefore give a survival estimate that is potentially biased upwards, relative to what might occur for smaller smolts (because larger smolts are thought to potentially have higher survival). VEMCO has recently developed a series of much smaller tags that operate at a higher-frequency (180 kHz): the V6, V5, and V4. However, miniaturization comes at the cost of further reductions in acoustic power (143 dB, 143 dB, and 134 dB, respectively) and detection range. More critically, a shift to tracking smaller smolts using 180 kHz tags with the POST array as it is presently configured is not possible because receivers used in the POST sub-arrays are not capable of detecting the 180 kHz transmitters.

Another emergent issue with the POST array is there have been only three sites in the ocean where smolts can be detected. The precursor to identifying the most significant factors affecting marine survival of juvenile salmon is to determine when and where along the migration path mortality is occurring. For example, the area between the northern Strait of Georgia sub-array (NSOG) and northern Queen Charlotte Strait (QCS) is potentially a zone of high mortality (Welch et al. 2009; Clark et al. 2016), but it is unclear where the majority of this mortality is occurring, because the region spans 240 km and encompasses several distinct marine environments (Discovery Passage, Johnstone Strait, Broughton Archipelago) as well as the northern 1/5th of the Strait of Georgia. The placement of the existing NSOG sub-array south of the northern end of the Strait of Georgia precludes us from estimating survival to the very northern end of the Salish Sea, which is a primary objective of the SSMSP.

To address these issues, the design and deployment of two dual-frequency receiver sub-arrays in the Discovery Islands and Johnstone Strait capable of detecting the smaller transmitters was granted to Kintama by the SSMSP under a separate contract (Figure 1; Figure 2). The PSF negotiated a long-term loan of 41 VR4 acoustic receivers from the OTN for the duration of the SSMSP. Kintama provided two additional VR4 receivers on short-term lease to increase coverage on the Johnstone Strait sub-array.

With these new sub-arrays in place, it became possible to conduct a pilot study to test the performance of the array design at detecting the smaller V4 tags (Objective A) as well as to provide finer-scale survival estimates for salmon smolts between the northern Salish Sea and northern Queen Charlotte Strait (Objective B). To do so, we double-tagged steelhead smolts from the Seymour River Hatchery with V9 (69 kHz) and V4 (180 kHz) tags and tracked them through the array. Although salmon research in British Columbia has historically tended to focus on the other five species of Pacific salmon, steelhead populations are of large economic value to the sport fishing communities and have collapsed in parallel to the problems seen in the other species (Welch et al. 1998, 2000, 2004; Smith et al. 2000). Seymour River steelhead have also had a similar large drop in adult returns and are, in common with other Strait of Georgia steelhead populations, considered an “extreme conservation concern” (Ahrens 2004; Province of British Columbia 2016). Additionally, Seymour River summer steelhead are quite large at release relative to other steelhead populations so it was possible to implant two transmitters into each fish while maintaining a low tag burden.

Completing these measurements in 2015 added to the time series of survival data collected between 2006-2009 when the Seymour steelhead population was the primary focus of collaborative survival experiments between Kintama and the Seymour Salmon Society, which systematically evaluated a number of hypotheses over the years through the use of formal scientific experiments Balfry et al. 2011b). Other investigators can also use these results to compare with measurements of bottom-up processes (e.g. plankton abundance or occurrence of harmful algal blooms) as well as key data on speed of migration, which is necessary to establish residence time (and thus, exposure) to processes occurring in various basins of the Salish Sea.

Finally, as part of separate initiative, Kintama has been designing and developing prototype acoustic amplifiers to boost the range over which acoustic tags can be detected by telemetry receivers. The reduced acoustic power of the new smaller tags means that it will be necessary to deploy a much denser array to achieve the current performance of the larger V7 and V9 tags[3]. The ability to boost the

[3] Kintama’s testing of the V6 180 kHz tags uniformly found maximum detection ranges of 80-100m in all freshwater, estuarine, and marine environments evaluated. (These tests include the marine waters of the Strait of Georgia). In contrast, 69 kHz V7 & V9 tags have maximum detection ranges of 300m and 400m, respectively.

detection range of an array of receivers for a given tag thus has substantial economic implications. To test the amplifiers, in 2015, Kintama deployed a test sub-array consisting of amplified acoustic receivers (69 and 180 kHz) paired with standard acoustic receivers (69 and 180 kHz) in Malaspina Strait just south of the existing eastern section of the NSOG sub-array. We used the double-tagged Seymour River steelhead smolts released in this study to assess the amplified receivers in the field as well as to assess detection efficiency of the V4 transmitters on the Malaspina Strait sub-array[4].

This difference in maximum detection range (rmax) with different tags has profound implications for developing cost-effective, efficient, arrays. Assuming for simplicity an anisotropic environment, a receiver can monitor a horizontal area of πr^2; the ratio of maximum detection ranges of V4 vs V7 & V9 tags (1/3~ ¼) implies that 9 times more 180 kHz receivers would be required to achieve the detection efficiency of V7 tags on a given sub-array (65-70%), and 16 times more 180 kHz receivers to achieve the 85-90% detection efficiency of V9 tags.

[4] Extensive additional confirmatory tests on the performance of the amplified receivers were conducted in freshwater in November-December of 2015 that were not part of this contracted work. These results also failed to demonstrate an increase in detection range over the unamplified receivers.

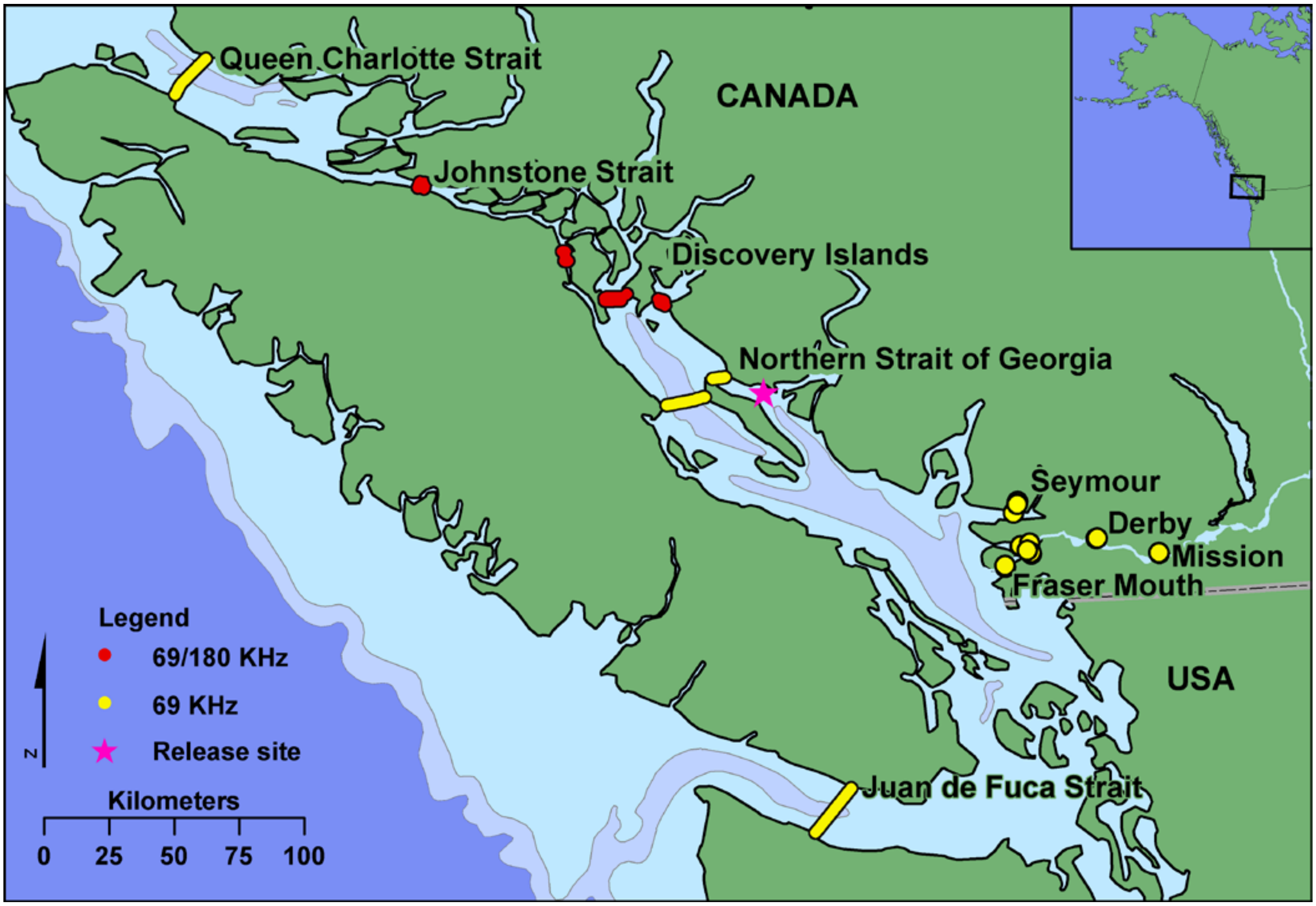


Figure 1. Map of the acoustic array and release location of double-tagged Seymour River steelhead (star). Kintama's test sub-array in Malaspina Strait is not shown, but was deployed ~550 m south of the eastern section of Northern Strait of Georgia sub-array. See Figure 2 for a zoomed in view.

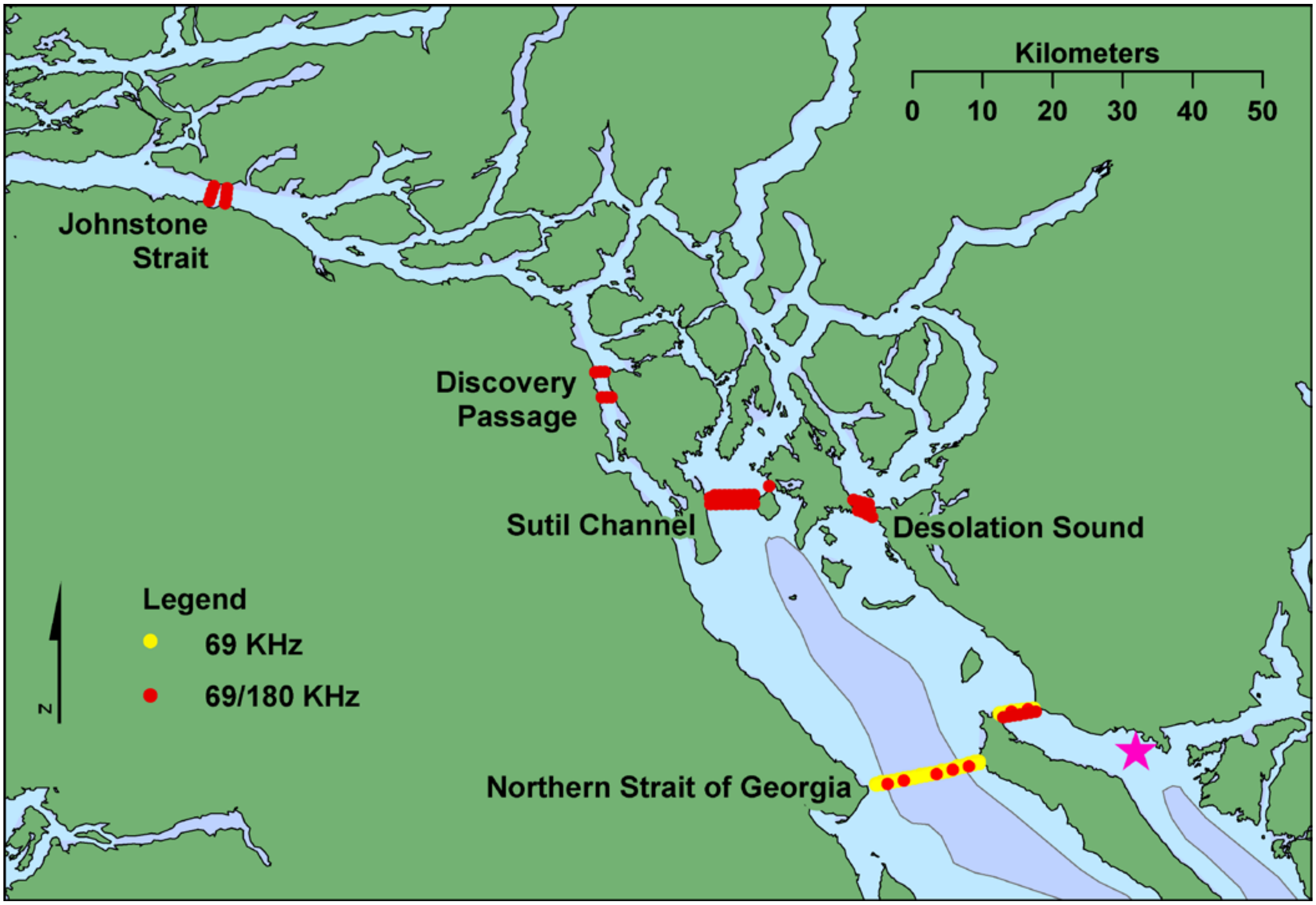


Figure 2. Map of dual frequency sub-arrays of the northern Salish Sea region. The Discovery Islands (Discovery Passage, Sutil Channel, and Desolation Sound receivers, collectively) and Johnstone Strait sub-arrays were deployed as double lines of receivers as part of redesigning the sub-array geometry for detecting 180 kHz transmitters. Kintama's test sub-array in Malaspina Strait (not labelled but is shown as a red line located ~550 m south of the eastern section of NSOG) was also capable of detecting both frequencies. The NSOG sub-array also has eight dual-frequency receivers (of 27 total).

2. Methods

2.1. Tagging

On May 13-14th 2015, we double-tagged 50 steelhead smolts with VEMCO V9-1H and V4-1H acoustic transmitters (Figure 3; Figure 4). These smolts were summer-run, hatchery-origin, steelhead from the Seymour River between 175-236 mm fork length at tagging, and 14 months of age at time of release. The combined tag weight in air was 4.0 grams and the average tag burden was 4.8%. No fish carried a burden greater than 7% (Figure 5). The tags were implanted using Kintama's standard surgical protocols (Porter et al. 2012b; Appendix C). Smolts were selected without regard to size and were reflective of the size-frequency of the overall hatchery population at release. The V9-1H tags (9 mm diameter, 24 mm long, 3.6 g in air, 69 kHz) were programmed to transmit an acoustic signal at random intervals between 30 and 90 sec (60 sec average) until battery death or until they were turned off 107 days after activation. VEMCO estimates that 95% of V9 tags should still be active 102 days after activation (estimated tag lifespan). The V4-1H tags (5.7 mm width, 11 mm long, 3.6 mm height, 0.42 g in air, 180 kHz) were programmed to remain silent for the first 4 days after activation. On day 5 they began transmitting randomly every 13 to 27 sec (20 sec average) until battery death or until they were turned off 54 days after activation. VEMCO estimates that 95% of the V4 tags should be active at 36 days after activation, and that 50% should be active at 42 days after activation (tags were activated on May 12th).

Figure 3. VEMCO V9-1H (69 kHz) and V4-1H (180 kHz) acoustic transmitters.

Figure 4. A Seymour River summer steelhead smolt implanted with V9-1H and V4-1H acoustic transmitters.

On June 9th 2015, we tagged a further 20 Seymour steelhead smolts with VEMCO V7-2L acoustic transmitters contributed to our study by Professor Scott Hinch's (UBC) research group. These additional tags were intended to test the ability of Kintama's acoustic amplifiers to detect V7 tags which are commonly used in Salish Sea smolt studies. The V7-2L tags (7 mm diameter, 20 mm long, 1.6 g in air, 69 kHz) were programmed to transmit an acoustic signal at random intervals between 20 and 40 sec (30 sec average) for the first 14 days after activation, and between 40 and 80 sec (60 sec average) until battery death. The faster initial transmission interval was intended to improve detection efficiency during freshwater migration since these tags were originally purchased for use in Chilko River sockeye smolts released into the Chilko River B.C. VEMCO estimates that 95% of the V7 tags should be active 123 days after activation. The tag burdens for these fish ranged between 1.3 and 3.5%.

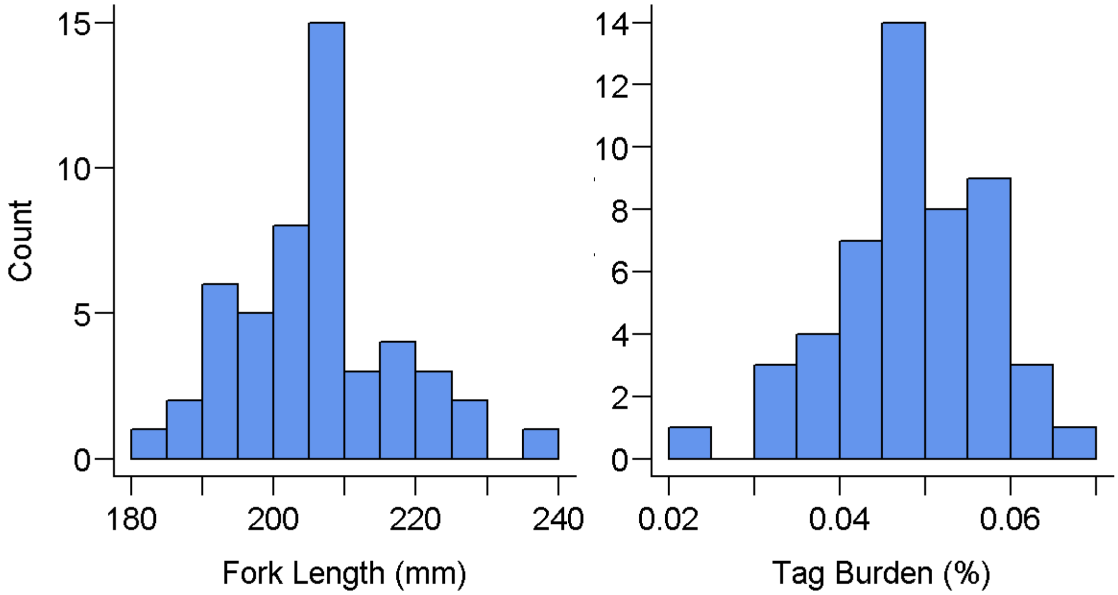


Figure 5. Fork length and tag burden distributions for Seymour River steelhead smolts double-tagged with V9 and V4 transmitters in 2015.

2.2. Transport and Release

Although we originally planned to have the tagged smolts released with the untagged hatchery population into English Bay on May 19th from DFO's Centre for Aquaculture and Environmental Research Lab ("West Van Lab" or WVL), transport from the hatchery for release was held back for several additional weeks. This extended holding period was necessary to accommodate Objective C which was to test Kintama's new solid state acoustic amplifiers (see below for progress on Objective C). The manufacture of the molds used to fabricate the amplifiers was delayed into June, and as a result the smolts were held at the hatchery until mid-June until the amplifiers could be fabricated and then deployed in Malaspina Strait. The day after the Malaspina sub-array was deployed, we loaded the tagged smolts into a fish transportation tank along with ~150 unmarked individuals ("decoys"), and moved them by truck for 2.5 hours to Fisherman's Wharf in False Creek (downtown Vancouver). Here they were loaded onto a Canadian Fishing Company (Canfisco) vessel the *Denman Isle*, and shipped for a further eight hours for release in Malaspina Strait (Figure 1; Figure 2) at 1:00 am on June 16, 2015 (Figure 6). The release site was 18.5 km south of the Malaspina Strait sub-array and smolts were expected to migrate north. Tank temperature (range 11.7-12.8 °C) and dissolved oxygen concentration (7.3-13.7 ppm) were monitored throughout the transportation process.

Figure 6. Loading and transporting double tagged Seymour River steelhead smolts.

During boat transportation, surface temperature in the Strait of Georgia was consistently warmer than expected (~17-18 °C at 2 meters depth) and it did not drop as we steamed north and away from the Fraser River plume. Therefore we did not have the opportunity to acclimate the fish to seawater during transport as originally expected (because we expected the water to cool as we moved north). Buoy data indicated that temperatures at the release site were ~12 °C in the days leading up to release; however a temperature shift had occurred in the Strait of Georgia just prior to smolt release.

2.3. Acoustic Array

The array is composed of a series of "sub-arrays" of receivers spaced along the migration route (Figure 1; Figure 2). The newly deployed PSF and OTN funded dual-frequency sub-arrays in the Discovery Islands (DI), and Johnstone Strait (JS) were deployed by Kintama Research in 2015, and were equipped to detect both the V4 (180 kHz) and V9 (69 kHz) tags. Kintama's test sub-array in Malaspina Strait (MS) was also capable of detecting both frequencies. The Northern Strait of Georgia (NSOG), Queen Charlotte Strait (QCS), and Strait of Juan de Fuca (JDF) sub-arrays can detect only 69 kHz tags[5].

The Discovery Islands and Johnstone Strait sub-arrays were deployed in the spring of 2015 and are equipped with VEMCO VR4 dual-frequency (69 and 180 kHz) receivers which can remain continuously deployed for multiple years with data access via remote upload. All of the DI receivers (35) and six of the eight receivers deployed in JS are OTN-owned; two JS receivers were Kintama-owned. The OTN-owned receivers will remain in place for the duration of the SSMSP, but the Kintama receivers were deployed for the summer only. These two sub-arrays were deployed in paired lines (termed sub-sub-arrays). Similar to POST/OTN sub-arrays, the receivers forming each of the sub-sub-arrays were spaced at ~750 m, however, the spatial geometry of the combined two sub-arrays was altered to increase the probably of detecting V4 tags, as well as to provide finer resolution of migratory behaviour between sub-sub-arrays.

We designed and deployed the Malaspina Strait sub-array in June 2015 specifically to test 69 kHz and 180 kHz acoustic amplifier prototypes (Objective C). For this purpose, each of seven sub-array moorings was deployed with four single frequency VR2 receivers: amplified and unamplified 69 kHz receivers, and amplified and unamplified 180 kHz receivers (Figure 7). Unlike VR3 and VR4 receivers, VR2 receivers must be recovered to collect the data. The MS sub-array was deployed in a single line from Texada Island to Powell River on the BC mainland.

[5] Eight of 27 positions on NSOG are instrumented with VR4 receivers that can detect both 180 and 69 kHz tags. Additionally, 1 position is instrumented with a VR2W.

Figure 7. Malaspina Strait sub-array moorings equipped with amplified and unamplified 69 kHz VR2 receivers, and amplified and unamplified 180 kHz VR2 receivers. The ABS frames are designed to flood and be almost completely transparent to sound.

The NSOG, JDF, and QCS sub-arrays are mostly[5] equipped with VEMCO VR3 receivers which may remain deployed for several years with data access via modem. They differ from VR4s in that they are not capable of detecting 180 kHz tags[6]. These three sub-arrays were configured in single lines with receivers spaced at ~800 m to monitor fish migrating via the Salish Sea straits.

We successfully uploaded the data from all acoustic receivers in the Discovery Islands and Johnstone Strait sub-arrays between Aug 30th and Sept 3rd, 2015. We also uploaded all receivers from the NSOG sub-array Sept 2nd-3rd. Although this sub-array is maintained by OTN, we uploaded it prior to the standard fall OTN upload date (see below) in order to provide data for immediate analysis. All NSOG units were successfully uploaded with the exception of the VR2 receiver deployed near the Vancouver Island coast (position 27) which we did not attempt since it required physical recovery of the mooring to access the data rather than remote upload.

[6] The VR3 receivers forming the NSOG, JDF, and QCS sub-arrays can detect 69 kHz and can also detect any tags transmitting at 81 kHz; however, 81 kHz tags are rarely used.

We recovered the Malaspina test sub-array on July 24th, 2015 shortly after we were alerted by the Canadian Coast Guard and a fisherman that two units were found floating at the surface. During recovery, we found that the receivers at positions 3 and 5 were on the surface but still attached to their anchor. These units were equipped with depth sensors, and analysis of the depth data indicated that they were near the surface periodically throughout deployment depending on the tidal height. For reasons specific to the test of the acoustic amplifiers (Objective C), we intended to deploy this sub-array such that the transducers were close to the surface, where the steelhead were expected to travel; however, positions 3 and 5 were inadvertently deployed with tethers that were slightly too long relative to the actual bottom depth taken from hydrographic charts, and thus the receivers broke the surface periodically. We considered these two units to be only partially operational because surface waves would potentially have disrupted the line of sight for sound signals transmitted by the tags. The five remaining moorings and all receivers on the permanent sub-arrays were fully functional throughout deployment.

OTN serviced the NSOG, QCS, and JDF sub-arrays in late November (25th-28th). All receivers were successfully uploaded with the exception of position 21 on the NSOG sub-array; however, data from this position were available from Kintama's September upload. Data from the OTN sub-arrays necessary for our analysis was provided in early February 2016.

2.4. Data Management

Prior to analysis, we screened all data for false detections. Although false detections are rare with the type of acoustic telemetry used in this study, they may occur as a result of environmental conditions creating transmissions similar to those used for telemetry, or from collisions between acoustic-tag transmissions that reach the receiver from direct or reflected paths (echoes). Tag codes with two or more detections within 0.5 hours and with more detections spaced with short intervals (<0.5 hour spacing) than with long intervals (>0.5 hours spacing) were passed. Detections that failed this first step were assessed individually and were passed if the migration sequence was reasonable and if the travel time for the segment was within the 10th-90th percentiles of travel times for each treatment. None of the 10,934 detections of Seymour steelhead were classed as false.

We also examined the sequence of detections to identify fish that milled between sub-arrays (i.e. they migrated back south after being detected north of release): we classed 1360 detections of five individual fish as out of sequence (all these fish were detected on NSOG after detection on DI). These detections were excluded from estimates of detection efficiency, survival, and travel time, but were included in the animation.

2.5. Objective A- Evaluate the detection efficiency of the 180 kHz tags on new dual frequency sub-arrays

The goal of Objective A was to assess the performance of both the DI and JS sub-arrays at detecting V4 tags; however, most of the V4 batteries had weakened or expired by the time smolts reached Johnstone Strait because of the short battery life and delayed release of the fish (Figure 8). Therefore Objective A analyses and results focus on the performance of the DI sub-array. The performance of the MS sub-array, although not the focus of the Objective, was also assessed and is reported as a component of Objective A. We did not assess the V4 detection efficiency at NSOG or QCS (or JDF) because these sub-arrays were not equipped to detect 180 kHz V4 tags (although see footnote 5).

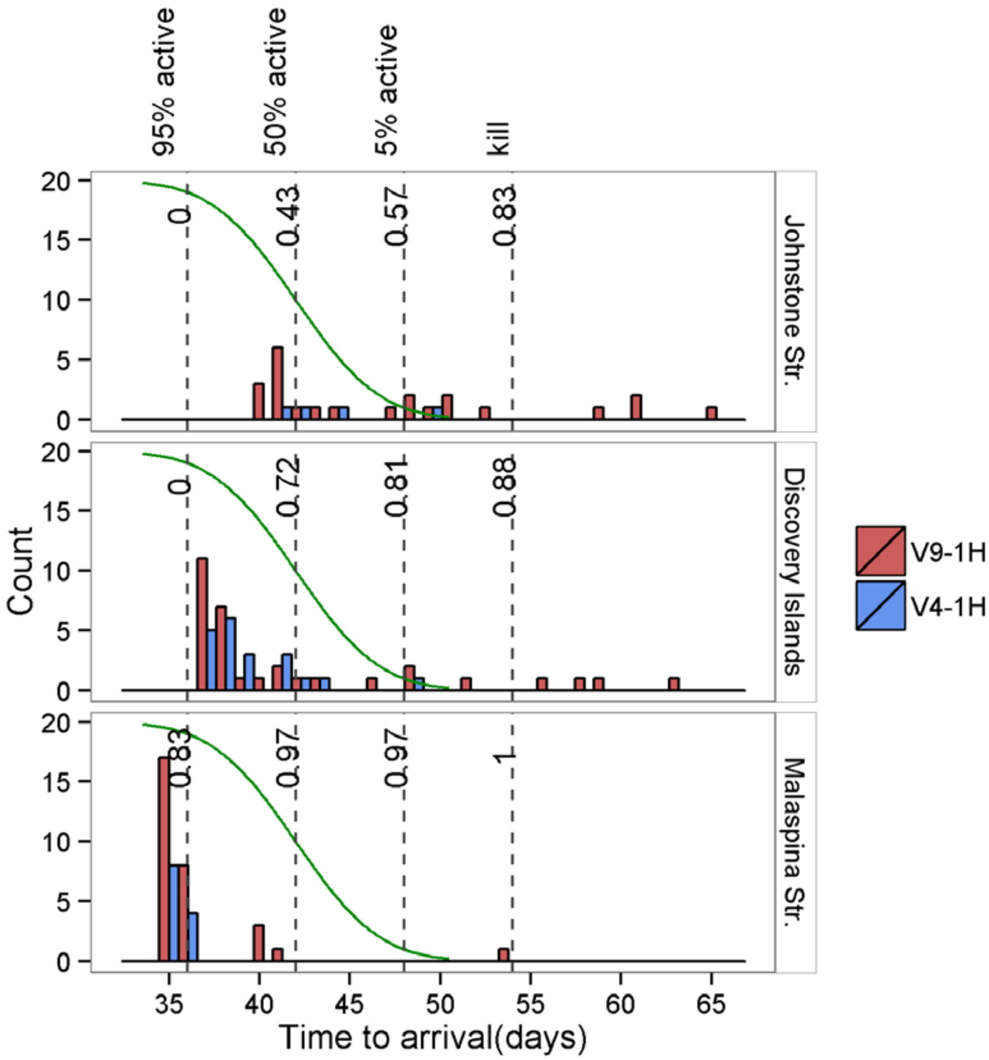


Figure 8. Time between tag activation and arrival (first detection) of double-tagged Seymour River steelhead smolts at the acoustic sub-arrays equipped to detect V4 tags. The dotted lines show the dates at which VEMCO estimated that 95%, 50%, and 5% of the V4 tags would remain active, and the kill date at day 54. The numbers on each dotted line are the percentiles of fish that arrived at the sub-arrays by these dates of V4 expiry. For example, 72% of the fish had arrived at the DI sub-array by the 50% active date of V4s. The green line illustrates the expected percent of tags active on each day and is the complement of the cumulative normal distribution. It predicts the proportion of tags still active at various times after activation based on the mean time of tag failure and the standard deviation (see text) and ranges from 100% of tags active to 0%; the counts on the y-axis do not apply.

Detection efficiency of V9 tags

To evaluate the V4 tags, we first needed to determine the detection efficiency (DE) of the V9 tags. The V9 DE for all sub-arrays north of the release point (MS, NSOG, DI, JS) was calculated as the number of fish detected at that sub-array divided by the number of tagged fish known to have been there (fish detected + fish not detected but detected at any later point in the migration route). The uncertainty in measurements of DE was calculated as the standard error of a proportion $SE(p) = \sqrt{p(1-p)/N}$, where *p* is the detection efficiency and N is the sample size. Typically, we use Cormack-Jolly-Seber (CJS; Cormack 1964, Jolly 1965, Seber 1965) models to estimate survival and detection probabilities, and the associated error around these parameters, but this was not necessary because DE was 100% for the V9 tags on NSOG, DI, and JS (although we did use the CJS model to simulate the more common situation where a secondary tag or method is not available to verify tag presence; see below). DE for V9 tags on the MS sub-array was <100% (see section 3.1 Results); however, DE of V9s on the NSOG sub-array was perfect, and therefore we used the number of fish detected on NSOG to evaluate the V4 DE on MS because these two arrays were deployed very near each other.

We determined the V9 DE for the DI and JS sub-sub-arrays as well using the same procedure above, but we also included any detections from the other sub-sub-array in the pair in the total of fish known to have been present (i.e., technically we must assume that mortality was zero in the short [<4 km] distance that the tagged fish travel from the first sub-sub-array to the second, so that the cross-comparison is fully valid).

Detection efficiency of V4 tags: Proportion method

Because the presence of the smolts was known at all sub-arrays from the V9 detections, we calculated the DE of the V4 tags (at MS and DI, and at each of the DI sub-sub-arrays) by counting the number of V4 tags codes detected, and calculating the proportion of V4 tags detected relative to the V9s. We called these estimates “raw” because they were made using the count of tags detected and not corrected for tag expiry (see below). The uncertainty in all measurements of DE for the V4 tag was calculated as for the V9 tags using the formula for the standard error of a proportion.

As part of counting the number of V4 tag codes detected, we calculated the difference in the arrival times at each sub-array between each V4 and its paired V9. We took this step because we had detected some milling behaviour around the Discovery Islands sub-array. If a fish milled over the acoustic sub-arrays, each pass provided an additional opportunity for the V4 tag to be detected and the resulting detection efficiency estimates could be biased upwards relative to what would be observed if the fish migrated continuously north without milling. Since we hope the results from our study can be used to inform future projects, we reduced this bias by excluding all V4 tags that were first detected >24 hours after their paired V9 (N=3 at Discovery Islands and Discovery Islands North; N=5 at Discovery Islands South).

The estimates of detection efficiency calculated as described above probably underestimate the true detection efficiency of the V4 tags because the V4 (but not the V9) tags began to expire while the smolts were still in the study area (Figure 8). The impact of this problem grows progressively worse at more distant locations because a greater proportion of tags failed prior to the fish arriving on the sub-array. To explore the effect of tag expiry at each sub-array, we calculated the cumulative detection efficiency using only the first date that fish were detected on a given sub-array, and then progressively included more and more of the detection record until the kill date for the V4 tags was reached (day 54).

Detection efficiency of V4 tags: Proportion method corrected for tag expiry

We corrected for probable V4 tag expiry by weighting the count of V4 detections in each 12 hr period by the reciprocal of the tag lifespan curve ("corrected"). VEMCO (Drs. D. Webber and R. Vallee, pers. comm., June 14 2016) has measured tag lifespans for large numbers of V4 tags and reports that the tag failure time distribution is closely Gaussian, and well fitted by two parameters: the mean time of failure ($\bar{t}$), and the standard deviation (σ_t). Thus, the cumulative normal function ($\mathrm{N}(\bar{t},\sigma_t)$) describes the percentage of tags expected to have expired before time (t). The weighting function $\omega(t) = 1 - \mathrm{N}(t \mid \bar{t}, \sigma_t)$ then describes the predicted proportion of V4 tags expected to still be active at time t, and the reciprocal $\omega^{-1}(t)$ provides a multiplicative weight to inflate the observed V4 tags detected on a given day to compensate for tags that have already failed. For example, at the mean time of failure 50% of the tags are predicted to have failed, so the number of V4 tags detected on that day will be doubled.

There are a few cautions associated with this approach. First, VEMCO notes that there is some variability in the tag lifespan curve across tag production batches and the specific tags we implanted into

Seymour River steelhead were not tested. Second, since the times of arrival were not exactly the same between the V4 and V9 tags, we used the arrival time of the V9 as *t*. Finally, the inflation factors lying in the right hand tail of the distribution (i.e., applied to tag detections occurring later in the observational record, when few tags are predicted to be still active), are likely to incur substantial errors due to even slight departures from normality (see above).

Calculating DE of the Malaspina sub-array for both tag types was more complicated than for the other detection sites because of its unusual configuration: 1) it contained replicate deployments for amplified and unamplified receivers, 2) it spanned only Malaspina Strait rather than the full Strait of Georgia causing uncertainty for non-detected fish, and 3) two of the seven receiver deployments were exposed at the surface through at least part of the tidal cycle due to errors in the charted bottom depths. (For technical reasons associated with testing the amplifiers, we attempted to position the receivers ~15 m below the surface in ca. 310-320 m water depths). To assess the DE of MS we considered several factors:

- We excluded data from receivers that were instrumented with acoustic amplifiers. This made the Malaspina sub-array more representative of standard POST deployments.

- We excluded southern migrants. It was necessary to assess if the tagged smolts migrated directly north over the array undetected, or if they migrated south initially and then turned north sometime after passing the southern tip of Texada Island to migrate on the western side of Texada Island. We classed 4 fish as southern migrants based on three criteria. First, they were not detected on either the Malaspina Strait sub-array, or on the eastern half of the NSOG (hereafter called NSOG East). The probability that a fish could have migrated over both sub-arrays undetected was no more than 3.5% even if we use DE values calculated assuming all 4 fish were indeed missed ($(1\text{-}DE_{Malaspina})*(1\text{-}DE_{NSOG})$ = (1-0.71)*(1-0.88)). Second, these fish were all detected on the western half of the NSOG (hereafter called NSOG West). Since only 3 of the 38 fish detected on NSOG East were subsequently detected on NSOG West (and none moved from NSOG West to NSOG East), the probability of western migration was uncommon, only ~8%. Thus, the combined probabilities of these fish being missed on both eastern sub-arrays and then being detected on NSOG West was very low (0.28%). Finally, the elapsed travel time taken between release and arrival on NSOG West was sufficient to allow the smolts to migrate the extra distance around the south end of Texada Island.

Detection efficiency of V4 tags: CJS method for comparison

For MS and DI we also estimated V4 DE directly using CJS models. Because we generally do not have any additional information to confirm fish survival (i.e., fish are not generally double-tagged with a more powerful transmitter, as they were in this study), we wanted to estimate the error that might be obtained in future studies using the 180 kHz tags where DE is uncertain, and where survival and DE (and their variances) are estimated simultaneously within the CJS framework. The CJS model is used for live recaptured animals where each sub-array of acoustic receivers that the smolts encountered was considered a recapture event. It jointly estimates survival and detection probability within a maximum likelihood framework and is used when the true detection rate is unknown or less than one.

As our data from the 180 kHz tags violate the basic CJS model assumption that all tags remain active during the study period, we simulated a dataset for the CJS analysis but that was not affected by tag expiry. That is, we used the values in Table 3 (detection probabilities for V4 tags corrected for tag expiry) and Table 5 (survival probabilities) to generate capture histories using a custom script in R. In this simulated dataset, each fish (N=50 to equal our sample size at release) was designated as 'detected', or 'not detected' at each sub-array in the migration sequence (Malaspina Strait, DI, and JS). Since tag expiry prevented us from estimating the V4 detection probability for JS, the final recapture site, we assumed that the DE at JS would equal the DE at DI. This assumption is reasonable because both sub-arrays were deployed with the same geometry and had zero gear loss. By setting the DE of JS equal to DI, we could generate capture history sequences that would allow us to estimate survival and detection probability at DI. We used the simulated capture histories and Program Mark (White and Burnham 1999) to construct CJS models though the R (R Development Core Team 2015) package RMark (Laake 2015). Error was estimated using the profile-likelihood option available in Program Mark.

Detections per fish per tag type

After calculating DE for both transmitter types, we further compared the performance of the V9 and V4 tags by counting the number of transmissions recorded for each surviving fish. VEMCO technology is robust to false detections, so the presence of a tagged fish can be reasonably inferred from a single detection, particularly when coupled with additional evidence of presence from migratory behaviours such as (e.g., travel time and migration sequence). However, it is generally necessary to have multiple detections closely spaced together in time to be fully certain the fish was present. In our case, single detections from the V4 tags were verified by multiple detections of the more powerful V9 transmitter.

2.6. Objective B- Provide survival data for Seymour steelhead in 2015

We originally proposed to release the steelhead smolts from the DFO West Vancouver Lab (WVL) which is the typical release site for Seymour River Hatchery smolts (Seymour steelhead are not released at the hatchery). However, we ultimately transported the tagged steelhead from the hatchery and released them in Malaspina Strait to reduce mortality that occurs between WVL and the NSOG sub-array (Balfry et al. 2011b) and to boost numbers further by concentrating all of the released smolts within the relatively narrow Malaspina Strait. Transporting smolts to Malaspina Strait thus precluded estimating survival between the WVL and NSOG; however, the increased sample size at the northern sub-arrays means that survival estimates are more precise in the critical areas north of the NSOG sub-array. As Professor Scott Hinch's (UBC) tagging operations were moved to Seymour River Hatchery in 2015 due to the inability to catch large sockeye smolts up at Chilko Lake (because of exceptionally high lake levels), survival estimates for Seymour steelhead from the conventional WVL release site to the NSOG sub-array are available from the SSMSP-funded UBC study.

Because detection efficiency was 100% for the V9 transmitters at the NSOG, DI, and JS sub-arrays, we assumed it was also 100% at QCS in order to calculate survival to the northern end of Vancouver Island (see section 3.1 Results for Objective A). Cumulative survival could thus be calculated simply as the number of fish detected divided by the number of fish released, and the uncertainty calculated as the standard error of a proportion $SE(\varphi) = \sqrt{\varphi(1-\varphi)/N}$ where φ is survival and N is the sample size. We used the same formulas to calculate survival in each migration segment (release to NSOG, NSOG to DI, DI to JS, and JS to QCS), but with the number of fish detected at the start of the migration segment as the denominator.

We also estimated survival for the three possible migratory routes through the Discovery Islands to the Johnstone Strait sub-array. For this calculation, we allocated fish to their migratory route (Discovery Passage, Sutil Channel, or Desolation Sound; Figure 2) based on the location of their last detection on the Discovery Islands sub-array. Two fish detected in the Discovery Islands (both at Sutil Channel) were subsequently detected at NSOG (i.e., they were last detected migrating south) and were removed from this analysis. Survival and the associated error for each migratory route were then calculated using the proportion method as described above.

To compare survival estimates in different length habitats, we converted the survival estimates for each segment into survival rates per unit time and distance as $S^{1/d}$ where S=calculated survival (and the lower and upper confidence intervals of the survival estimates) and d=the median distance or travel time. Travel time was calculated for each fish from either release or the last detection on a sub-array (departure date) to the last detection on the next sub-array. Distance was calculated for each fish as the shortest route in water between release and the receiver where the fish was first detected on each sub-array. Travel time and distance estimates were only calculated for smolts detected on both sub-arrays bracketing the segment in question.

2.7. Objective C- Evaluate the improved performance of VEMCO acoustic receivers retro-fitted with a solid-state acoustic amplifier

Kintama designed solid-state acoustic amplifiers for 69 and 180 kHz acoustic receivers, fabricated molds using 3-D printers, and then fitted individual receivers with the amplifiers. The amplified receivers were deployed in pairs with standard VEMCO VR2W receivers at seven positions that together formed an acoustic sub-array spanning Malaspina Strait (see Figure 1; Figure 2). In total, each position was supplied with four receivers because it was necessary to use separate receivers to monitor the 69 and 180 kHz frequencies (for the V9 and V4 tags respectively).

To assess the performance of the amplifiers we calculated the DE of the amplified and standard units using the method described for V9 tags (see section 2.5 Methods). We also compared the number of detections recorded per fish at each position on the sub-array. Since there was no visible effect of amplification on receiver performance (see section 3.3 Results), it was not necessary to conduct statistical analyses.

We initially thought the lack of amplification may have been partly due to a significant flaw with the 69 kHz mold supplied by the 3-D printer and used to fabricate the 69 kHz amplifiers. This flaw was not identified (by Kintama) until the amplifiers had been fabricated and prepared for deployment and therefore there was not enough time to correct the problem before deployment. The 69 kHz amplifiers were subsequently corrected by re-manufacturing the 69 kHz mold and then tested in Horne Lake, BC, in two additional experiments occurring between November 26th-Dec 15th 2015; however, there was still no difference in performance.

3. Results

Of the 50 Seymour steelhead smolts released, 42 were detected on the acoustic array (Table 1). All but one individual migrated north; this one fish exited Georgia Strait to the south via the Strait of Juan de Fuca. Four others initially moved south after release but then turned north at some point after passing the southern tip of Texada Island to migrate north in the western channel between Vancouver and Texada Island. Four different tags were detected milling back and forth between the NSOG and DI sub-arrays with three of them last detected at NSOG (i.e., they were last detected travelling south).

An animation of the movements of the Seymour River steelhead smolts released in 2015 is available on our website (http://kintama.com/visualizations/). The animation can be panned and zoomed, and the display can be customized. Tags and receivers can also be queried to obtain summary statistics as well as full detection histories.

The results from supplementary analyses of travel time, travel rate, and cross-channel distributions are available in Appendix A (Migratory Behaviours).

Table 1. Count of Seymour River steelhead smolts detected migrating over the acoustic array in 2015. Sub-arrays are mapped in Figure 1. The sample size at release was 50.

Sub-array	V9-1H	V4-1H
Malaspina Strait	30	12
Northern Strait of Georgia	42	7
Discovery Islands	32[a]	20
Desolation Sound	3	2
Sutil Channel	15	12
Uganda Harbour	1	0
Discovery Passage	20	9
Johnstone Strait	23	4
Queen Charlotte Strait	14	0
Strait of Juan de Fuca	1	0

[a]Seven of the fish detected on the Discovery Islands sub-array were detected on more than one sub-sub-array.

3.1. Objective A- Evaluate the detection efficiency of the 180 kHz tags on new dual frequency sub-arrays

The 69 kHz V9-1H transmitters had 100% DE at the NSOG, Discovery Islands, and Johnstone Strait sub-arrays (i.e., all fish that survived to reach each sub-array were detected; Table 2; Figure 9). The V9 DE was also high for the individual sub-sub-arrays forming the Discovery Islands and Johnstone Strait sub-arrays (>91%). At all these sites, the vast majority of the V9 tags (>75%) were detected more than 5 times; zero or single detections were rare (Figure 11; Table 4). Performance was somewhat reduced on the Malaspina Strait sub-array, but this drop was likely due to the equipment issues at this site, with 2 of the 7 units only partially operational.

Table 2. Detection efficiency calculated for V9-1H tags implanted in Seymour River steelhead smolts in 2015. N=number, DE=detection efficiency, SE=standard error, NA=not available.

Detection Site	N Present	N Detected	V9 DE (SE)
Sub-arrays			
Malaspina Strait	38[a]	30	0.79 (0.066)
NSOG	42	42	1 (0)
Discovery Islands	32	32	1 (0)
Johnstone Strait	23	23	1 (0)
QCS	NA	14	NA
Sub-sub-arrays			
Discovery Islands South	32	31	0.97 (0.03)
Discovery Islands North	32	32	1 (0)
Johnstone Strait East	23	23	1 (0)
Johnstone Strait West	23	21	0.91 (0.06)

[a]Total excludes 4 fish first detected on the west side of NSOG after migrating around the southern end of Texada Island.

The raw detection efficiency of the V4 transmitters on the Discovery Islands sub-array using the proportion of tags detected for the duration of the study was 61%. If we limit the time period to up to the time when >50% of the tags were active, then the raw DE was 64% (Figure 9; Table 3). The daily cumulative DEs for this period ranged between 55-68% (Appendix B).

If all tag batteries had been actively transmitting, we estimate that detection efficiency of the V4 transmitters on the Discovery Islands sub-array would be 76% (Figure 9; Table 3). The corrected daily cumulative DEs ranged between 61-79% (Figure 10; Appendix B). This range of estimates is the cumulative DE for each day from the first day of detection up to the mean date of predicted battery expiry for the V4 tags (day 42). Beyond the mean date, estimates continued to be stable for some days and then became progressively affected by reduced sample size, tag failure and breakdown in the correction for tag failure (prediction of detection efficiencies >100%), indicating that the tag failure rate model over-estimated failure rate in the very last stages of battery life. Most tagged fish (79%[7]) arrived at the Discovery Islands sub-array before the mean date of tag expiry.

Although these values suggest promising performance of the sub-array at detecting these smaller tags, 21% (n=4) of the tags detected on this sub-array were detected only a single time (Figure 11; Table 4). Single detections are often questionable in telemetry studies, but in this study single detections were classified as true detections because the paired V9 tag was detected as well. Array design, tag programming, and migration speed are factors that affect the detection rate; therefore, the range of estimates we provide may vary depending on the specific conditions of future studies. However, having no prior experience with this transmitter, we were quite pleased with the outcome.

The DE of the V4 transmitters on the MS sub-array was not significantly affected by V4 tag expiry because most fish arrived here before tags began to expire (83% arrived before or on the date that 95% of the tags were expected to be active [day 36]). DE estimates for the MS sub-array were 32-34% in the period before tag expiry (up to day 36), and 31-34% using all detections up to the mean date of tag expiry. Correction for tag expiry increased these estimates by 1-2%. The reduced performance relative to the Discovery Islands sub-array is not surprising because the MS sub-array was deployed as a single line, and two of the receiver moorings (of seven) were only partially operation during the migration.

The detection efficiency estimates of the V4 180 kHz transmitter on the Discovery Islands sub-sub-arrays was 27-41% on DI South and 33-35% on DI North using the proportion of tags detected and including detections recorded up to the mean date of V4 tag expiry. When corrected for tag failure, the DE estimates increased to 30-55% and 37-43%, respectively. These estimates are somewhat higher than obtained for MS, so it is reasonable to assume that the MS performance was indeed influenced by the two receivers that were only partially operational. In all cases, the number of detections recorded per fish was well below that for the V9 tags (10-28% of V9 tags were detected >5 times on the single-line deployments).

[7] This is the percentage of fish arriving before the kill date (at day 54) for the V4 tags which is the maximum count that can be used to estimate the detection efficiency of the V4 tags. In contrast, Figure 8 reports the percentage of *all* fish detected on the Discovery Islands sub-array that arrived before the mean date of V4 tag failure (72%).

The difference in the confidence intervals around the DE estimates was negligible for V4 tags when estimated either as the standard error of a proportion or via CJS modeling. In contrast, estimates of survival using the CJS modeling approach for the V4 tags did have wider confidence intervals relative to the estimates obtained with the proportion method (see section 3.2 Results Figure 15).

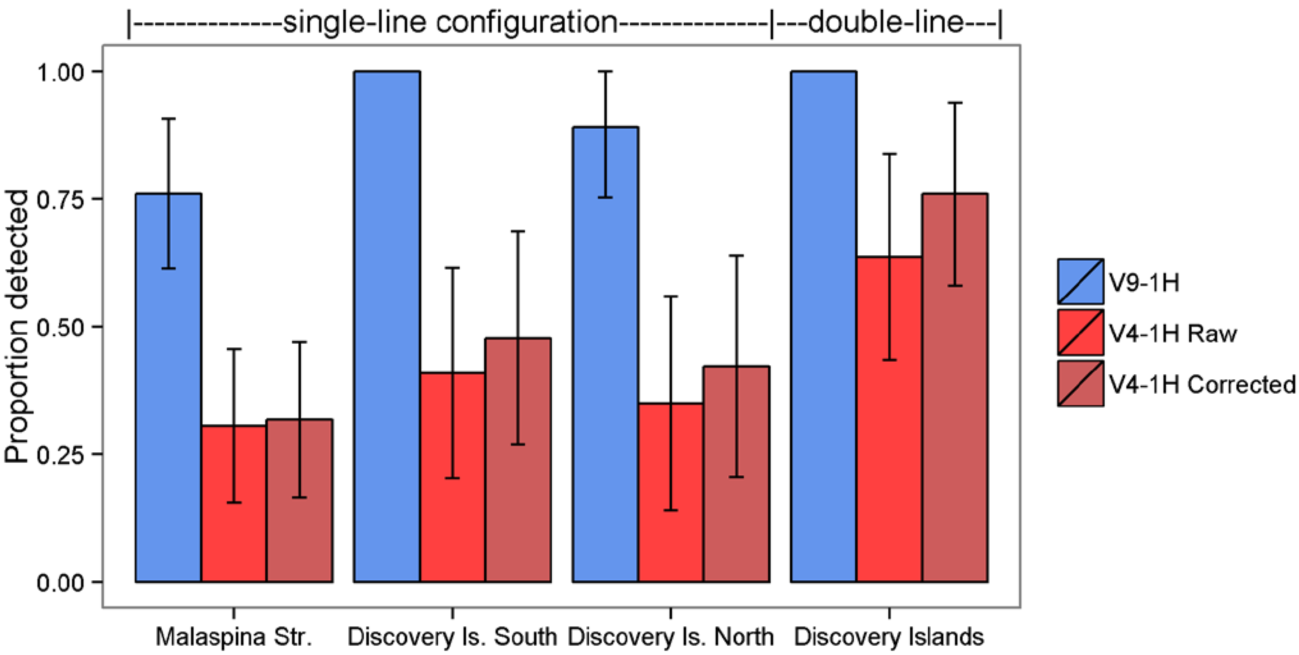


Figure 9. Detection efficiency estimates (with 95% confidence intervals) for V9-1H and V4-1H tags implanted in Seymour River steelhead smolts in 2015. Estimates for the V4 tags were made using all detections recorded before day 42 when 50% of V4 tags were predicted to have expired. Estimates for the V9 tags were made using all detections recorded since the batteries in the V9 tags did not begin to expire during the study period. Raw=estimates were made from the proportion of fish detected uncorrected for tag expiry; Corrected=estimates corrected for tag expiry (see Methods section 2.3).

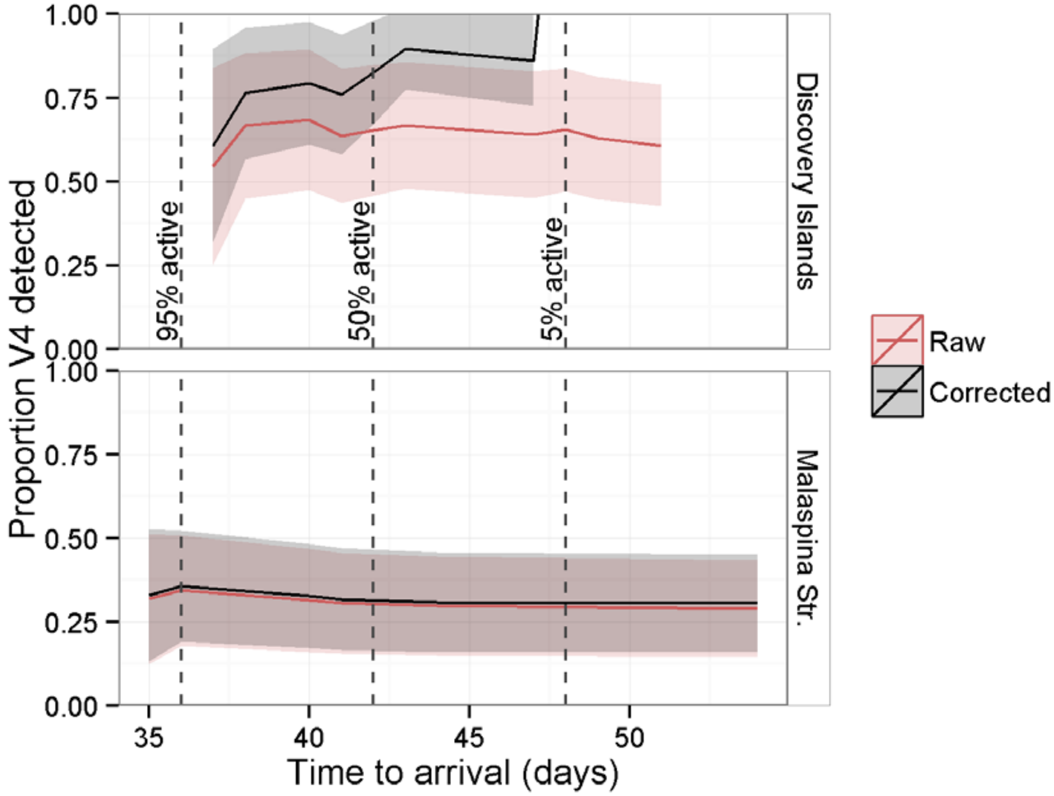


Figure 10. Cumulative detection efficiency estimates (with shaded 95% confidence intervals) for V4-1H tags calculated by progressively including more and more of the detection record until the kill date for the V4 tags (day 54). Grey dotted lines indicate the percent of tags expected to be active by each date. Raw=estimates were made from proportion of fish detected uncorrected for tag expiry; Corrected=estimates corrected for tag expiry (see Methods section 2.3). These data are available in table format in Appendix B.

Table 3. Detection efficiency calculated for V4-1H tags implanted in Seymour River steelhead smolts in 2015. These estimates were made using either all detections until the tags were programmed to turn off (Time period=All), or all detections recorded before day 42 when 50% of V4 tags were predicted to have expired (Time period=<50% expired). Numbers detected in both time periods exclude counts of V4 tags that were first detected >24 hours after their paired V9 (N=3 at Discovery Islands, N=5 at Discovery Islands South, and N=3 at Discovery Islands North).

Sub-array	Time Period	N Present	N Detected	N Corrected	Raw DE (SE)	Corrected DE (SE)
Discovery Islands	<50% expired	22	14	16.71	0.64 (0.1)	0.76 (0.09)
	All	28	17		0.61 (0.09)	
Malaspina Strait	<50%expired	36	11	11.44	0.31 (0.08)	0.32 (0.08)
	All	38	11		0.29 (0.07)	
Discovery Is. South	<50% expired	22	9	10.49	0.41 (0.1)	0.48 (0.11)
	All	27	11		0.41 (0.09)	
Discovery Is. North	<50% expired	20	7	8.46	0.35 (0.11)	0.42 (0.11)
	All	28	11		0.39 (0.09)	

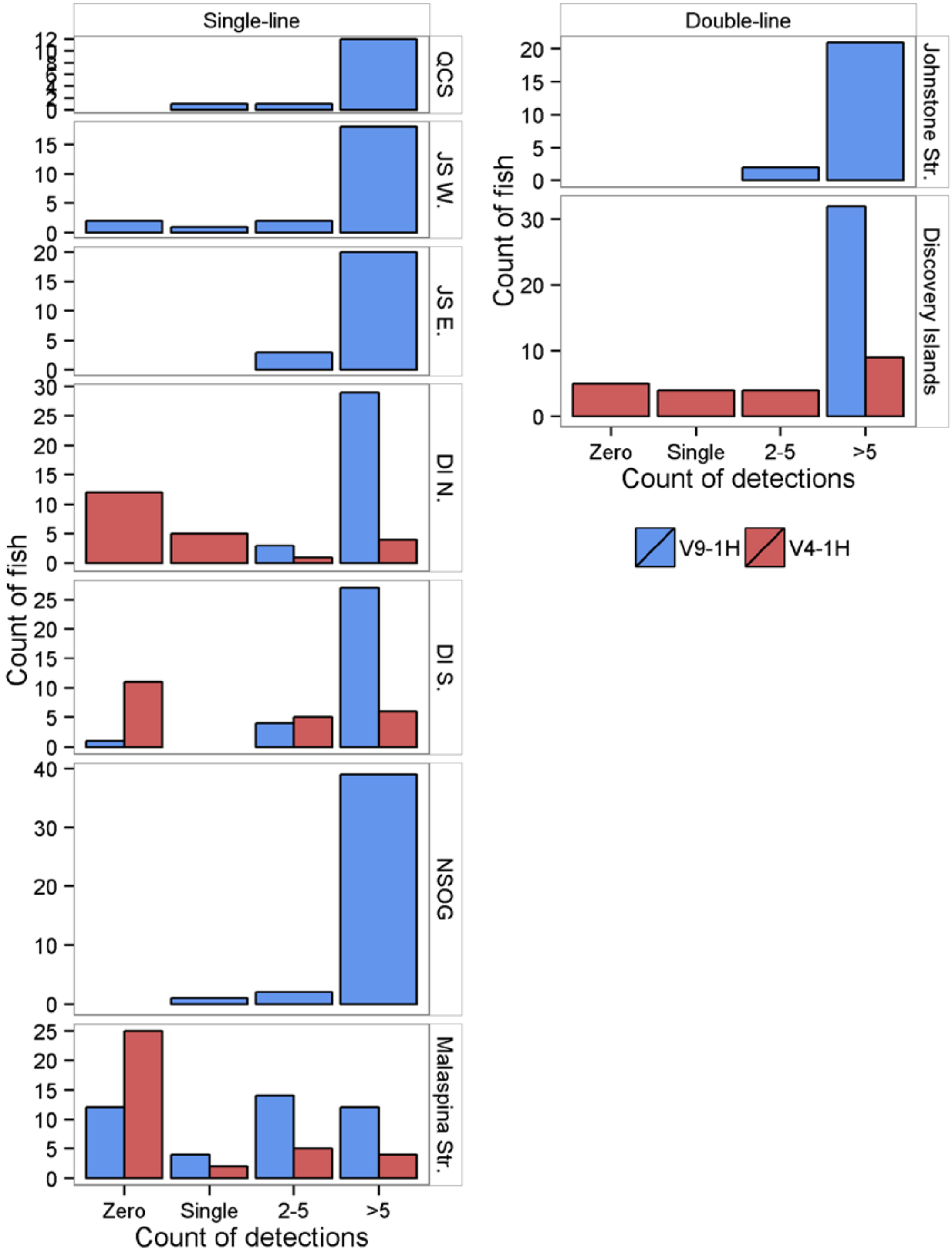


Figure 11. Count of detections of individual double-tagged Seymour River steelhead smolts. Counts are divided into categories indicating zero, single, sufficient (2-5), and abundant detections (>5). For V4 tags, counts were made using detections recorded before day 42 when 50% of V4 tags were predicted to have expired. For V9 tags, counts were made using all detections.

Table 4. Count of detections recorded for individual Seymour River steelhead smolts. Detailed caption in Figure 11.

	Detection Counts							
	V9-1H				V4-1H			
Detection Site	**Zero**	**Single**	**2-5**	**>5**	**Zero**	**Single**	**2-5**	**>5**
Double-line deployments								
Discovery Islands	0	0	0	32	5	4	4	9
Johnstone Strait	0	0	2	21	0	0	0	0
Single-line deployments								
Malaspina Strait	12	4	14	12	25	2	5	4
Northern Strait of Georgia	0	1	2	39	0	0	0	0
Discovery Islands South	1	0	4	27	11	0	5	6
Discovery Islands North	0	0	3	29	12	5	1	4
Johnstone Strait East	0	0	3	20	0	0	0	0
Johnstone Strait West	2	1	2	18	0	0	0	0
Queen Charlotte Strait	0	1	1	12	0	0	0	0

3.2. Objective B- Provide survival data for Seymour steelhead in 2015

Survival between release in Malaspina Strait and NSOG was 84% (Figure 12; Table 5). It then dropped slightly between NSOG and DI (76%), dropped again DI to JS (72%), and again in the final segment between JS and QCS (61%). Cumulative survival over the ~270 km from release to Queen Charlotte Strait was 28% (Figure 13; Table 5). Survival per day was slightly higher between NSOG and the Discovery Islands than in other segments (Figure 14), and survival per km was slightly lower for the initial segment between release and NSOG than it was in the segments beyond.

As part of Objective A, we used the V4 data and CJS models to estimate survival and detection probabilities, and to assess how estimates might change without the V9 tag data. Survival estimates are similar for the two methods, but the CI’s are wider for the CJS method (Figure 15).

Of the double-tagged steelhead detected on the Discovery Island sub-array, 20 were last detected in Discovery Passage, 11 in Sutil Channel, and 1 in Desolation Sound. Survival to JS was 100% for those individuals that used Discovery Passage and 22% (SE=14%) for Sutil Channel (excluding the two fish that migrated south to NSOG after detection in Sutil Channel). The single fish detected in Desolation Sound survived to reach JS.

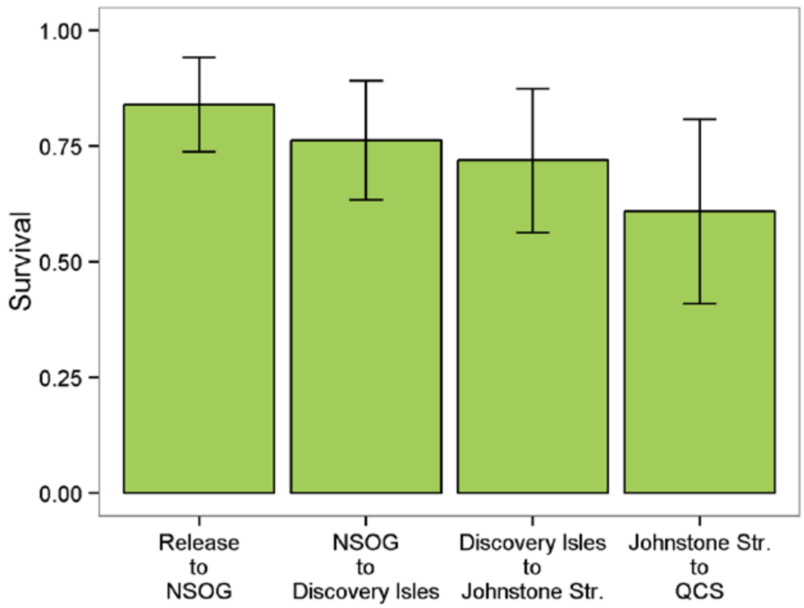


Figure 12. Segment-specific survival estimates (95% CIs) for double-tagged Seymour River steelhead smolts released in Malaspina Strait in 2015. Estimates were obtained from V9 detections which had 100% DE on NSOG, DI and JS. QCS was assumed to have 100% detection efficiency for V9 tags.

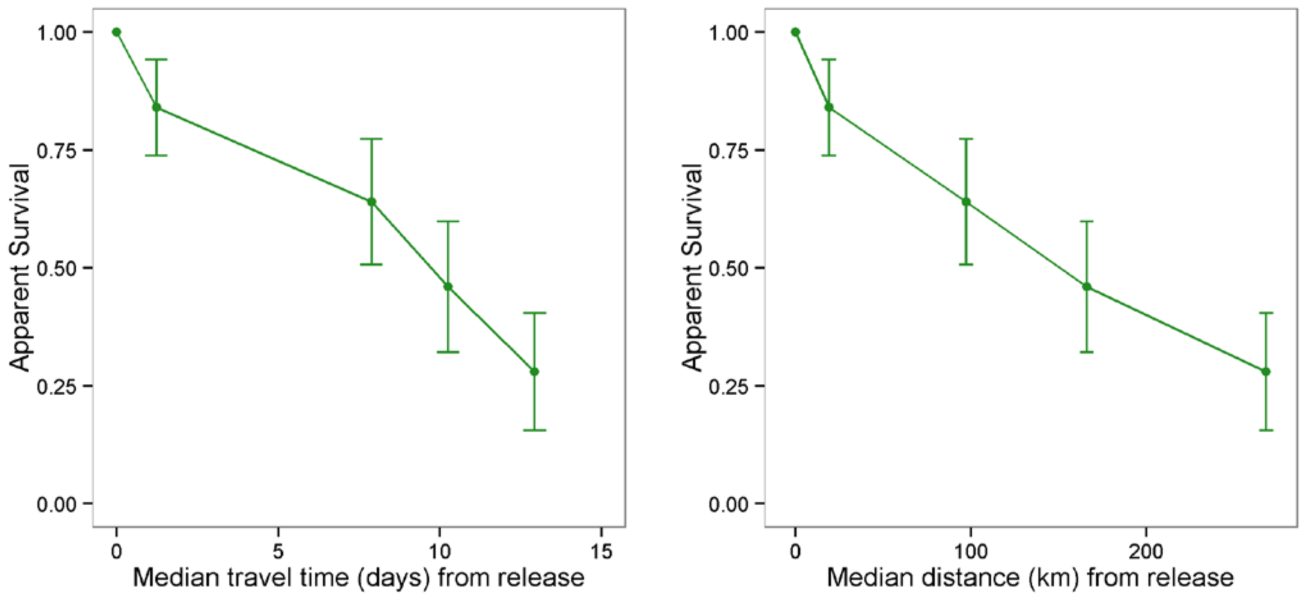


Figure 13. Cumulative survival estimates (95% CIs) with time and distance for double-tagged Seymour River steelhead smolts released in Malaspina Strait and migrating to NSOG, DI, JS, and QCS in 2015.

Table 5. Segment-specific and cumulative survival estimates (with SE) for double-tagged Seymour River steelhead smolts released in Malaspina Strait in 2015. Estimates were obtained from V9 detections which had 100% DE on NSOG, DI, and JS. QCS was assumed to have 100% DE. $S_{segment}$=survival in the segments between release and NSOG, and then between each set of sub-arrays; $S_{cumulative}$=survival from release to each sub-array.

Sub-array	$S_{segment}$	$S_{Cumulative}$
NSOG	0.84 (0.052)	0.84 (0.05)
Discovery Islands	0.76 (0.07)	0.64 (0.07)
Johnstone Strait	0.72 (0.08)	0.46 (0.07)
QCS	0.61 (0.10)	0.28 (0.06)

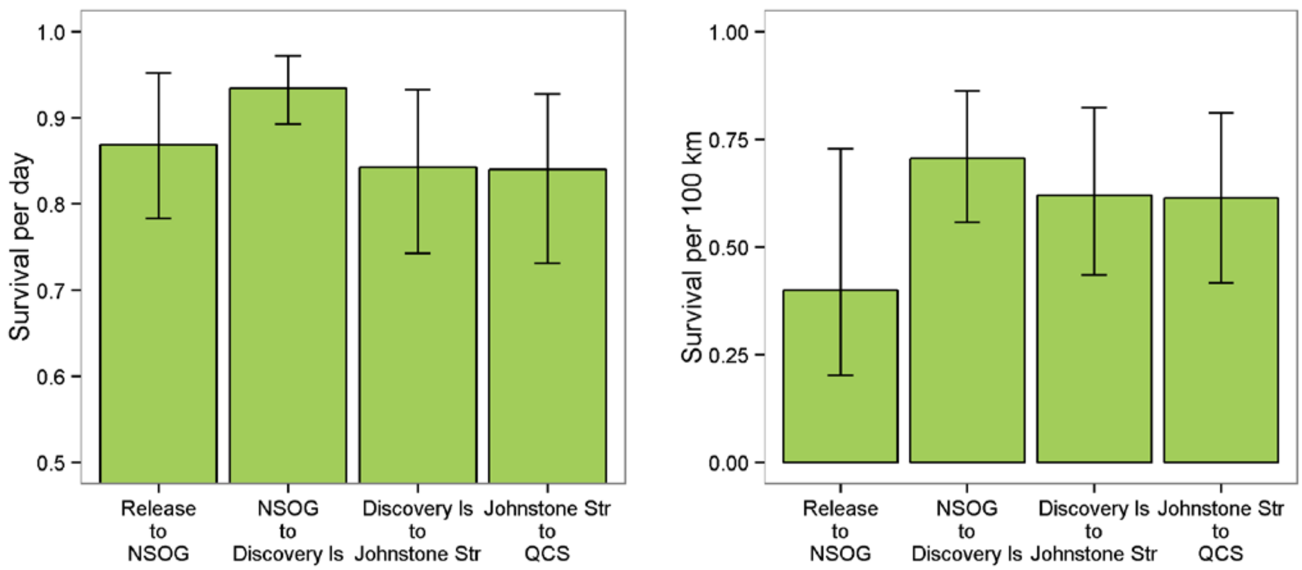


Figure 14. Survival per day and per 100 kms (95% CIs) in each migration segment for double-tagged Seymour River steelhead smolts released in Malaspina Strait in 2015. Estimates were obtained from V9 detections which had 100% DE on NSOG, DI, and JS. QCS was assumed to have 100% DE.

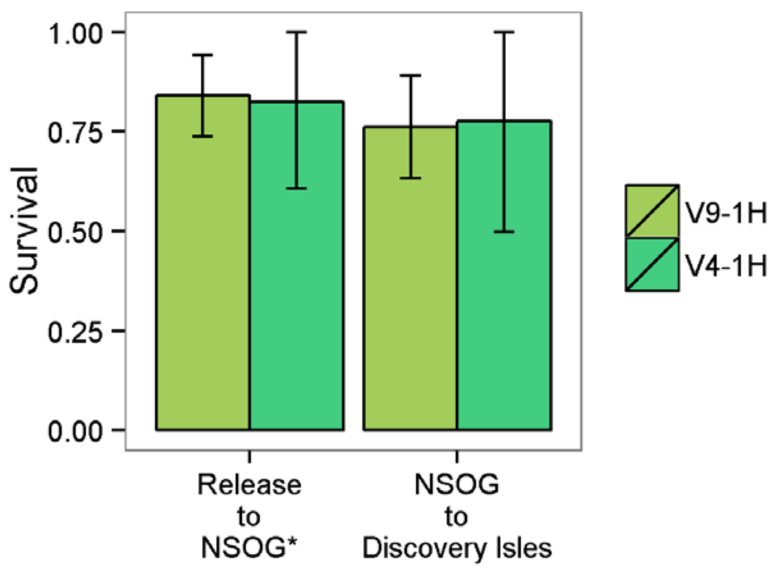


Figure 15. Comparison of the segment-specific survival estimates (95% CIs) for double-tagged Seymour River steelhead smolts made using the V9 tag (proportion method) versus the V4 tag (CJS method). Fish were released in Malaspina Strait in 2015. *V4s were actually detected at the Malaspina Strait sub-array which was deployed 550 m south of the NSOG sub-array in 2015 (i.e., at essentially the same location given the scale of migration). Note the wider confidence intervals resulting from the use of the lower acoustic power V4 tag.

KINTAMA

3.3. Objective C- Evaluate the improved performance of VEMCO acoustic receivers retro-fitted with a solid-state acoustic amplifier

The addition of solid-state acoustic amplifier did not improve the detection efficiency of the VEMCO receivers at either frequency (Figure 16). Additionally, there was no difference in the number of detections recorded per fish (Figure 17).

Because there was a flaw with the mold used to fabricate the 69 kHz amplifiers used in Malaspina Strait, we re-tooled the 69 kHz mold and then tested both the new 69 kHz and the old 180 kHz amplifiers in Horne Lake, BC, between November 26th-Dec 15th 2015. There was still no difference in performance between amplified and standard receivers in Horne Lake (results not shown).

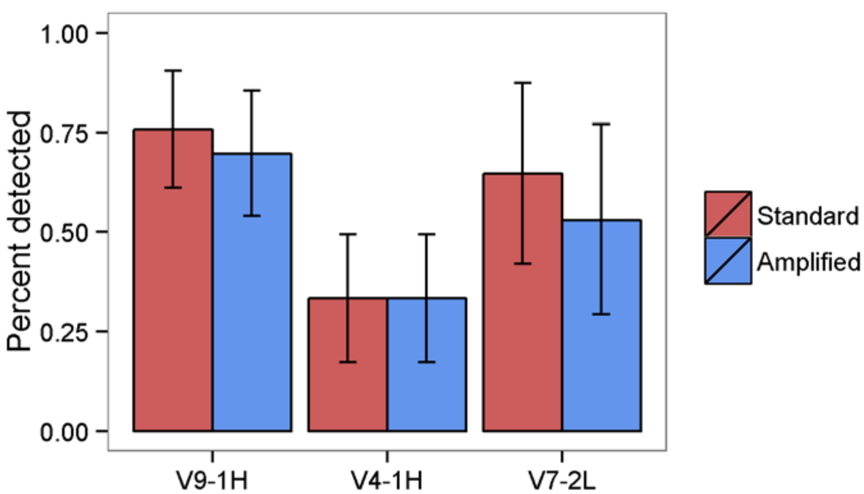


Figure 16. Detection efficiency of amplified and standard 69 and 180 kHz acoustic receivers deployed in Malaspina Strait in 2015. The receivers detected Seymour River steelhead smolts implanted with VEMCO V4 180 kHz, V9 69 kHz, and V7 69 kHz acoustic tags.

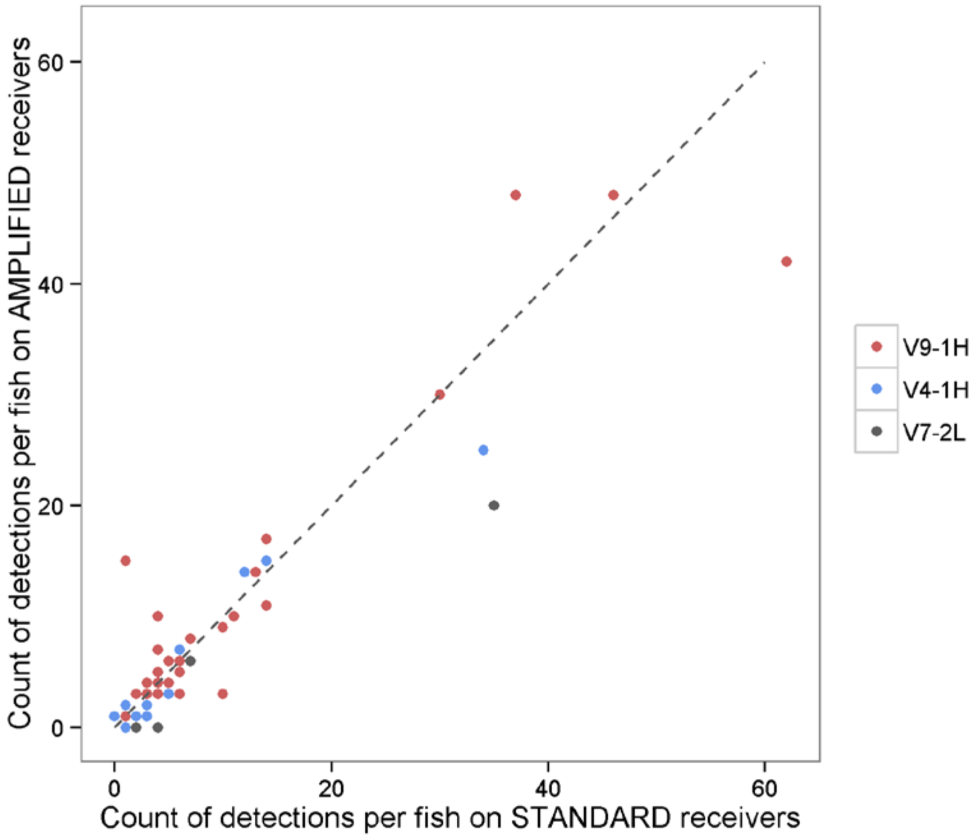


Figure 17. Count of the number of times each Seymour River steelhead smolt was detected on standard versus amplified receivers at each position on the Malaspina Strait sub-array in 2015. The smolts were implanted with VEMCO V4 180 kHz, V9 69 kHz, and V7 69 kHz acoustic tags. The grey dotted line is the 1 to 1 line.

4. Discussion

Objective A. Evaluate the detection efficiency of the new 180 kHz tags on the new dual frequency sub-arrays

The Discovery Islands sub-array detected 64% of the V4 tags despite up to 50% tag battery failure. When we applied a correction for tag expiry, the DE increased to 76% (Figure 9; Table 3). The estimated daily cumulative DE ranged between 61-79% (Figure 10), which is on par with the performance of the larger V7 tag using the original geometry of the POST arrays (Welch et al. 2011, Clark et al. 2016) and suggests that, with revised sub-array geometry and more capital-intensive sub-arrays, it is now possible to track smolts ~10 cm fork length in the Salish Sea and beyond with acceptable statistical precision.

To achieve this level of performance, the Discovery Islands sub-array required twice the number of receivers used in the traditional POST design and additional infrastructure costs. Despite this extra cost, we recommend the re-designed configuration because the performance of the original POST design geometry was substantially lower (27-55% for individual sub-sub-arrays; 32-36% at Malaspina where two units were not fully operational) which may prevent precise estimates of early marine survival.

We have presented a range of plausible detection efficiency estimates for the V4 tag because battery failure in the V4 tags (but not the V9 tags) began while the fish were still arriving at the detection sub-arrays. The true detection efficiency would have been underestimated had we not corrected for tag failure, but the accuracy of the correction is unclear. We caution that the confidence limits on the DE estimates are unavoidably wide given that this was a pilot-scale study with only 50 fish released and 32 surviving to reach Discovery Islands.

An important consideration for future survival studies is that the number of detections recorded per fish was reduced with the V4 tag. False detections are rare with VEMCO technology, but multiple detections spaced closely in time are typically required to prove the fish was present. Single detections are potentially false, but can be accepted as real if they meet screening criteria (i.e. see section 2.4 Data Management). In this study, we were confident of fish presence because multiple detections were recorded of the paired V9 tag. If single detections were removed from the dataset, the performance of the Discovery Island sub-array would drop to ~55%. Although we do not think it is necessary to remove all single detections, these results indicate that the promising performance we achieved for the V4 tags in this study may vary with the specific conditions of each study (tag programming, fish swimming speed, etc).

We note that the Discovery Islands sub-array was deployed in an area of strong ocean currents (daily maximums of >5 knots) which can potentially degrade sound transmission and reduce the amount of time the tags are in proximity of the receivers. However, currents may also sweep smolts back and forth past the receivers by the cycling of the tides which raises the possibility of repeated bouts of potential detection. The Seymour River steelhead smolts used in this study milled in the area of the Discovery Islands with some individuals moving between Sutil Channel and Discovery Passage in the Discovery Islands, and others moving north and south between Discovery Islands and NSOG. Since these behaviours may not apply to other stocks, we made our detection efficiency estimates more reflective of a single pass by removing all V4 tags that arrived more than a day after their paired V9. The 24 hour window allows for some milling behaviour, but removes fish that clearly left the area before returning.

Despite the potential issues, the results suggest that the V4 tag can likely be used in the ocean with a reasonably cost-effective increases in array cost, and return sufficiently tight statistical confidence intervals on the resulting survival estimates to provide scientifically useful results. Importantly, the ability to tag smolts as small as 10 cm opens up the possibility of extending POST-style studies to populations of wild sockeye, coho, Chinook, and steelhead to smolt sizes that have been previously impossible to study.

Objective B. Provide survival data for Seymour steelhead in 2015

Estimation of steelhead smolt survival was initially the prime objective of our study, but the new dual-frequency sub-arrays in the Discovery Island and Johnstone Strait provided an opportunity to also focus on testing the performance of potential new array designs for use with the V4 tag, which has clearly important implications for future SSMSP studies. In 2015, Professor Scott Hinch's (UBC) tagging operations were fortuitously moved to the same hatchery after high water levels at Chilko Lake made it impossible for DFO to deploy the weir used to facilitate capture of two year old sockeye smolts during the 2015 outmigration. The UBC group were able to release a substantial number of Seymour steelhead tagged with V7 tags at the conventional release sites for this stock (Lower Seymour River and DFO West Vancouver Lab; N=243[8]), supplementing our own study. As a result, survival estimates for Seymour steelhead released from the conventional sites are available from the UBC SSMSP-funded study. In this report we have provided survival estimates of our double-tagged fish (V4 + V9) for the northern migration segments after release near the NSOG sub-array.

Cumulative survival between NSOG and QCS (33%) was similar to but slightly lower than that obtained by the UBC group in 2015 (37-41%). Since our smolts were exposed to additional transport and at a later date, it is possible that their survival is not representative of the general population of hatchery smolts; however, there was considerable overlap of confidence intervals in all migration

[8] Thirty additional fish were tagged in the UBC study but are not counted here because they were released in the Seymour River upstream of the December 2014 rockslide site and were never detected on any river or ocean receivers.

segments. It is also possible that an initial spate of high mortality due to naïve hatchery-reared smolts being eaten by predators soon after release could also produce the same result (Brown and Day, 2002; Rechisky et al. 2012); surviving smolts from the cohort released off WVL would have had the initially less-fit individuals culled quickly so that only the experienced smolts would be left to compare with the survival of naïve smolts released in Malaspina Channel. Survival for the NSOG-QCS segment ranged between 20-53%[9] for Seymour steelhead in previous studies (2006-2009; Balfry et al. 2011b), 19-61% for Chilko Lake sockeye (2010-2013; Clark et al. 2016), and 37-60% for Cultus Lake sockeye (2004-2007; Welch et al. 2009), consistent with the survival estimates for our study in the segments north of NSOG and suggesting that smolts were probably not significantly affected by the extra transport.

Survival in the segment immediately after release (south of NSOG) was lower than in subsequent segments when converted to survival rate per unit distance, but was on par with these estimates when converted to rate per unit time. Reduced survival immediately after release has been attributed to the effects of tagging and/or transport, as well as to naivety as hatchery-origin smolts are first exposed to life in the wild (Brown and Day, 2002; Rechisky et al. 2012). Since our smolts did not experience reduced survival per day, it seems likely that they milled for some time after release before beginning their migration north.

The two new sub-arrays within the Discovery Islands and Johnstone Strait allowed us to divide the ~240 km segment between NSOG and QCS into three smaller areas to better identify mortality hotspots. For our tagged steelhead smolts, mortality was generally similar in all these segments. Mortality was slightly higher in the final and longest segment between Johnstone Strait and the northern end of Queen Charlotte Strait, but this difference was not evident after we account for segment length and travel time.

The new sub-array in the Discovery Islands was configured to monitor the three routes smolts might take to migrate north after exit from the Salish Sea. Most fish took the Discovery Passage route (67%), followed by Sutil Channel (30%). Interestingly, survival was 100% for the smolts that used Discovery Passage but only 22% (SE=14%) for the smolts that used Sutil Channel. Only a single individual was detected migrating through Desolation Sound, but this fish survived to reach Johnstone Strait. These patterns were also apparent for the UBC fish: most took the Discovery Passage route

[9] From Table 3 in Clark et al. 2016; excluding groups where <5 fish survived to each NSOG.

(65%) where survival was also highest (85% versus 40% for Sutil Channel). As with our study, only one of the UBC fish migrated north through Desolation Sound and it too survived to reach Johnstone Strait. Therfore, it appears that steelhead smolts may express preferences in migration routes and we may have identified potentially lower survival rates in Sutil Channel.

An alternative explanation for some of the mortality we observed is that smolts may have migrated south or residualized between the sub-arrays; however, this behaviour was only rarely observed. One individual migrated north to NSOG and then turned south and exited the Salish Sea through the Strait of Juan de Fuca (compared with the 32 fish known to have migrated north at least as far as the Discovery Islands). Two other individuals migrated as far as the Discovery Islands before turning south so that their last detection was on the NSOG sub-array (compared with 23 fish known to have subsequently migrated north as far as Johnstone Strait). Finally, four individuals almost certainly travelled south immediately after release in Malaspina Channel, but then turned north after passing the southern tip of Texada Island so that their first detections on the array were on the western side of the NSOG sub-array. Since we didn't deploy an acoustic sub-array in Malaspina Strait south of the release location, additional smolts may have also headed south without detection (to a maximum of 8 fish that were not detected on the acoustic array). However, because of the excellent detection efficiency the V9 tags, it is unlikely that fish passed over the acoustic array without detection.

We also explored how precise CJS survival estimates were using only the V4 tags, and then compared this to the known survival calculated using the V9 tags. The point estimates were nearly identical, but the error associated with the V4 survival estimates was larger (Figure 15). This is because detection probability of the V4 tags was less than one which increases the uncertainly in the survival estimate.

Objective C. Evaluate the improved performance of VEMCO acoustic receivers retro-fitted with a solid-state acoustic amplifier

An additional component of this study was to evaluate the performance of VEMCO acoustic receivers which were retro-fitted with a prototype solid-state acoustic amplifier. We tested the amplified receivers on the Malaspina Strait sub-array and again in Horne Lake. The addition of solid-state acoustic amplifier did not improve the detection efficiency of the receivers at either frequency.

5. Deliverables

The deliverables for this project are complete:

- Progress reports to SSMSP submitted June 3rd and December 17th, 2015.
- Final report to SSMSP (this document).
- Technical report to DFO State of the Ocean submitted April 19th, 2016
- Although the proposal lists that we will submit a manuscript for peer-reviewed publication on the performance of amplified detection systems, this will not be completed because of the null result.
- An animation of the movements of the Seymour River steelhead smolts released in 2015 is available on our website (http://kintama.com/visualizations/). The animation can be panned and zoomed, and the display output can be customized by the user. Tags and receivers can also be queried to obtain summary statistics as well as full detection histories.

6. Dissemination of Results

Conference Presentations

Advances in Tracking Juvenile Salmon: 2015 Salish Sea Array Deployments and Promising Performance of VEMCO's New V4 Transmitter. Salish Sea Ecosystem Conference Vancouver, BC, Canada. April 2016.

Advances in Tracking Juvenile Salmon in the Ocean: 2015 Salish Sea Array Deployments and Promising Performance of VEMCOs New V4 Transmitter. Western Division of the American Fisheries Society 2016 Annual General Meeting, Reno, NV, USA. March 2016.

Telemetry-based Estimates of Early Marine Survival and Residence Time of Juvenile Steelhead in the Strait of Georgia and Queen Charlotte Strait, 2015. State of the Pacific Ocean: 2016 Workshop, Nanaimo, BC, Canada. March 2016.

Salmon Tracking Studies and Advances in Salish Sea Acoustic Telemetry in 2015. BC Salmon Farmers Association Research Review Workshop, Nanaimo, BC, Canada. Feb. 2016.

Advances in Salish Sea Acoustic Telemetry: 2015 Array Deployments and V4 Transmitter Performance. Salish Sea Marine Survival Project Workshop (2015), Richmond, BC, Canada. Dec 2015.

Advances in Salish Sea Acoustic Telemetry: 2015 Array Deployments and V4 Transmitter Performance. Salish Sea Marine Survival Project Workshop (2015), Nanaimo, BC, Canada. Nov 2015.

Poster Presentation

Four Ways to Make Telemetry Arrays Cost-effective. Salish Sea Marine Survival Project Workshop Donor Event Poster Session, Richmond, BC, Canada. Dec 2015.

7. References

Ahrens, R. 2004. The Status of Steelhead Trout (*Oncorhynchus mykiss*) in British Columbia. Page 61 plus appendices. Unpublished report for the Pacific Fisheries Resource Convervation Council.

Balfry, S. 2011a. The effect of surgically implanted acoustic-tags on survival, tag retention, smoltification and growth performance in Chinook salmon (Oncorhynchus tshawytscha). *In* A. D. Porter, D. W. Welch, E. L. Rechisky, W. O. Challenger, M. C. J. Scott, H. Lydersen, P. M. Winchell, L. Neaga, J. D. Robb, & Y. K. Muirhead (Eds.), Marine and freshwater measurement of delayed and differential-delayed mortality of Columbia & Snake River yearling Chinook smolts using a continental-scale acoustic-telemetry array, 2010. (pp. 253-262). Portland, Oregon: Report to the Bonneville Power Administration by Kintama Research Services Ltd., Contract No. 46389, Project No. 2003-114-00.

Balfry, S., D. W. Welch, J. Atkinson, A. Lill, and S. Vincent. 2011b. The Effect of Hatchery Release Strategy on Marine Migratory Behaviour and Apparent Survival of Seymour River Steelhead Smolts (Oncorhynchus mykiss). PLoS ONE 6(3):e14779.

Beauchamp, D., et al. 2012. Marine Survival of Salmon and Steelhead in the Salish Sea – Puget Sound Component: Hypotheses and Preliminary Research Recommendations. p. 209. Available from: http://marinesurvivalproject.com/wp-content/uploads/Nov-2012-Salish-Sea-Workshop-Series-Recommendations-FINAL-4April2013.pdf.

Berejikian, B., M. Moore, and S. Jeffries. 2016. Predator-prey interactions between harbor seals and migrating steelhead trout smolts revealed by acoustic telemetry. Marine Ecology Progress Series 543:21–35.

Brown, C. and R.L. Day. 2002. The future of stock enhancements: lessons for hatchery practice from conservation biology. Fish Fish. 3: 79-94.

Chittenden, C., K. Butterworth, K. Cubitt, M. Jacobs, A. Ladouceur, D. Welch, and R. McKinley. 2009. Maximum tag to body size ratios for an endangered coho salmon (O-kisutch) stock based on physiology and performance. ENVIRONMENTAL BIOLOGY OF FISHES 84(1):129–140.

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 In press. Tracking wild sockeye salmon smolts to the ocean reveals distinct regions of nocturnal movement and high mortality. Ecological Applications:n/a-n/a.

Collins, A. L., S. G. Hinch, D. W. Welch, S. J. Cooke, and T. D. Clark. 2013. Intracoelomic Acoustic Tagging of Juvenile Sockeye Salmon: Swimming Performance, Survival, and Postsurgical Wound Healing in Freshwater and during a Transition to Seawater. Transactions of the American Fisheries Society 142(2):515–523.

Cormack, R. 1964. Estimates of survival from sightings of marked animals. Biometrika 51:429-438.

English, K. K., G. J. Glova, A. C. Blakley, and David Suzuki Foundation. 2008. An upstream battle declines in 10 Pacific salmon stocks and solutions for their survival. David Suzuki Foundation, Vancouver, B.C.

Jolly, G. 1965. Explicit estimates from capture-recapture data with both death and immigration: stochastic model. Biometrika 52:225-247.

Laake, J.L. 2015. RMark: An R Interface for Analysis of Capture-Recapture Data with MARK. AFSC Processed Rep 2013-01, 25p. Alaska Fish. Sci. Cent., NOAA, Natl. Mar. Fish. Serv., 7600 Sand Point Way NE, Seattle WA 98115.

Melnychuk, M. C., J. Korman, S. Hausch, D. W. Welch, D. J. F. McCubbing, and C. J. Walters. 2014. Marine survival difference between wild and hatchery-reared steelhead trout determined during early downstream migration. Canadian Journal of Fisheries and Aquatic Sciences.

Moore, M. E., B. A. Berejikian, F. A. Goetz, A. G. Berger, S. S. Hodgson, E. J. Connor, and T. P. Quinn. 2015. Multi-population analysis of Puget Sound steelhead survival and migration behavior. Marine Ecology Progress Series 537:217.

Morrison, P. R., E. P. Groot, and D. W. Welch. 2013. The Effect of Short-Duration Seawater Exposure and Acoustic Tag Implantation on the Swimming Performance and Physiology of Presmolt Juvenile Coho Salmon. Transactions of the American Fisheries Society 142(3):783–792.

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. Transactions of the American Fisheries Society 144(1):25–33.

Porter, A.D., D.W. Welch, E.L. Rechisky, M.C. Jacobs Scott, P.M. Winchell, and J. Day. 2012a. Key Findings of the Coastal Ocean Acoustic Salmon Tracking (COAST) project, 2006-2011. Report to the Bonneville Power Administration by Kintama Research Services Ltd., Contract No. 56199, Project No. 2003-114-00. 128 pp.

Porter, A.D., D.W. Welch, E.L. Rechisky, M.C. Jacobs Scott, P.M. Winchell, and J. Day. 2012b. Marine and freshwater measurement of delayed and differential-delayed mortality of Columbia & Snake River yearling Chinook smolts using a continental-scale acoustic-telemetry array, 2011. Report to the Bonneville Power Administration by Kintama Research Services Ltd., Contract No. 52071, Project No. 2003-114-00. 314 pp. Retrieved from http://pisces.bpa.gov/release/documents/documentviewer.aspx?doc=P129415.

Province of British Columbia. 2016. Provincial Framework for Steelhead Management in British Columbia. Ministry of Forests, Lands, and Natural Resource Operations, Fish and Wildlife Branch.

R Core Team. 2015. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org.

Rechisky, E. L., D. W. Welch, A. D. Porter, M. C. Jacobs-Scott, P. M. Winchell, and J. L. McKern. 2012. Estuarine and early-marine survival of transported and in-river migrant Snake River spring Chinook salmon smolts. Sci. Rep. 2.

Seber, G. 1965. A note on multiple-recapture census. Biometrika 52:249-259.

Smith, B.D., B.R. Ward, and D.W. Welch. 2000. Trends in British Columbia steelhead (Oncorhynchus mykiss) abundance indexed by angler success. Canadian Journal of Fisheries and Aquatic Sciences, 57: p. 1-16.

SSMSP. 2014a. U.S. – Canada 2013 Research Planning Retreat Follow-up Report. Available from: http://marinesurvivalproject.com/wp-content/uploads/US-CA-SSMSP-2013-Retreat-Report-14May2014.pdf.

SSMSP. 2014b. Research Work Plan: Marine Survival of Puget Sound Steelhead. p. 117. Available from: http://marinesurvivalproject.com/wp-content/uploads/FINAL-WORK-PLAN-PS-steelhead-marine-survival-31Jan2014.pdf.

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. Proceedings of the National Academy of Sciences.

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(5):736–750.
Welch, D., B. Ward, and S. Batten. 2004. Early ocean survival and marine movements of hatchery and wild steelhead trout (Oncorhynchus mykiss) determined by an acoustic array: Queen Charlotte Strait, British Columbia. DEEP-SEA RESEARCH PART II-TOPICAL STUDIES IN OCEANOGRAPHY 51(6–9):897–909.
Welch, D. W., B. R. Ward, B. D. Smith, and J. P. Eveson. 1998. Influence of the 1990 ocean climate shift on British Columbia steelhead (O. mykiss) and coho(O. kisutch) populations. Pages 77–87*in* G. Holloway, P. Muller, and D. Henderson, editors.Aha Huliko'a Hawaiian Winter Workshop on Biotic Impacts of Extratropical Climate Variability in the Pacific. University of Hawaii: Honolulu.
Welch, D. W., B. R. Ward, B. D. Smith, and J. P. Eveson. 2000. Temporal and spatial responses of British Columbia steelhead(Oncorhynchus mykiss) populations to ocean climate shifts. Fisheries Oceanography 9(1):17–32.
White, G. C., and K. P. Burnham. 1999. Program MARK: survival estimation from populations of marked animals. Bird Study 46(Suppl.):120–138.

8. Financial Summary

Our original proposal submitted to the PSF included the evaluation of the 180 kHz tags as well as equipment lease, deployment and recovery of a 180 kHz sub-array at the northern Strait of Georgia, and the development of an acoustic amplifier. The total cost of the project including in-kind contributions was $542,808, most of which was in-kind from Kintama for development and testing of the acoustic amplifiers which would also allow testing of the 180 kHz transmitters ($362,703 plus $80k from NRC IRAP). Kintama requested $56,980 from the SSMSP specifically for the evaluation of the 180 kHz transmitters. In the months following proposal submission, OTN agreed to a long-term loan of 41 VR4 receivers to the PSF and the SSMSP, and the PSF funded Kintama to design and deploy dual-frequency sub-arrays in the Discovery Islands and Johnstone Strait. This work was covered under the March 23, 2015 Service Agreement between the PSF and Kintama. As the 180 kHz transmitters could be tested on the new sub-arrays, our project Objectives shifted, but the requested funding from the SSMSP remained the same. As specified in the April 28th Service Agreement between the PSF and Kintama, we requested funding for 100 acoustic tags (50 V9s and 50 V4s), data analysis, report preparation, and an animation of steelhead movements.

Most other expenditures were provided in-kind by Kintama ($111,020 plus $35,000 from NRC IRAP). Vessels charters for deployment of the Malaspina Strait sub-array and transport of the double-tagged steelhead smolts to Malaspina Strait were organized by the PSF, CANFISCO, and BCSFA.

Kintama submitted invoice #2015-005 to the PSF for 100 transmitters ($44,800), and invoice #2015-009 for data analysis and submission of the November Progress Report ($6,090). As per the Service Agreement between the PSF and Kintama, one additional payment will be made by the PSF following receipt of this Final Report ($6,090).

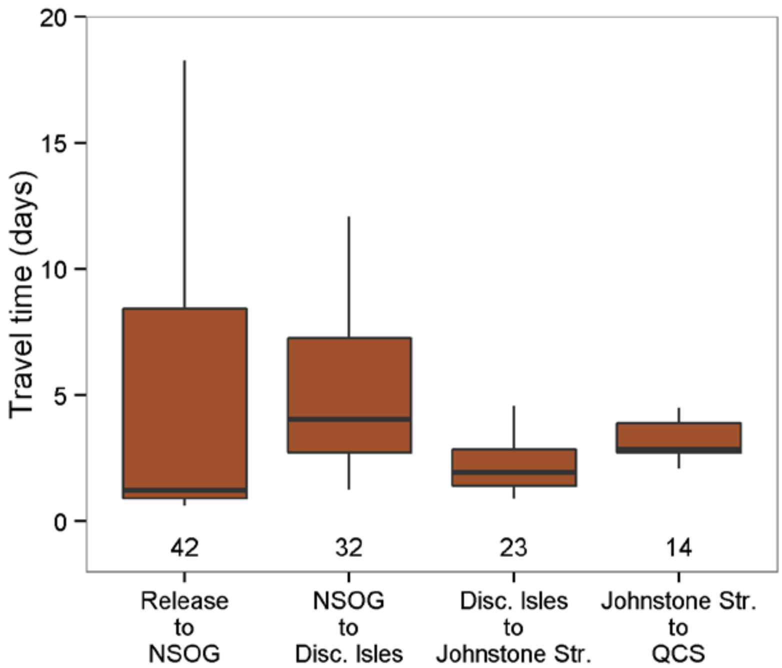
Expenses

Professional fees, labour: $11,600
Materials, supplies, equipment: $40,000
Overhead: $0
Taxes GST (for services) & PST (for transmitters): $2,580 + $2,800
Total from SSMSP: $56,980

A. Migratory Behaviours

A.1.1. Travel Times

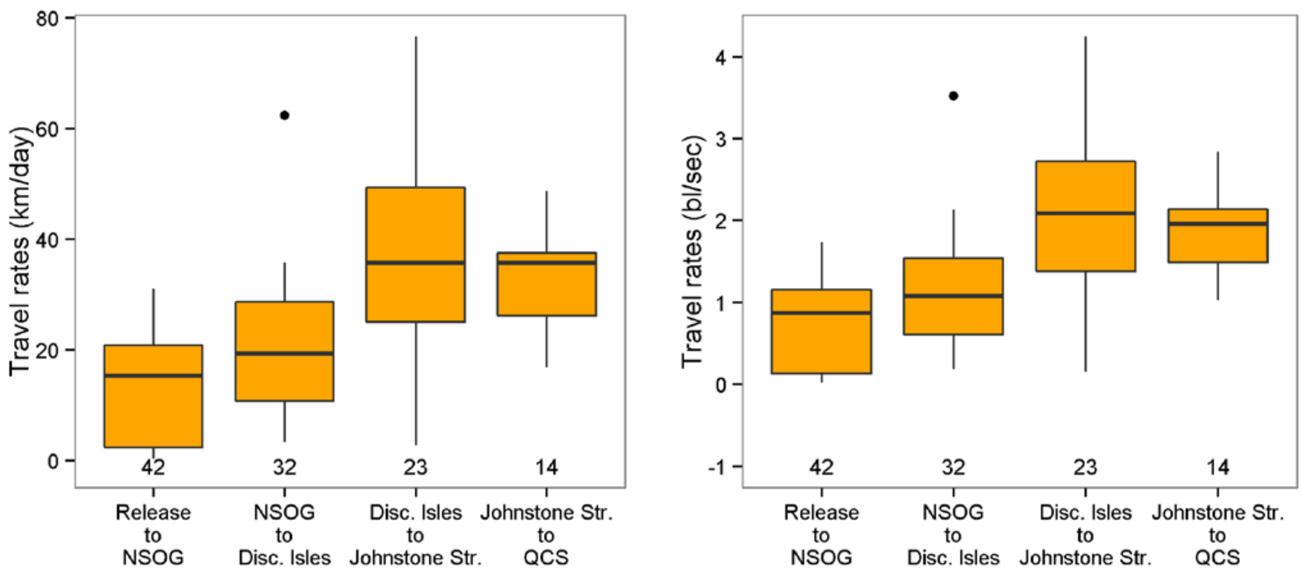
Travel time was calculated for each Seymour River steelhead smolt from either release or from the last detection on a sub-array (departure date) to the last detection on the next sub-array. These estimates were only conducted for smolts detected on both sub-arrays bracketing the segment in question.



	Sub-arrays		Travel Time (days)							
	Departure	Arrival	Count	Mean	SE	0%	25%	50%	75%	100%
Cumulative	Release	NSOG	42	5.87	1.51	0.61	0.91	1.24	8.44	50.29
		Discovery Islands	32	10.48	1.39	2.74	4.41	7.89	13.83	28.96
		Johnstone Strait	23	14.91	2.44	5.58	7.21	10.26	16.51	52.89
		QCS	14	15.16	1.58	9.33	10.46	12.94	18.30	29.12
Segment	Release	NSOG	42	5.87	1.51	0.61	0.91	1.24	8.44	50.29
	NSOG	Discovery Islands	32	5.75	0.78	1.25	2.73	4.04	7.26	23.46
	Discovery Islands	Johnstone Strait	23	3.67	1.13	0.90	1.40	1.93	2.85	24.50
	Johnstone Strait	QCS	14	3.30	0.29	2.09	2.71	2.85	3.91	6.03

A.1.2. Travel Rates

We converted the travel times into travel rates as distance/time. Distance was calculated as the median of the approximate shortest route in water taken by each fish between release and the receiver where the fish was first detected on each sub-array. Travel time was calculated as described above (A.1.1 Travel Times). Rates are presented as km/day and body-lengths/second. For the second calculation, body lengths were measured as fork length at tagging.

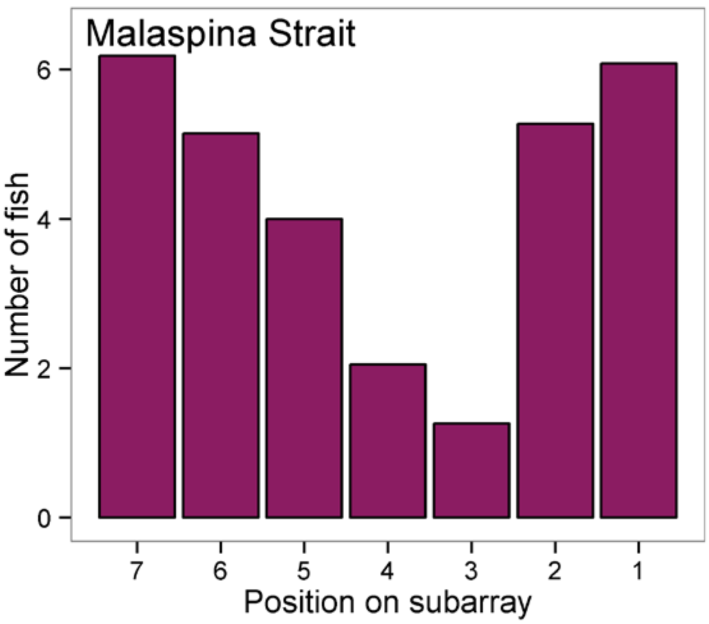


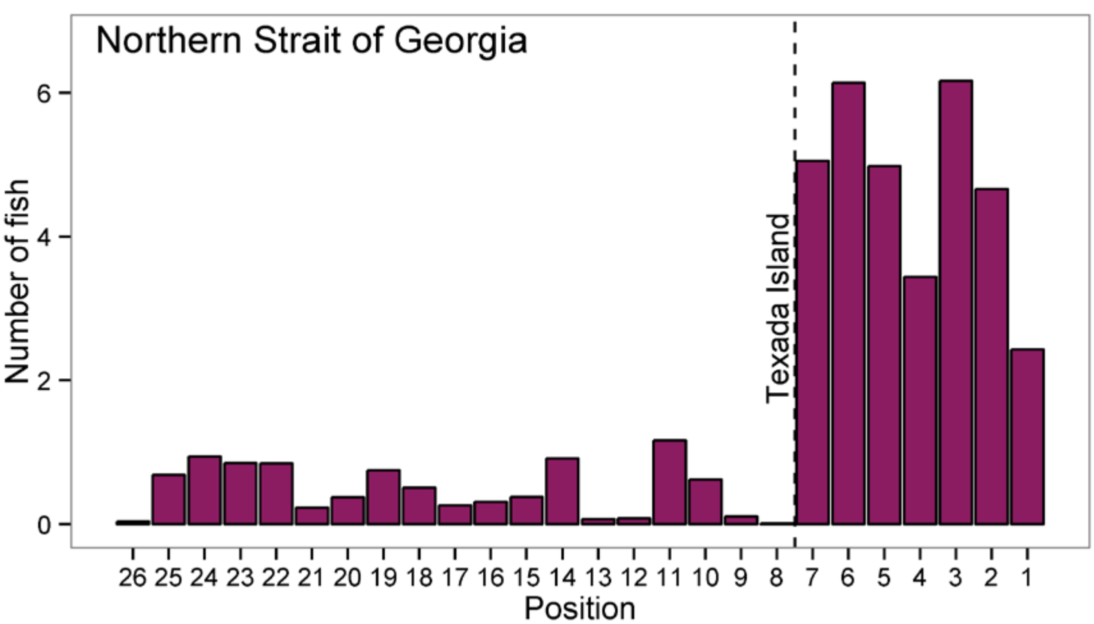
	Sub-arrays		Travel Rates							
Units	**Departure**	**Arrival**	**Count**	**Mean**	**SE**	**0%**	**25%**	**50%**	**75%**	**100%**
km/day	Release	NSOG	42	13.84	1.41	0.38	2.38	15.36	20.86	31.11
	NSOG	Discovery Islands	32	20.21	2.17	3.34	10.78	19.39	28.71	62.40
	Discovery Islands	Johnstone Strait	23	37.32	4.11	2.82	25.05	35.73	49.36	76.68
	Johnstone Strait	QCS	14	33.64	2.51	16.92	26.19	35.78	37.59	48.79
bl/sec[a]	Release	NSOG	42	0.78	0.08	0.02	0.13	0.87	1.16	1.74
	NSOG	Discovery Islands	32	1.14	0.12	0.18	0.61	1.07	1.54	3.52
	Discovery Islands	Johnstone Strait	23	2.10	0.23	0.16	1.38	2.09	2.72	4.25
	Johnstone Strait	QCS	14	1.89	0.14	1.03	1.49	1.96	2.14	2.84

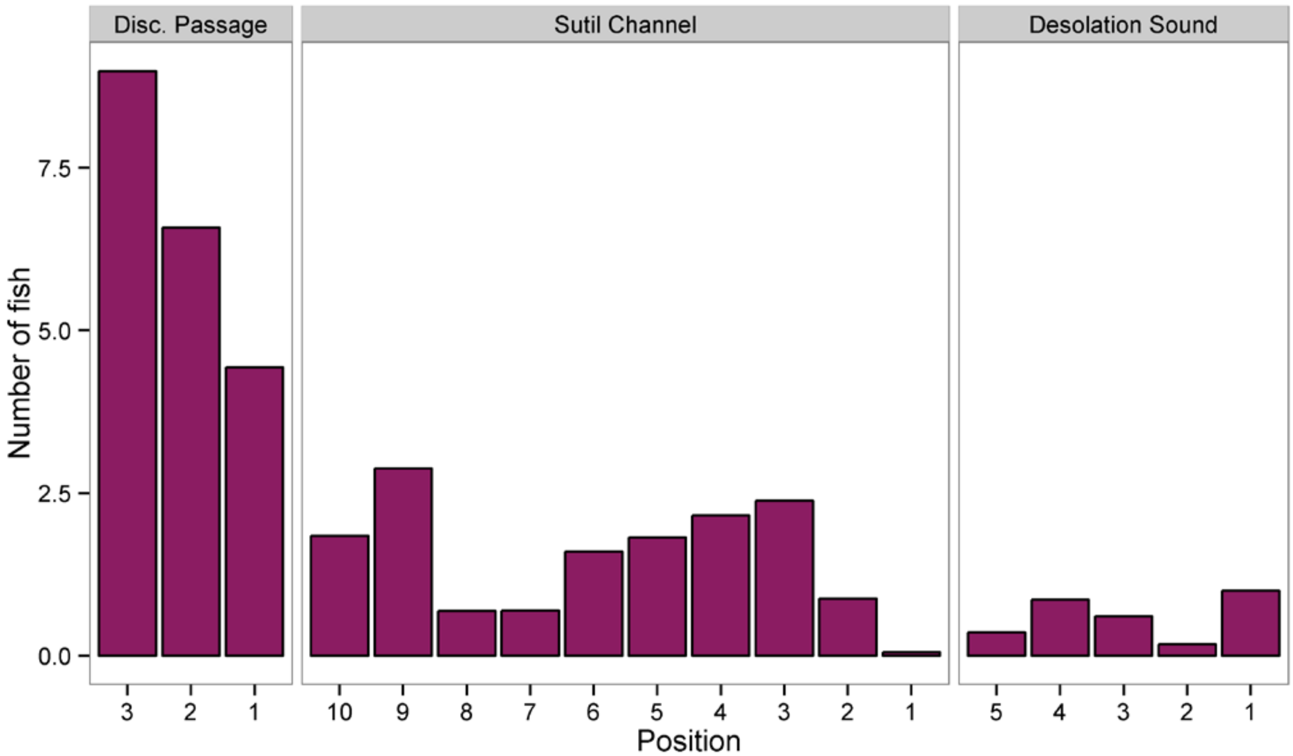
[a]bl/sec=body lengths per second

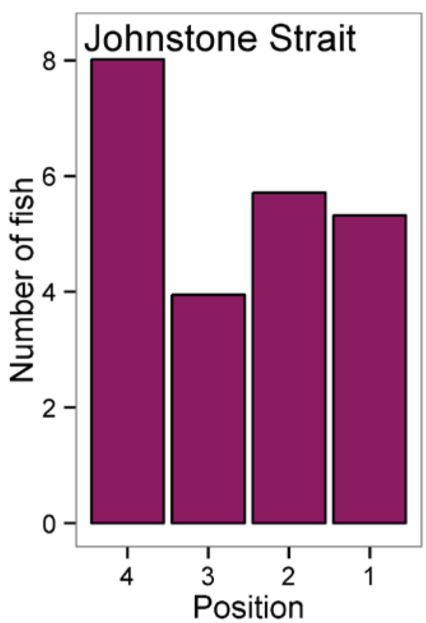
A.1.3. Cross-Channel Distributions

To identify possible migratory pathways, we plotted the number of Seymour River steelhead smolts that were heard at each position on each sub-array of acoustic receivers in 2015. Because individual fish are usually heard at more than one position on a line, we allocated a proportion of each fish to each of the receivers on which it was detected (i.e., if a fish was heard at three positions, each position was allocated 0.33 of a fish).






Disc. Passage
Sutil Channel
Desolation Sound
Number of fish
0.0
2.5
5.0
7.5
3 2 1
10 9 8 7 6 5 4 3 2 1
5 4 3 2 1
Position


Johnstone Strait
Number of fish
0
2
4
6
8
4 3 2 1
Position

B. Supplementary Table: Estimates of Cumulative Detection Efficiency for V4-1H Tags

Because the V4-1H tags began to expire while tagged smolts were still arriving at the detection subarrays, we calculated the cumulative detection efficiency estimates for these tags by progressively including more and more of the detection record until their kill date (day 54). This Appendix provides the full dataset of the raw and corrected counts of the tags detected and the resulting detection efficiency estimates for the V4 tags. Days where no fish were detected are not reported for that sub-array. For full methods, see Methods section 2.5 Objective A- Evaluate the detection efficiency of the 180 kHz tags on new dual frequency sub-arrays.

Sub-arrays	Day	Daily Count			Cumulative Count			Detection Efficiency (SE)	
		V9	V4		V9	V4			
			raw	corrected		raw	corrected	raw	corrected
Discovery Islands	37	11	6	6.68	11	6	6.68	0.55 (0.15)	0.61 (0.15)
	38	7	6	7.06	18	12	13.74	0.67 (0.11)	0.76 (0.1)
	40	1	1	1.32	19	13	15.07	0.68 (0.11)	0.79 (0.09)
	41	3	1	1.64	22	14	16.71	0.64 (0.1)	0.76 (0.09)
	42	1	1	2.25	23	15	18.96	0.65 (0.1)	0.82 (0.08)
	43	1	1	2.56	24	16	21.52	0.67 (0.1)	0.90 (0.06)
	47	1	0	0.00	25	16	21.52	0.64 (0.1)	0.86 (0.07)
	48	1	1	25.00	26	17	46.52	0.65 (0.09)	>1
	49	1	0	0.00	27	17	46.52	0.63 (0.09)	>1
	51	1	0	0.00	28	17	46.54	0.61 (0.09)	>1
Discovery Is. South	37	11	3	3.31	11	3	3.31	0.27 (0.13)	0.3 (0.14)
	38	7	5	5.86	18	8	9.17	0.44 (0.12)	0.51 (0.12)
	40	1	1	1.32	19	9	10.49	0.47 (0.11)	0.55 (0.11)
	41	3	0	0.00	22	9	10.49	0.41 (0.1)	0.48 (0.11)
	42	1	0	0.00	23	9	10.49	0.39 (0.1)	0.46 (0.1)
	43	1	1	2.56	24	10	13.06	0.42 (0.1)	0.54 (0.1)
	47	1	0	0.00	25	10	13.06	0.40 (0.1)	0.52 (0.1)
	48	1	1	25.00	26	11	38.06	0.42 (0.1)	>1
	49	1	0	0.00	27	11	38.06	0.41 (0.09)	>1
Discovery Is. North	37	6	2	2.25	6	2	2.25	0.33 (0.19)	0.37 (0.2)
	38	8	3	3.37	14	5	5.62	0.36 (0.13)	0.4 (0.13)

Sub-arrays	Day	Daily Count			Cumulative Count			Detection Efficiency (SE)	
		V9	V4		V9	V4			
			raw	corrected		raw	corrected	raw	corrected
	39	2	1	1.20	16	6	6.82	0.38 (0.12)	0.43 (0.12)
	40	2	0	0.00	18	6	6.82	0.33 (0.11)	0.38 (0.11)
	41	2	1	1.64	20	7	8.46	0.35 (0.11)	0.42 (0.11)
	42	2	1	2.00	22	8	10.46	0.36 (0.1)	0.48 (0.11)
	43	2	2	4.81	24	10	15.27	0.42 (0.1)	0.64 (0.1)
	47	1	0	0.00	25	10	15.28	0.40 (0.1)	0.61 (0.1)
	49	2	1	25.00	27	11	40.28	0.41 (0.09)	>1
	51	1	0	0.02	28	11	40.30	0.39 (0.09)	>1
Malaspina Strait	35	22	7	7.25	22	7	7.25	0.32 (0.1)	0.33 (0.1)
	36	10	4	4.19	32	11	11.44	0.34 (0.08)	0.36 (0.08)
	40	3	0	0.00	35	11	11.44	0.31 (0.08)	0.33 (0.08)
	41	1	0	0.00	36	11	11.44	0.31 (0.08)	0.32 (0.08)
	44	1	0	0.00	37	11	11.44	0.3 (0.08)	0.31 (0.08)
	54	1	0	0.18	38	11	11.62	0.29 (0.07)	0.31 (0.07)