

STOCK COMPOSITION AND COASTAL MIGRATION CHARACTERISTICS OF COHO
SALMON IN FISHERIES OF NORTON SOUND, ALASKA

By

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Abstract

Knowledge of the dynamic interactions between directed fishing effort and exploitable stocks of Pacific salmon *Oncorhynchus* spp. is needed to balance harvest opportunities against diversity conservation in mixed stock fisheries. This is often accomplished by relating stock proportions in commercial landings with spatial and temporal strata of harvests, but catch partitioning is hindered in fisheries targeting local stocks that do not display enough discernable variation for classification using modern tools (e.g., genetic stock identification). This study investigates the composition and migratory behavior of Coho Salmon *O. kisutch* stocks in the Norton Sound district of Alaska by mimicking local fisheries to capture and tag 578 fish in the contiguous Shaktoolik and Unalakleet subdistricts over two seasons. A network of acoustic receivers monitored coastal movement and freshwater entry, and 341 individuals last detected in spawning areas were assigned to a stock of origin based on assumed natal site fidelity. In Chapter 1, models using spatiotemporal and demographic variables were fit to commercial harvest data in project years and estimated that 32.9% of Shaktoolik subdistrict catch was Shaktoolik stock, while 86.7% of landings were Unalakleet stock in Unalakleet subdistrict. In Chapter 2, significant differences in migratory characteristics were identified among stocks within the study area, with local stocks swimming slower and further offshore relative to fish bound for spawning streams outside the study area, and residency time within coastal fishery boundaries decreased for all stocks as the season progressed. Detection histories were used to estimate parameters for multistate movement models which indicated that Unalakleet stock members are more likely than other observed stocks to explore coastal waters outside their natal subdistrict before moving into freshwater. Results of this study confirm that coastal salmon fisheries have access to a mixture of stocks whose unique migratory characteristics might be leveraged for stock identification and diversity conservation.

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Introduction

In the context of Pacific salmon *Oncorhynchus* spp. (hereafter ‘salmon’) fisheries management, exploitable populations are often conceptually grouped together into complexes known as stocks. Stock delimitation metrics can be complicated (Begg and Waldman 1999), but a managed stock complex should theoretically display predictable spawner-recruitment dynamics in response to harvest strategies that are based on unique productivity parameters and sustainable exploitation rates shared among constituent populations within a stock (Hilborn 1985). Diversity among stocks and their constituent populations has become widely accepted as a hallmark of sustainable fisheries due to the buffering effects of variability in life history and phenology (Hilborn et al. 2003; Schindler et al. 2010; Dann et al. 2013). As fishery ecosystems face uncertain anthropogenic futures and dynamic climatic impacts, conserving population heterogeneity is increasingly becoming a top priority for fishery managers and stakeholders (Connors et al. 2020).

Maintaining diversity within salmon fisheries is achieved by management action that distributes harvest pressure among stocks according to respective biological reference points (e.g., maximum sustainable yield). This is a perennial conundrum for managers of fisheries that target a mixture of stocks, where disproportionate exploitation may create an imbalance in harvest-biodiversity trade-offs (Hilborn et al. 2012; Walters et al. 2019; Connors et al. 2022). While gear restrictions are often used to direct harvest among morphometrically divergent stocks (e.g., regulating mesh size to target at the species level), differences in spatiotemporal habitat use may also be exploited to manage fishing pressure among stocks that display divergent movement behaviors (e.g., short fishery openers distributed over management subdistricts). The dynamics of distinct movement behaviors among salmon populations has broad relevance to the ecology, conservation, and management of salmon stocks because migration timing and pathways are ultimately dictated by

interannual environmental variation and heritable traits reflecting local adaptations (Quinn et al. 2000; Mundy and Evenson 2011; Kovach et al. 2012; Thompson et al. 2020). A growing body of research suggests that fine-scale stock structure based on phenology and habitat use may exist within genetically homogenous stocks (Boatright et al. 2004; Clark et al. 2015; Moses et al. 2019; Stratton et al. 2021), and several studies have demonstrated that effective management of mixed stock fisheries may be possible by exploiting divergent migration characteristics (Creelman et al. 2011; Hess et al. 2016; Beacham et al. 2019). While large scale disparities in migrations among stocks can accommodate selective harvesting, movement behavior variability may also manifest according to sex (Clark et al. 2015), seasonal migration timing (Crossin et al. 2007), and interannual trends (Carey et al. 2017). Therefore, investigations scrutinizing movement characteristics of exploitable stocks should also consider fine variation among stock components.

The process of classifying salmon by stock is achieved by leveraging specific identification markers, which can take the form of inherited or acquired characteristics. Inherited markers have proven useful for discerning among groups that exhibit enough genetic variation for stock discrimination (Carvalho and Hauser 1994), dependent on the resolution of contemporary differentiation methods. Among genetically similar stocks, acquired expression of environmental history such as otolith chemistry may be a more effective marker (Brennan et al. 2015; Nazir and Khan 2021). Ideally, multiple markers are available for a holistic approach to stock identification (Armstrong et al. 2018; Cunningham et al. 2018; Whitlock et al. 2018), which, beyond genetic and otolith identifiers, include age classification, life history characteristics, and morphometry (see Begg and Waldman 1999 for an exhaustive list of stock identification methods). Further, stock-specific migratory characteristics can be discerned by partitioning catches and relating the stock composition of fishery landings to the spatial and temporal distribution of fishing effort (Dann et

al. 2013; Cunningham et al. 2018; Svenning et al. 2019), again highlighting the importance of developing stock identification techniques in mixed fisheries.

Some small-scale salmon fisheries that support cultural and economic well-being in rural communities target local stocks that do not display enough discernable variation to conveniently and accurately elucidate stock structure (Berntson and Moran 2009; Araujo et al. 2014), and the composition and distribution of exploitable stocks within the fishery is vague or unknown. In these cases, tagging studies can be employed to classify stocks available for harvest across spatial and temporal strata within a fishery that has harvest access to a mixture of stocks. Stocks can be tagged while they are geographically discrete and then evaluated during distributional overlap within fisheries (Weitkamp 2010; Harris et al. 2022), or mixtures can be marked and then monitored to assess separation that infers stock structure (Meyers et al. 2009; Bell et al. 2018; Faust et al. 2019). While tagging studies can be cost- and labor-intensive compared with other stock identification techniques, they have the added benefit of elucidating high-resolution movement characteristics that are difficult to infer from methods that do not account for migratory behavior (Goethel et al. 2019).

Acoustic telemetry has been proven to be an effective tagging technique for investigating stock composition and movement dynamics in mixed fisheries targeting anadromous salmon (Armstrong et al. 2018; Bell et al. 2018). Because salmon are famous for a high degree of natal spawning site fidelity, individuals from a mixture of stocks that are tagged while intermingling in coastal waters can be assigned to a stock based on subsequent detection by passive acoustic receivers in geographically delimited spawning areas. This information can be leveraged in a management context by relating stock attributes to the distribution of fishing effort and approximating the composition of fishery landings. For instance, the stock-specific combination of demographic

(e.g., age, sex, length), abiotic orientation (e.g., fine-scale distribution based on temperature, wind speed and direction, tidal stage, etc.), and spatiotemporal (e.g., migratory movement) characteristics that are revealed by acoustic telemetry can act as a stock identification marker to be applied to concurrent commercial catch.

Pacific salmon have supported the peoples of Norton Sound in northwest Alaska for thousands of years (Darwent et al. 2016; Miszaniec et al. 2019), and residents continue to rely on salmon for food security, cultural well-being, and economic livelihood (Magdanz et al. 2009; Wolfe and Spaeder 2009). In 1961, the Alaska Department of Fish and Game (ADF&G) established the Norton Sound District commercial fishery management area, enabling residents to subsidize local subsistence economies with cash incomes (Menard et al. 2009). The region was divided into six coastal subdistricts, each containing the outlet of one or more major salmon-producing streams. Although the subdistricts were established to facilitate the management of individual stocks returning to streams within subdistrict boundaries (i.e., the natal/local stock), research in the region suggests that non-local stocks (i.e., transitory stocks) are simultaneously available for harvest as they move through coastal waters along migration routes (Gaudet and Schaefer 1982; Bell et al. 2018). Methods of catch partitioning using acquired and inherited biological identification markers are currently unable to classify mixtures of exploitable stocks within subdistrict fisheries, likely due to chemical similarities among many proximate spawning and rearing habitats (disallowing differentiation based on otolith microchemistry, Zimmerman et al. 2013), and maintained limited genetic contact among stocks (voiding genetic stock identification, Beacham et al. 2011). Therefore, the composition and distribution of stocks available for harvest in Norton Sound salmon fisheries remains ambiguous and stock-specific movement is poorly understood. Beyond the relevance to commercial fishery management and catch partitioning, coastal migratory patterns

are an obscure aspect of salmon life history, and the Norton Sound provides an excellent opportunity to investigate nearshore behavior in a relatively intact ecosystem. Further, while exploitable salmon stocks in many fisheries in Alaskan waters and beyond are bolstered by hatchery-raised fish, populations available for harvest in the Shaktoolik and Unalakleet subdistricts represent wild, unenhanced stocks eliminating the need to disentangle hatchery influences on stock movements.

This investigation uses acoustic telemetry during the 2020 and 2021 fishing seasons to describe Coho Salmon *O. kisutch* stocks available for harvest in the southern Norton Sound, estimate their proportional compositions in Shaktoolik and Unalakleet subdistrict fishery landings, and characterize nearshore movement behavior of adults in the final stages of marine spawning migration. In Chapter 1, project objectives were to 1) identify exploitable stocks of Coho Salmon in southern Norton Sound, 2) describe unique characteristics of local and transitory stocks in Shaktoolik and Unalakleet subdistrict fisheries, and 3) apply these distinctions to partition commercial catch and approximate proportional contributions to fishery landings. In Chapter 2, detection histories of tagged Coho Salmon were used to 1) characterize swim speeds and lateral migration distance relative to the shoreline, 2) summarize residency time within fishery boundaries, and 3) estimate movement probabilities among discrete fishery subdistricts and spawning areas. Coho Salmon were captured throughout the 2020 and 2021 fishing seasons in both subdistricts by mimicking local commercial set-gillnet methods, and tagged fish were tracked through coastal waters to spawning destinations allowing stock assignment, assuming natal spawning site fidelity. Model selection was used to identify significant demographic, abiotic, and spatiotemporal variables from nested candidate models that characterize natal stocks returning to the Shaktoolik and Unalakleet subdistricts. The resulting combination of independent predictors

were used as stock markers to partition subdistrict landings by fitting multinomial models to commercial catch data and estimating stock proportions in harvests. To characterize stock movement, we calculated swim speeds and measured lateral migratory distance from shore, and estimated residency time within Shaktoolik and Unalakleet subdistricts, all while accounting for migratory characteristics among stocks, sexes, seasons, and years. Multistate models were fit to detection history data to estimate movement probabilities and nested candidate models were compared to test the significance of demographic and spatiotemporal effects that may influence migratory behavior. Results describe the dynamic interactions between stock mixtures and directed fishing effort in the southern Norton Sound and could be used to develop management strategies that preserve biodiversity while maximizing harvest opportunities in fisheries that lack convenient stock classification methods.

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Chapter 1: Acoustic telemetry yields stock membership clues for salmon harvested in coastal mixed fisheries¹

Abstract

Estimates of Pacific salmon *Oncorhynchus* spp. stock proportions in mixed fishery landings are needed to balance harvest opportunities against biodiversity conservation but catch partitioning can be hindered by imperceptible identification markers that undermine the effectiveness of modern stock classification tools. This study uses acoustic telemetry to investigate the stock composition of commercial landings in the Norton Sound district of Alaska by mimicking local fisheries to capture and tag 578 Coho Salmon *O. kisutch* in the contiguous Shaktoolik and Unalakleet commercial subdistricts over two seasons. A total of 341 individuals last detected in demarcated spawning areas were assigned to a stock of origin based on assumed natal site fidelity, and sex, and location and seasonal timing of capture were predictors of stock membership. Models fit to commercial harvest data in project years estimated that 32.9% of Shaktoolik subdistrict catch was Shaktoolik stock, 51.5% was Unalakleet stock, and the remainder consisted of other transitory stocks. Conversely, 86.7% of landed Coho Salmon were Unalakleet stock in Unalakleet subdistrict, and Shaktoolik and transitory stocks made up < 10%, respectively. These results suggest that coastal salmon fisheries have access to a variable mixture of stocks whose unique characteristics can be leveraged to examine the effects of directed harvest effort on stock diversity.

¹ Henslee, L. H., P. A. H. Westley, Z. W. Liller, and A. C. Seitz. *In prep for Transactions of the American Fisheries Society*. Acoustic telemetry yields stock membership clues for salmon harvested in mixed fisheries.

Introduction

Populations of Pacific salmon *Oncorhynchus* spp. (hereafter referred to as ‘salmon’) transition to coastal waters during the final phase of spawning migration, and their distributions mix and overlap as they become available to harvest in nearshore fisheries. From a resource perspective, these salmon populations can be grouped into interbreeding, geographically co-occurring units that are managed as stocks (Begg and Waldman 1999; Booke 1999), each with unique productivity parameters and sustainable exploitation rates (Hilborn 1985; Cunningham et al. 2018). An abundance of work focused on commercial catch partitioning suggests that practically all coastal salmon fisheries harvest from a mixture of stocks to varying degrees (Cunningham et al. 2012; Munro et al. 2012; Bradbury et al. 2016). Exploitation of multiple stocks can stabilize fishery yield across years due to the buffering effects of interpopulation variability in life history and phenology (Schindler et al. 2010), but indiscriminate harvest pressure can have disproportionate effects on depleted or endangered stocks and leave productive stocks underutilized (Walters et al. 2019; Freshwater et al. 2020; Moore et al. 2021). Balancing harvest opportunities against biodiversity requires a thorough knowledge of the dynamic composition of exploitable mixtures within the fishery to direct complex interactions between migrating salmon stocks and fishing effort (Cadrin and Secor 2009; Dann et al. 2013; Connors et al. 2020; Hilborn et al. 2021).

Identifying exploitable stocks present in mixed fisheries is often achieved by analyzing unique inherited (e.g., genetic) and/or acquired (e.g., otolith microchemical) biological markers (Begg and Waldman 1999), but some small-scale fisheries target local stocks that do not display enough discernable variation to conveniently and accurately elucidate stock structure (Berntson and Moran 2009; Araujo et al. 2014). Mark recapture techniques have long been used to classify stocks

available for harvest across spatial and temporal strata by marking individuals within exploitable stock mixtures and evaluating separation that infers stock structure (Gaudet and Schaefer 1982). Acoustic telemetry improves upon this method by using strategically placed passive hydrophone receivers to monitor tagged salmon movement in lieu of recapture events (Armstrong et al. 2018; Bell et al. 2018; Faust et al. 2019; Harris et al. 2022). For salmon species that display a high degree of natal spawning site fidelity, individuals that are tagged while intermingling in coastal waters can be assigned to a stock based on subsequent detection by passive acoustic receivers in geographically delimited spawning areas. This information can be leveraged in a management context by relating stock attributes to the distribution of fishing effort and approximating the composition of fishery landings. For instance, the stock-specific combination of demographic (e.g., age, sex, length), abiotic orientation (e.g., fine-scale distribution based on temperature, wind speed and direction, tidal stage, etc.), and spatiotemporal (e.g., migratory movement) characteristics that are revealed by acoustic telemetry can act as a stock marker to be applied to concurrent commercial catch. While this method of catch partitioning can be relatively costly and time-consuming, tagging studies are able to provide high-resolution spatial data compared to other methods of mixed stock assessment (Goethel et al. 2019).

In the Norton Sound of northwest Alaska, residents rely on salmon for food security, cultural well-being, and economic livelihood (Magdanz et al. 2009; Menard et al. 2009). The nearshore waters of the region's salmon fishing district are divided into six subdistricts (Figure 1.1) that are managed by the Alaska Department of Fish and Game (ADF&G) based on comparative commercial catch statistics (Table 1.1), escapement abundance (number of fish that escape fisheries to spawn, Table 1.2), and weather conditions (Menard et al. 2022). Most of the harvest pressure in the region is based in the Shaktoolik and Unalakleet subdistricts (locally referred to as 'southern' Norton

Sound), where commercial fisheries consistently attract buyers for Coho Salmon *O. kisutch*. Although the subdistricts were established to facilitate the management of individual stocks returning to streams within subdistrict boundaries (i.e., the natal stock), research in the region suggests that other stocks bound for distant spawning streams (i.e., transitory stocks) are simultaneously available for harvest as they move through coastal waters along migration routes (Gaudet and Schaefer 1982; Bell et al. 2018). Based on evidence that stocks are highly mixed in the contiguous Shaktoolik and Unalakleet subdistricts, management actions are often simultaneously enacted across these fisheries, assuming commensurate effects on exploitable stocks (Menard et al. 2022). Methods of catch partitioning using acquired and inherited biological identification markers are unable to classify mixtures of exploitable stocks within subdistrict fisheries, likely due to similarities in spawning and rearing habitats and persistent gene flow among stocks (Beacham et al. 2011; Zimmerman et al. 2013). Therefore, the composition and distribution of stocks available for harvest in Norton Sound salmon fisheries remains ambiguous and obscure proportional contributions to commercial landings hinders managers' ability to measure stock-specific exploitation.

This investigation uses acoustic telemetry during the 2020 and 2021 fishing seasons to 1) identify exploitable stocks of Coho Salmon in southern Norton Sound, 2) describe unique characteristics of natal and transitory stocks in Shaktoolik and Unalakleet subdistrict fisheries, and 3) apply these distinctions to partition commercial catch and approximate proportional contributions to fishery landings. Coho Salmon were captured throughout the 2020 and 2021 fishing seasons in both subdistricts by mimicking local commercial set net methods, and tagged fish were tracked through coastal waters to spawning destinations allowing stock assignment assuming natal spawning site fidelity. Model selection was used to identify significant demographic, abiotic, and spatiotemporal

variables from nested candidate models that characterize natal stocks returning to the Shaktoolik and Unalakleet subdistricts. The resulting combination of unique predictors were used as stock markers to partition subdistrict landings by fitting multinomial models to commercial catch data and estimating stock proportions in harvests. Results describe the dynamic interactions between stock mixtures and directed fishing pressure in the southern Norton Sound and could be used to develop management strategies that preserve biodiversity while maximizing harvest opportunities in fisheries that lack convenient stock classification methods.

Methods

Study area

Adult Coho Salmon were captured and tagged in the coastal waters of the Shaktoolik and Unalakleet subdistricts (hereafter ‘study area’) in the Norton Sound commercial management district (Figure 1.1), and movement was monitored throughout the region by a network of marine and inriver passive acoustic receivers. Receiver arrays were placed to detect tagged Coho Salmon movement at the eastern boundary of Elim subdistrict and the boundaries of the Norton Bay, Shaktoolik, and Unalakleet subdistricts (Figure 1.2). The nearshore environment in southern Norton Sound is characterized by shallow water depths (generally < 20 m) and sandy substrate with a mean tidal range of 0.85 m. Tagged Coho Salmon inriver migration was monitored in all major spawning streams in the region, including the Kwiniuk and Tubutulik rivers in Elim subdistrict; the Koyuk, Inglutalik, and Ungalik rivers in Norton Bay subdistrict; the Shaktoolik and Tagoomenik rivers in Shaktoolik subdistrict (both drain into Shaktoolik Bay); and Egavik Creek, and the Unalakleet and Golsovia rivers in Unalakleet subdistrict (Figure 1.2). Rivers within the study area experience highly variable water levels depending on tides, watershed precipitation, and the previous winters’ snowfall.

Tagging and tracking

Coho Salmon were captured using gillnets at fishing sites within 200 m of shore by two crews operating in Shaktoolik and Unalakeet subdistricts, respectively. Fishing effort resembled commercial fishing methods as closely as possible in gear, seasonal timing, and fishing locations. Fishing sites were advised by communicating with local harvesters and by directly observing commercial fishing operations throughout the season. Coordination with local fishery experts confirmed that gillnets are operated throughout the coastal waters of the Shaktoolik and Unalakeet subdistricts, although commercial fishing activity north of the mouth of Shaktoolik Bay and south of the Unalakeet River is relatively uncommon during Coho Salmon fishing season. Therefore, fishing sites were unfixed, and an effort was made to evenly distribute fishing effort (Figure 1.3). A single site per day was fished unless conditions necessitated relocating (e.g., inclement weather, absence of target species). Sampling events generally did not occur in rough seas for safety reasons and to minimize the impact of capture and sampling to Coho Salmon. Additionally, crews sought to avoid minus tides that increased the risk of running aground while navigating channels in tidal flats. Fishing crews recorded local environmental conditions such as water turbidity, wind speed and direction, and air and water temperatures at each new fishing site. Tide data were taken from the National Oceanic and Atmospheric Administration Tides and Currents website which continuously records the water depth at the Unalakeet River mouth (Station ID: 9468333). More details on measuring and recording environmental observations can be found in Appendix A.

Two mesh sizes were used to construct gillnets based on conversations with local fishers: 14.6 cm (5 $\frac{3}{4}$ in) mesh was used to target the smaller Coho Salmon that local knowledge suggests run early in the season, and 14.9 cm (5 $\frac{7}{8}$ in) mesh was used to capture the larger Coho Salmon targeted by the commercial fleet during the remainder of the season. Although regulations in the Norton Sound

district allow up to 182.9 m (100 fathoms) of aggregate net length per permit, project crews never deployed more than 91.4 m (50 fathoms) to ensure that captured Coho Salmon could be removed from the mesh as quickly as possible. Nets were continuously monitored while deployed and fish were immediately attended after becoming entangled in the mesh. Captured Coho Salmon were carefully removed from the net, cutting the web as needed, and placed in a tote of circulating sea water. The condition of each captured Coho Salmon was visually evaluated and only healthy fish (e.g., eye and operculum movements, no bleeding) were sampled for age, sex, and length (ASL) and tagged. Coho Salmon length was measured to the nearest millimeter from mid-eye to tail fork, three scales were removed for age determination, and the sex of each fish was determined using external characteristics such as body symmetry, kype development, and presence of an ovipositor (Eaton 2015). Species identification confirmation of marine phase (i.e., ‘ocean bright’) Coho Salmon was conducted postseason by analysis of scale patterns and any fish determined not to be Coho Salmon were removed from analysis ($n = 15$ in 2020 and $n = 0$ in 2021).

Acoustic tags were attached by inserting two stainless steel 14-gauge darts through the dorsal musculature and between proximal pterygiophores approximately 1.5 cm laterally from the dorsal fin and threading the wire ends of the tag mount assembly through the darts. This technique prevents muscle damage and premature rejection of the tag caused by tearing through muscle tissue due to hydrodynamic drag and has minimal effect on fish movement and behavior (Bridger and Booth 2003). After sampling and tagging, Coho Salmon were allowed to recover in a tote of circulating seawater (sensu Portz et al. 2006) before being released away from the net. The entire sampling and tagging process from removal from mesh to release of tagged Coho Salmon took an average of 7.5 min (SD = 3.6 min). Animal handling and care were approved by the University of Alaska Fairbanks Institutional Animal Care and Use Committee (Protocol 1556023; Appendix B).

Fishing schedules were based on ADF&G statistical weeks and occurred over the 5-year average duration of the commercial Coho Salmon fishing season (2015–2019). Captures began in the last week of July (stat week 31) and continued until the last week of August (stat week 35). Field crews fished in each statistical week of the schedule with the goal of deploying 40 tags per week, and a total of 200 tags deployed in each subdistrict, in each year (800 tags throughout the project). As many tags as possible were deployed during each sampling event until weekly goals were reached. Any tags that were not able to be deployed during a statistical week were added to the number of tags to be deployed during the next week. Coho Salmon capture was timed to occur between commercial fishing periods (i.e., during fishery closures) and when possible, crews deployed tags immediately following a fishery closure to give tagged fish time to reach spawning destinations before being subjected to harvest pressure in the subsequent opener. Informational fliers were posted in public places in the communities of Elim, Koyuk, Shaktoolik, and Unalakleet, AK and included instructions on how to recognize and return acoustic tags from recaptured Coho Salmon. Harvesters reporting recaptures were asked to provide the timing, location, and method of recapture.

The acoustic transponders used for this study were Lotek MM-M-11-28 tags with a transmitting frequency of 76 kHz, dimensions of 12 x 60 mm, a weight of 11 g in air, and a battery life expectancy of 111 days at a transmission interval of 7 seconds. Each tag transmitted a unique code to be detected by strategically placed passive acoustic hydrophone receivers (Lotek WHS 3250). Marine arrays were composed of six receivers deployed perpendicular to shore (Table C.1 and C.2), suspended 1.5 m above the sea floor with 50 kg concrete anchors deployed at depths less than 50 m. Receivers were suspended with subsurface and surface buoys to maintain vertical orientation and allow for fluctuations in water level (Figure C.1). Inriver acoustic receivers were

mounted on rebar driven into the riverbed in an area that provided the greatest chance of detecting tagged fish while minimizing disturbance to the receiver (Table C.3 and C.4). Two receivers were placed above tidal influence in all monitored rivers with one receiver ≥ 500 m upstream of the other to confirm movement directionality and for redundancy.

Passive acoustic receivers' ability to detect tag transmissions varies greatly with distance between transmitter and receiver (Hobday and Pincock 2011), and with environmental sources of acoustic interference such as rain, wind and waves, boat traffic, and substrate disturbance (Mathies et al. 2014). Systematic range testing over a range of environmental variables was used to determine appropriate spacing between individual receivers deployed in marine arrays and optimal deployment locations in riverine environments. In 2020, linear marine arrays were composed of six receivers placed 300 m apart for a total detection range of about 2.1 km from shore based on optimal detection ranges recorded by previous acoustic studies in the Norton Sound (Bell et al. 2018). In 2021, it was determined that receivers could be spaced further apart to achieve a linear detection range of approximately 3.1 km from shore based on an optimal range of 500 m. Refer to Appendix C for details on receiver hardware and settings, marine and inriver deployment and retrieval methods, and range testing.

Data organization

Telemetry files (.jst) were downloaded from receivers at the end of each season and sorted using acoustic detection conversion and organization software (Lotek WHS Host x64 V1.5.3373.1). Three data types were compiled for each tagged Coho Salmon: 1) tag deployment information including unique tag code, time, location, and environmental conditions during capture, and ASL data, 2) tag detection history including any detections by marine and/or inriver receivers, and 3)

recapture information, if any, reported by commercial, subsistence, and sport harvesters. All tagged Coho Salmon were assigned one of four final fates based on individual detection histories:

1. Last detected in spawning streams within the study area;
2. Last detected in waters outside the study area;
3. Last detected in marine waters within the study area;
4. Not detected after tag deployment.

Note that in this case, ‘detected’ refers to acoustic detections and physical recaptures. For cases in which tagged Coho Salmon were recaptured by subsistence and sport harvesters in freshwater below inriver receivers, it was assumed that the fish was in its spawning stream and was assigned to Fate 1 ($n = 10$ in 2020 and $n = 11$ in 2021). All fish assigned to Fate 1 or 2 received one of six stock assignments based on the location of final detection. The stock designations were:

Northern stocks: fish bound for spawning regions north of the study area;

Elim stock: fish bound for the spawning region within Elim subdistrict;

Norton Bay stock: fish bound for the spawning region within Norton Bay subdistrict;

Shaktoolik stock: fish bound for the spawning region within Shaktoolik subdistrict;

Unalakleet stock: fish bound for the spawning region within Unalakleet subdistrict; and

Southern stocks: fish bound for the spawning region south of the study area.

Stock assignments were based on the assumption that tagged Coho Salmon returned to spawn in their natal streams (i.e., not strays from a donor population). This assumption is supported by studies that have shown that Coho Salmon have relatively low straying rates compared to other salmon species (Labelle 1992; Westley et al. 2013). All fish assigned to a stock were also given a binary response variable that indicated whether they were bound for spawning streams within the subdistrict in which they were captured (i.e., natal stock), or were ultimately detected in spawning

regions outside their subdistrict of capture (i.e., transitory stock). Because fish assigned to Fates 3 and 4 were not ultimately detected in any of the designated spawning regions, they were removed from the dataset for this analysis.

Natal stock membership probabilities

Logistic generalized linear models (GLM) were used to identify variables influencing the probability that a Coho Salmon captured in a commercial subdistrict was returning to spawning streams within that subdistrict (i.e., the subdistrict's 'natal stock'). All putative predictors were used to construct a global model and nested models were compared using second order Akaike Information Criterion (AICc) model selection methods. Latitude and longitude of capture location were determined to be collinear (Pearson's product-moment correlation, $t = -53.63$, $p < 0.001$), and because the coastline of the study area is north-south oriented, only latitude was retained. Predictor variables were grouped into 'spatiotemporal,' 'demographic,' and 'abiotic' categories (Table 1.3). The spatiotemporal variable group explored stock-specific migration characteristics and included an interaction term between 'year' and 'day of year' to account for annual seasonal effects. Demographic variables were used to compare the effects of age, sex, and length on natal stock membership probabilities and abiotic predictors tested for environmental influences. Logistic generalized linear mixed-effects models were constructed following the general form:

$$\ln\left(\frac{p_i}{1-p_i}\right) = \text{logit}(p_i) = \boldsymbol{\beta}\mathbf{x}_i + a_j,$$

where p_i is the probability of natal stock membership for individual i , $\boldsymbol{\beta}$ is a vector of regression coefficients, \mathbf{x}_i is a vector of explanatory variables, and a_j is a random intercept for sampling event j . The addition of the random effect is to account for potential pseudoreplication given that Coho Salmon caught in the same 'sampling event' (defined as sets grouped by year, day of year, and

latitude) could be more likely to be migrating to the same spawning stream, resulting in nonindependent observations. Models within two likelihood/AICc units were determined to be comparable in evidence and models more than four units from the most parsimonious model had a much lower weight of evidence (Burnham and Anderson 2004). Variables not shared among models with comparable AICc scores were individually analyzed using a likelihood ratio test and retained at a significance level of $\alpha \leq 0.05$. Standard errors and 95% confidence intervals for model regression coefficients were estimated by 5,000 bootstrap iterations with replacement.

Commercial catch partitioning

The parsimonious logistic model from the previous section was used to inform construction of a predictive multinomial response model to estimate the proportion of each stock in Shaktoolik and Unalakleet subdistrict commercial landings during project years. For this analysis, stocks other than Shaktoolik or Unalakleet stocks were combined into one ‘transitory stock’ to decrease the possibility of separability effects caused by zero inflation in the dataset. The response variable p_j estimates the probability of membership to 1) Shaktoolik stock, 2) Unalakleet stock, or 3) a transitory stock. Note that the probabilities of membership to stock $j = 1, \dots, J$ sum to 1:

$$\sum_{j=1}^J p_j = 1 \text{ and } p_1 = 1 - \sum_{j=2}^J p_j$$

Information on commercial landings from each subdistrict came from two sources: 1) fish ticket data which include the date and total number of each salmon species in the delivery, and 2) ADF&G commercial catch sampling data which includes ASL measurements of a random subset of salmon landed during commercial openers. Model-predicted stock proportions were multiplied by the number of fish from each delivery to estimate the total number of Coho Salmon landed from each stock and 95% confidence intervals were calculated by 5,000 bootstrap iterations with replacement.

Results

Tag deployment and final fates

In 2020, 385 adult Coho Salmon were captured and tagged in both subdistricts (Figure 1.3). Of those fish, 257 (66.8%) were tracked to spawning regions (Fates 1 and 2), 101 (26.2%) were last detected in marine waters within the study area (Fate 3), and 27 (7.0%) were not detected after deployment (Fate 4, Table 1.4). Inclement weather, low Coho Salmon abundance, and logistical constraints resulted in much lower sample sizes in 2021 when 193 coho were captured and tagged. Of those, 84 (43.5%) were tracked to spawning regions, 64 (33.2%) were last detected in marine waters within the study area, and 45 (23.3%) were not detected (Table 1.4). The number of tags deployed in each statistical week varied widely (mean = 32.1, SD = 25.1, Figure 1.4) and was mostly dictated by Coho Salmon abundance and weather conditions. Several of the tags last detected in marine waters were recaptures in commercial and marine subsistence fisheries ($n = 18$ in 2020, and $n = 20$ in 2021), and it was not uncommon for sport and subsistence fishers to recapture tagged Coho Salmon in freshwater streams ($n = 32$ in 2020 and $n = 29$ in 2021), especially in the Unalakleet River ($n = 55$).

Stock identification and summary statistics

In 2020, 27.9% of the 136 Coho Salmon tagged in Shaktoolik subdistrict were tracked to Shaktoolik subdistrict spawning streams and 55.1% were bound for spawning streams in Unalakleet subdistrict. Only 2.2% migrated to Norton Bay streams, the same proportion went to other northern spawning regions, and 12.5% traveled south out of the study area. Similar proportions were observed in 2021: of the 31 Coho Salmon tagged in the Shaktoolik subdistrict tracked to spawning regions, 34.3% were Shaktoolik stock and 51.7% were Unalakleet stock. Another 10.3% were bound for northern spawning regions, 3.4% for Norton Bay streams and 6.9%

headed south (Table 1.5, Figure 1.5). The majority of Coho Salmon tagged in Unalakleet subdistrict that were tracked to spawning regions were Unalakleet stock: 84.3% of the 121 fish from 2020 and 94.3% of the 53 fish in 2021. In 2020, 1.7% of Coho Salmon were tracked to northern spawning regions, and only 0.8% went to Norton Bay subdistrict. Another 5.8% moved to Shaktoolik subdistrict streams and 7.4% went south. In 2021, 1.9% migrated north, another 1.9% moved to Norton Bay streams and no Coho Salmon went to Shaktoolik subdistrict. Only 1.9% of the Coho Salmon tagged in Unalakleet subdistrict tracked to spawning regions in 2021 traveled to southern spawning streams (Table 1.5, Figure 1.5). No Coho Salmon tagged in either subdistrict was tracked into Elim subdistrict spawning streams in either project year. The mean length of all tagged Coho Salmon was 541 mm (SD = 36.7), the mean age was 4 years (SD = 0.5), and the proportion of fish that was female was 0.42 (95% CI = 0.38, 0.46). There were no significant differences in age ($F = 0.75, p = 0.47$), sex ($\chi^2 = 1.16, p = 0.56$), or length ($F = 2.65, p = 0.07$) composition among fish assigned to stocks.

Model selection and coefficient interpretation

The addition of a random effect in the logistic generalized linear model was determined to be unnecessary, as residual variance among samples was < 0.001 , suggesting that individual tagged Coho Salmon should be considered independent observations. The model containing only spatiotemporal variables had the lowest AICc score, though the model containing spatiotemporal and demographic terms was nearly identical in evidence ($\Delta\text{AICc} = 0.09$, Table 1.6). Likelihood ratio tests determined that the ‘age’ ($\chi^2 = 4.39, p = 0.22$) and ‘length’ ($\chi^2 = 2.76, p = 0.10$) variables were not significant by themselves and were dropped from the model. The best model for estimating the probability of natal stock membership for a Coho Salmon of sex s caught in subdistrict c and in year y is given by:

$$\text{logit}(p_{s,c,y}) = \text{sex}_s + \text{capture.sd}_c + \text{year}_y + \beta_y \times \text{DOY} + \beta_1 \times \text{latitude},$$

where β_y is a year-specific slope.

In this model, a captured male Coho Salmon was significantly less likely to belong to the natal stock of the subdistrict in which it was captured (logit scale -1.059, $p = 0.001$, Figure 1.6), and a Coho Salmon caught in 2021 had a much higher likelihood of natal stock membership than one caught in 2020 (26.94, $p = 0.020$, Figure 1.7). Coho Salmon captured earlier in the season were more likely to belong to the natal stock in 2020 (0.067, $p = 0.011$), but an opposite trend was observed in 2021 (-0.116, $p = 0.022$, Figure 1.8). Generally, Coho Salmon captured at higher latitudes (13.42, $p < 0.001$) relative to the subdistrict of capture (6.79, $p < 0.001$) were more likely to belong to the natal stock (Figure 1.9). The model has an adjusted R^2 value of 0.44, with 37.7% of deviance explained, and bootstrapped confidence intervals and standard errors can be found in Table 1.7.

Stock composition of commercial catch

The probability of a commercially harvested Coho Salmon of sex s caught in subdistrict c and in year y belonging to stock j is given by:

$$\text{logit}(p_{s,c,y,j}) = \alpha_j + \text{sex}_{s,j} + \text{capture.sd}_{c,j} + \text{year}_{y,j} + \beta_{y,j} \times \text{DOY},$$

where α_j is a stock-specific intercept and $\beta_{y,j}$ is a year-specific slope for stock j . This model has an adjusted R^2 value of 0.68, with 63.7% of deviance explained. The ‘latitude’ variable that was significant in determining the probability of natal stock membership in the logistic model was dropped from the multinomial predictive model because harvest coordinates are not a reporting requirement for commercial landings and were unknown.

Of the 1,645 Coho Salmon commercially harvested in Shaktoolik subdistrict in 2020, the model estimates that 31.7% were natal Shaktoolik stock, 50.9% were Unalakleet stock, and 17.4% were transitory stocks. In 2021 there were 2,593 Coho Salmon landed in Shaktoolik subdistrict and the model estimates that 33.7% were natal stock, 51.9% were Unalakleet stock, and 14.5% were transitory stock. Of the 2,141 Coho Salmon commercially caught in Unalakleet subdistrict in 2020, 86.2% were estimated to be natal Unalakleet stocks, 4.8% were Shaktoolik stock, and 8.9% were transitory stocks. In 2021, of the 2,438 Coho Salmon commercially landed in Unalakleet subdistrict, 87.1% were natal stock, 5.6% were Shaktoolik stock, and 7.3% were from transitory stocks (Table 1.8, Figure 1.10). In both subdistricts and both project years, Coho Salmon deliveries were composed primarily of Unalakleet stocks according to model predictions (Figure 1.11). It is important to note that low Coho Salmon counts at enumeration projects in the region and poor commercial catch per unit effort (CPUE) prompted very conservative fishery openers in 2020 and both years were near-historical low harvests in the region.

Discussion

A mixture of stocks is available for harvest in salmon fisheries of the southern Norton Sound, and unique combinations of demographic and spatiotemporal characteristics can be used to partition commercial landings. Although multiple stocks were found in each subdistrict, the distribution of exploitable natal and non-natal Coho Salmon stocks appear to significantly overlap in Shaktoolik subdistrict compared to Unalakleet subdistrict, where the natal stock dominates the catch composition. Model selection methods presented evidence that natal stocks in each subdistrict can be distinguished from other transitory stocks based on sex, and time and location of capture. Estimated stock proportions in fishery landings were similar across project years, suggesting that the results are indicative of true regional stock structure based on phenology and behavior.

Each project year Coho Salmon were tracked to spawning regions north of the study area, which could include other watersheds in the Norton Sound (i.e., rivers in Nome and Golovin subdistricts) and beyond to Kotzebue Sound. No fish were tracked into Elim subdistrict streams in either year, however, suggesting that the relatively abundant Elim stock does not migrate through marine waters to the south and east of their home streams. Coho Salmon were also observed moving to spawning regions south of the study area, which is consistent with historical studies that document other salmon species migrating through southern Norton Sound fisheries *en route* to the Yukon River (Gaudet and Schaefer 1982). The significant availability of southern stocks in the Shaktoolik and Unalakleet subdistricts suggests that both fisheries benefit from harvesting fish likely bound for Yukon River tributaries. Other coastal mixed stock salmon fisheries have been documented significantly harvesting from transitory stocks (Cunningham et al. 2018) and it might therefore be informative to investigate relationships between southern Norton Sound fishery performance and Yukon River run strength.

Spatial variables were the most significant predictors of natal stock membership, especially the subdistrict of capture. The effect of this term suggests that a Coho Salmon harvested in Unalakleet subdistrict is highly likely to be a member of the natal Unalakleet stock, and only the edges of transitory stock distributions overlap into fishery waters. Conversely, Coho Salmon captured in Shaktoolik subdistrict are much more likely to belong to transitory stocks because of a larger degree of overlap with Shaktoolik natal stocks. It is interesting to note that the effect of latitude of capture does suggest that the probability of Shaktoolik natal stock membership increases with proximity to the mouth of Shaktoolik Bay, presumably because the natal stock must concentrate to enter spawning streams. The temporal characteristics of the natal stock in each subdistrict are less clear, with seasonal effects apparently reversed in project years. This could reflect variations

in migratory timing based on environmental conditions, phenology, or both (Keefer et al. 2008; Mundy and Evenson 2011; Carey et al. 2017). Migratory timing divergence is an important aspect of stock structure among anadromous fishes, as it suggests adaptation to local habitats and shared environmental pressure (Boatright et al. 2004; Clark et al. 2015; Harris et al. 2022). It is important to keep in mind, however, that low among-sample residual variance indicates that stock mixing occurs at very fine scales, and the distribution of stock-specific migratory routes overlap to varying degrees in coastal waters.

Male Coho Salmon captured in the southern Norton Sound are less likely than females to belong to natal stocks (i.e., significantly available to harvest outside their spawning region). Sex-specific movements in late-phase marine spawning migrations are not well understood, although several studies demonstrate differences in swimming speeds and river entry timing (Dahl et al. 2004; Davidsen et al. 2013). The significant availability of male Coho Salmon outside their natal spawning regions might demonstrate ‘testing behavior,’ which describes the documented tendency of male salmon to explore novel habitats before returning to natal spawning areas (Hard and Heard 1999; Anderson and Quinn 2007; Frechette et al. 2021). The demonstrated demographic effect depends on accurate sex identification using external secondary characteristics which are based on reproductive readiness and can be obscure in marine-phase salmon. Sexual dimorphism appears to be directly related to proximity to spawning areas (Quinn 2018; Bradley and Brown 2021), and while natal stocks that were encountered near spawning streams likely exhibited spawning morphometry, transitory stocks were probably sampled relatively early in their coastal spawning migration when dimorphism is less apparent. Although the higher proportion of males observed in our sample is consistent with local catch sampling (Menard et al. 2022) and previous field studies (Spidle et al. 1998), it is possible that sex assignment could be biased due to obscure secondary

sexual characteristics, and the apparent effect on natal stock membership probability may be the result of a statistical artifact. The sex identification methods of this study are identical to those used by ADF&G commercial catch samplers, however, and could therefore reflect existing systematic biases in harvest data. Scrutiny of sex determination methods in harvest samples could clarify possible bias and concomitant effects on management conceptions (Bradley and Brown 2021). Tangentially, it could be interesting to develop a simple metric of reproductive readiness (e.g., spawning colors) and explore its relationship to natal stock membership in nearshore salmon fisheries.

In mixed salmon fisheries of the southern Norton Sound, the unique combination of spatiotemporal and demographic characteristics displayed by exploitable stocks may be effectively used as classification ‘signals’ for catch partitioning (Begg and Waldman 1999). The consistent results between the two seasons of this study suggest that these signals may reflect actual stock structure in the southern Norton Sound and could act as a reference for future work. Ultimately, the spatiotemporal scales of management dictate stock delimitations in the context of biological, social, and economic objectives (Begg et al. 1999). While genetic-based structure enables convenient catch partitioning and clear delimitation of management units, it may create more conservative groupings (i.e., fewer stocks) than are required for effective resource governance in small-scale fisheries that support cultural and economic well-being in rural communities (Weeratunge et al. 2014; Donkersloot et al. 2020).

Beyond catch partitioning, management strategies to achieve conservation- and utilization-based objectives across a spectrum of mixed stocks must incorporate differences in intrinsic population dynamics parameters (Hilborn 1985; Freshwater et al. 2020; Moore et al. 2021). Estimates of productivity and carrying capacity for salmon stocks within a mixed fishery depend on accurate

measurement of spawner-recruit parameters (Staton et al. 2020), which is accomplished by monitoring escapement and attendant brood-year recruitment (i.e., harvest plus escapement). Work remains to estimate these relationships in southern Norton Sound Coho Salmon stocks. Although subdistrict harvest estimates and demographic data (i.e., ASL) of landed Coho Salmon exist from as far back as 1985, annual escapement has never been fully enumerated in the region. This is partly because the relatively late run timing of Coho Salmon coincides with deteriorating fall weather conditions in Norton Sound, making it difficult to maintain inriver monitoring projects or to enumerate escapement from aerial surveys. Further, Norton Sound salmon harvests are not partitioned and allocated by stock, and recruitment estimates could be drastically skewed if subdistrict harvests were to be used as an indicator of natal stock return abundance. For instance, results from this study suggest that combined harvest of Unalakleet stock Coho Salmon in the southern Norton Sound during project years was 34.3% greater than total landings in the Unalakleet subdistrict (6,163 fish versus 4,590), while the harvest of Shaktoolik stock was 58.5% less than catches in Shaktoolik subdistrict (1,635 fish versus 3,938). Bias might erroneously appear to justify liberalized harvest opportunities in Shaktoolik subdistrict, directing disproportionate pressure that may lead to long-term negative impacts to productivity and sustainability of the natal stock.

Because of the overlapping geographic occurrence of the Shaktoolik and Unalakleet stocks, and the evidence that suggests a significant degree of exploratory behavior in Coho Salmon males, it is likely that reproductive contact between stocks is at least partially maintained. This may allow gene flow that strengthens adaptations to shared ecologies and could provide evidence for an argument to manage populations returning to Shaktoolik and Unalakleet subdistricts as a single stock, as long as economic and cultural objectives can be maintained. The degree of diversity

among stock components within a fishery should be explicitly considered when strategizing management plans for the aggregate stock (Staton et al. 2020). The misinterpretation of the spatial and temporal scope in which populations share distinct combinations of genetic, life history, and habitat characteristics can be misaligned with expected spawner-recruit responses to harvest and lead to negative consequences for stock sustainability (Hawkins et al. 2016; Walters et al. 2019). Stock definition and identification continues to evolve with management needs, emergent technologies, and shifting resource distributions connected to climate change (Link et al. 2011; Connors et al. 2020), and stock assessment methods should be periodically scrutinized to ensure strategic delimitations accurately represent biological systems (Kerr et al. 2017; Cadrin 2020; Berger et al. 2021). Future management plans for Coho Salmon in southern Norton Sound should focus on honing methodologies that allow estimation of population dynamics parameters and derived biological reference points. It is important to note that the 2020 and 2021 fishing seasons saw record low Coho Salmon harvests and observed escapements in the Norton Sound since the early 2000s, highlighting the urgency of effective mixed stock management to sustain invaluable salmon resources.

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Figures

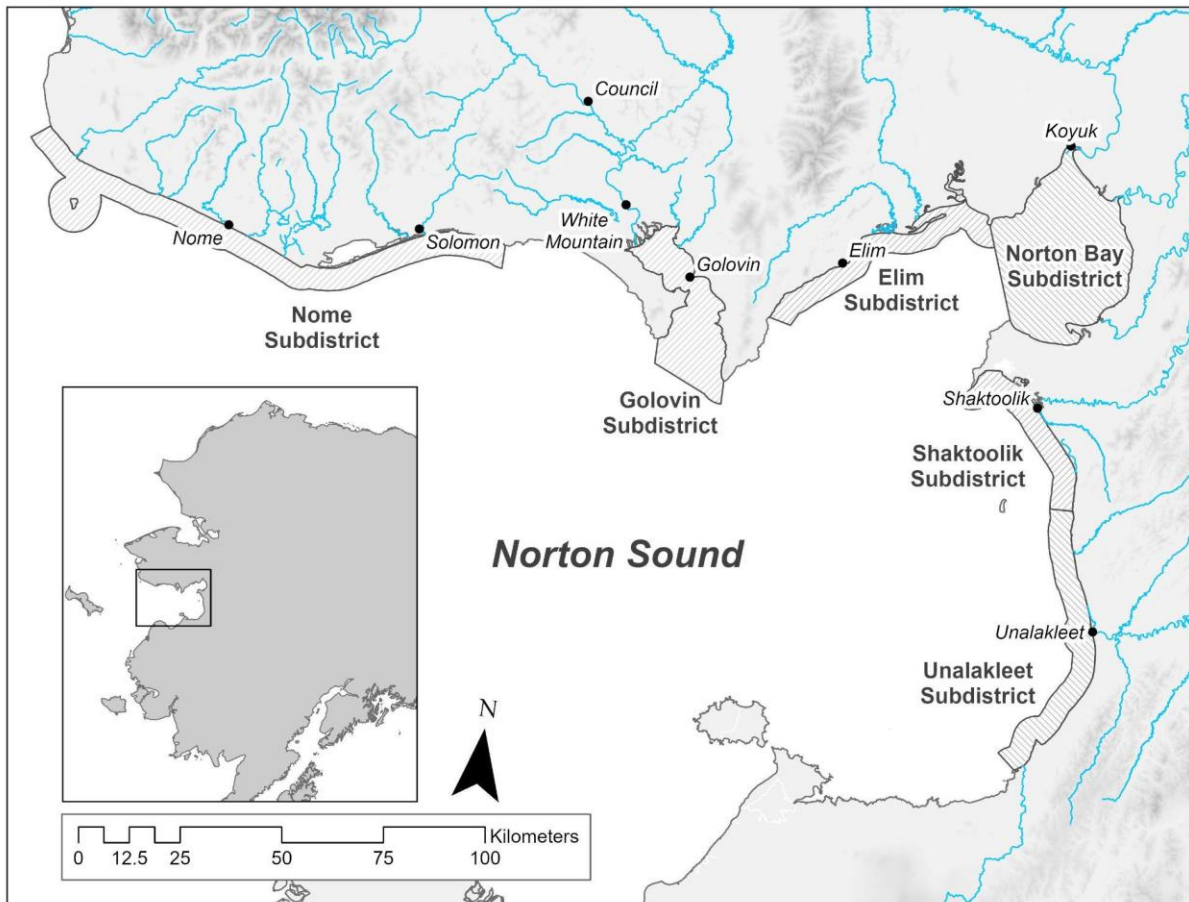


Figure 1.1 Communities and commercial fishing subdistricts of the Norton Sound district in western Alaska. Shaded areas represent coastal waters within subdistrict boundaries.

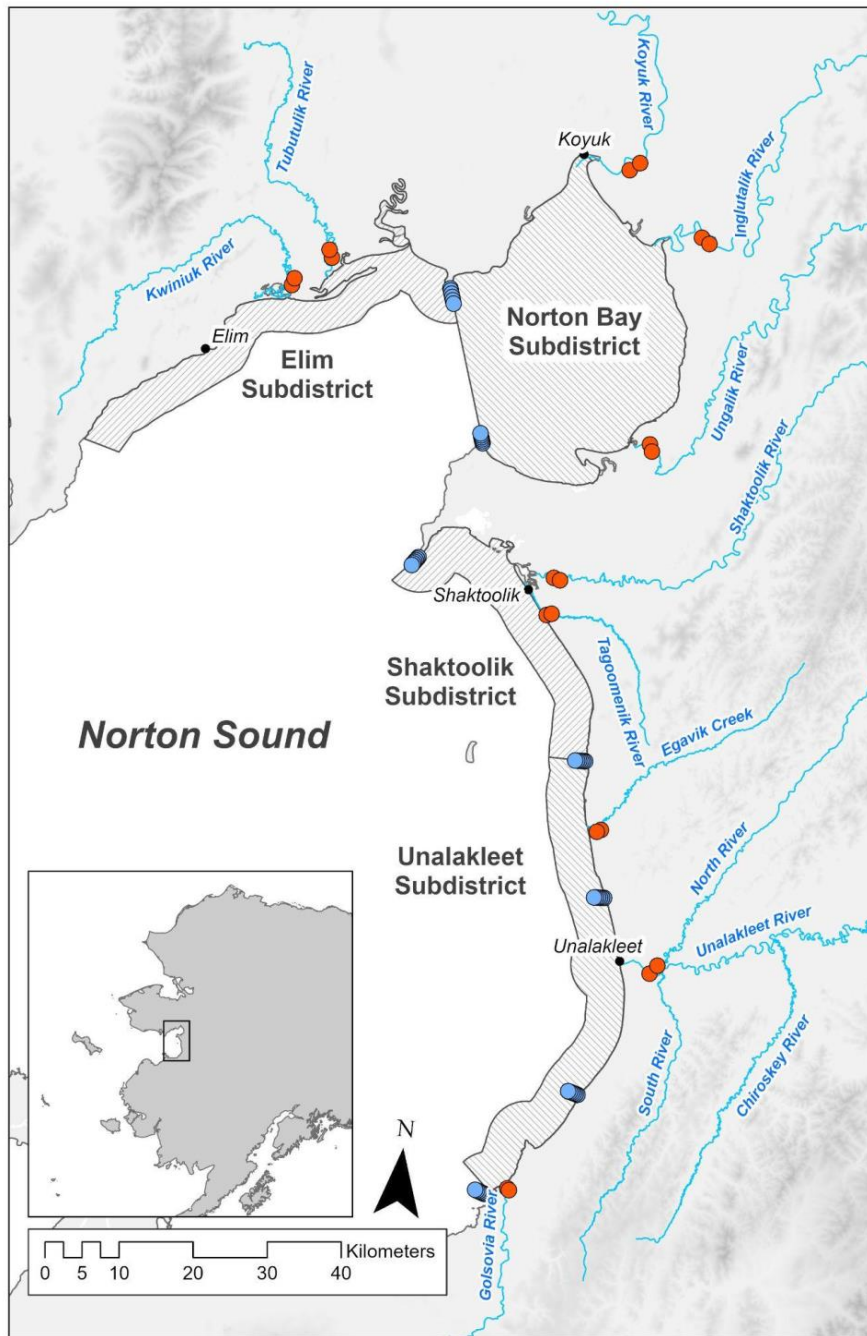


Figure 1.2 Acoustic receiver placement in the Norton Sound district of Alaska. Blue points show marine receiver locations and red points are inriver receiver locations. From north to south, the marine receiver arrays are: Bald Head, Point Dexter, Cape Denbeigh, Junction Creek, Blueberry Creek, Point Creek, and Black Point.

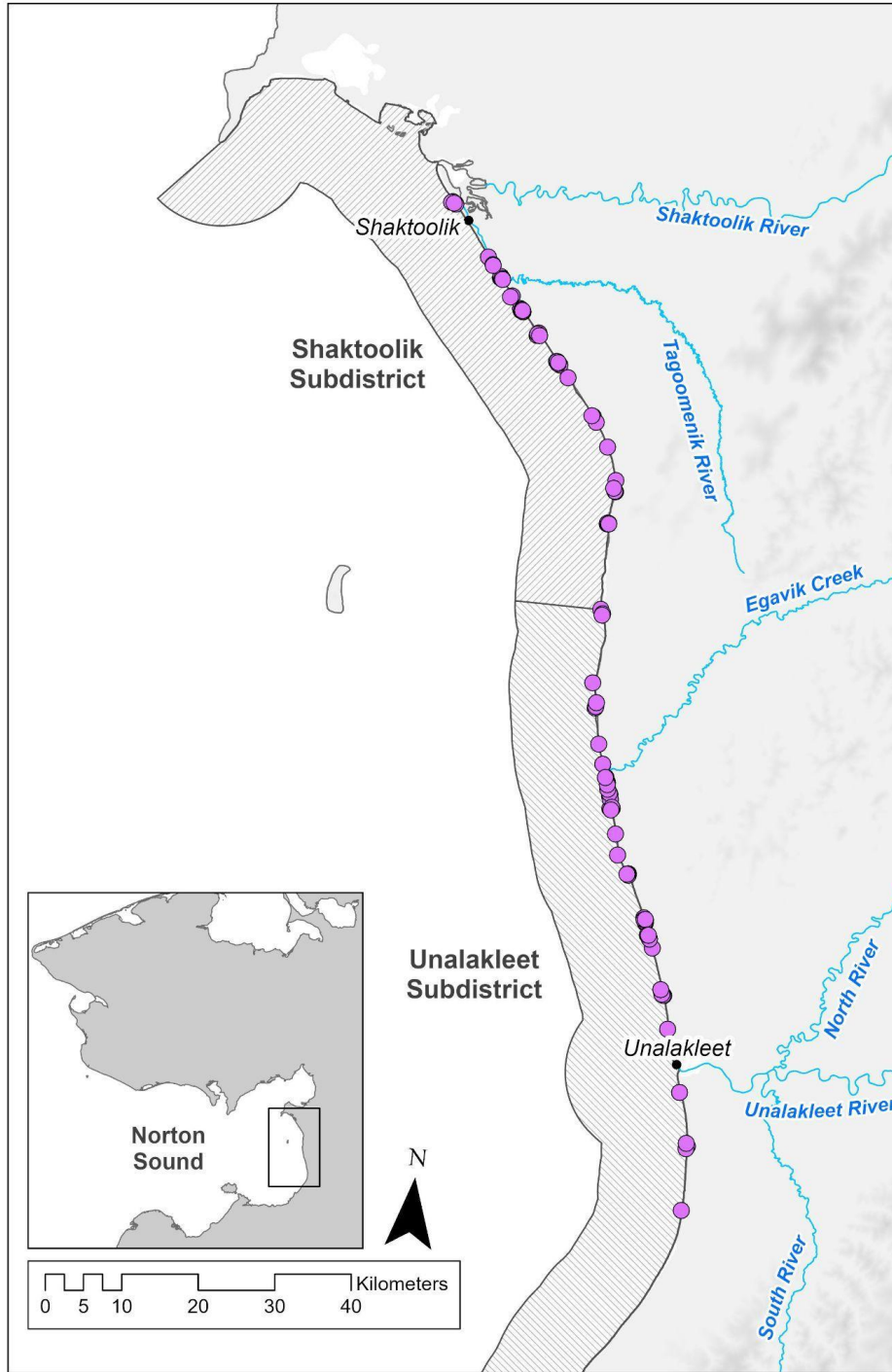


Figure 1.3 Coho salmon capture locations in the Norton Sound district of western Alaska.

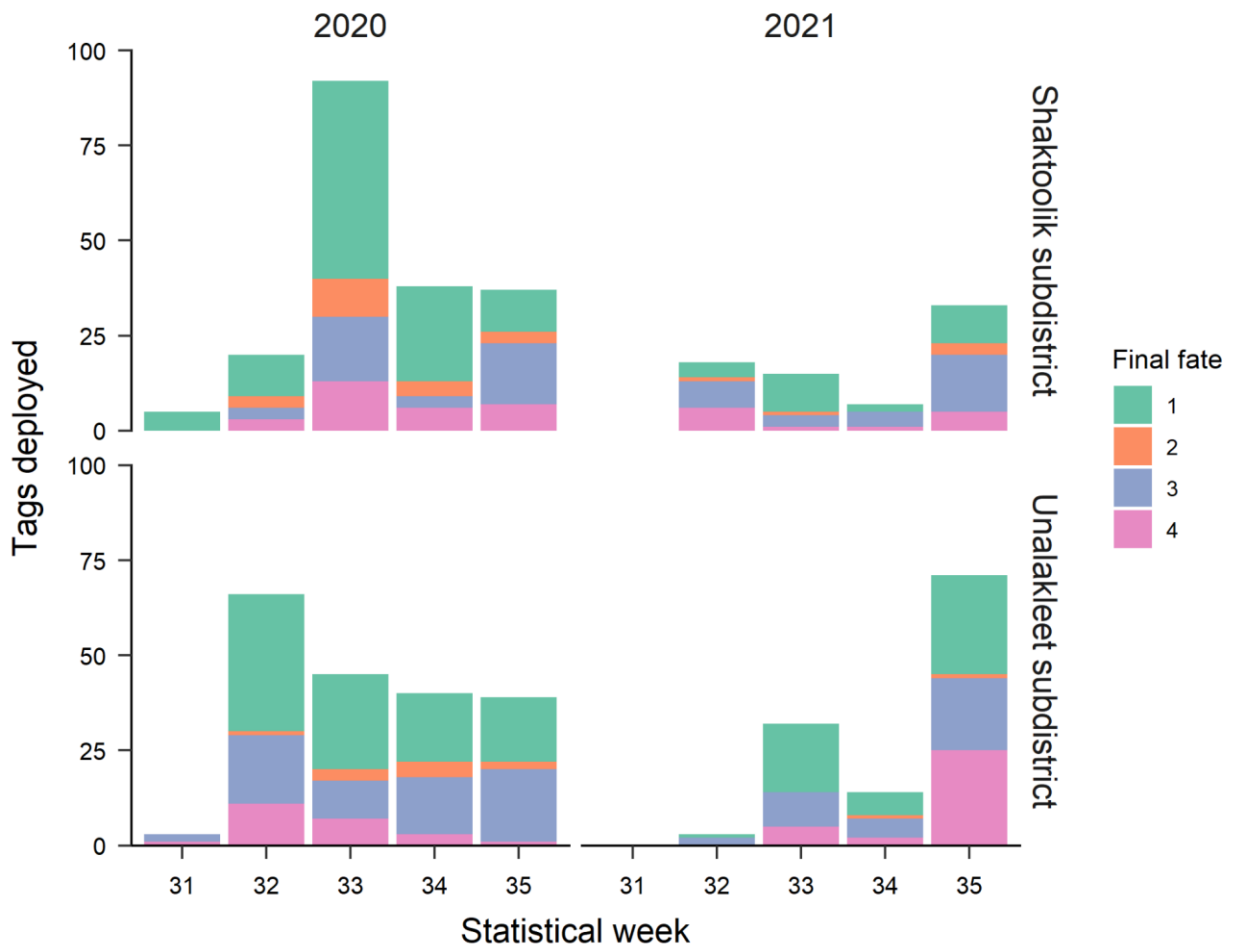


Figure 1.4 Number of acoustic tags deployed on Coho Salmon in each study subdistrict in the Norton Sound district of western Alaska in 2020 and 2021. The number of tags deployed in each statistical week are color coded by final fate: (1) Last detected in spawning streams within the study area, (2) last detected in waters outside the study area, (3) last detected in marine waters within the study area, and (4) not detected after tag deployment.

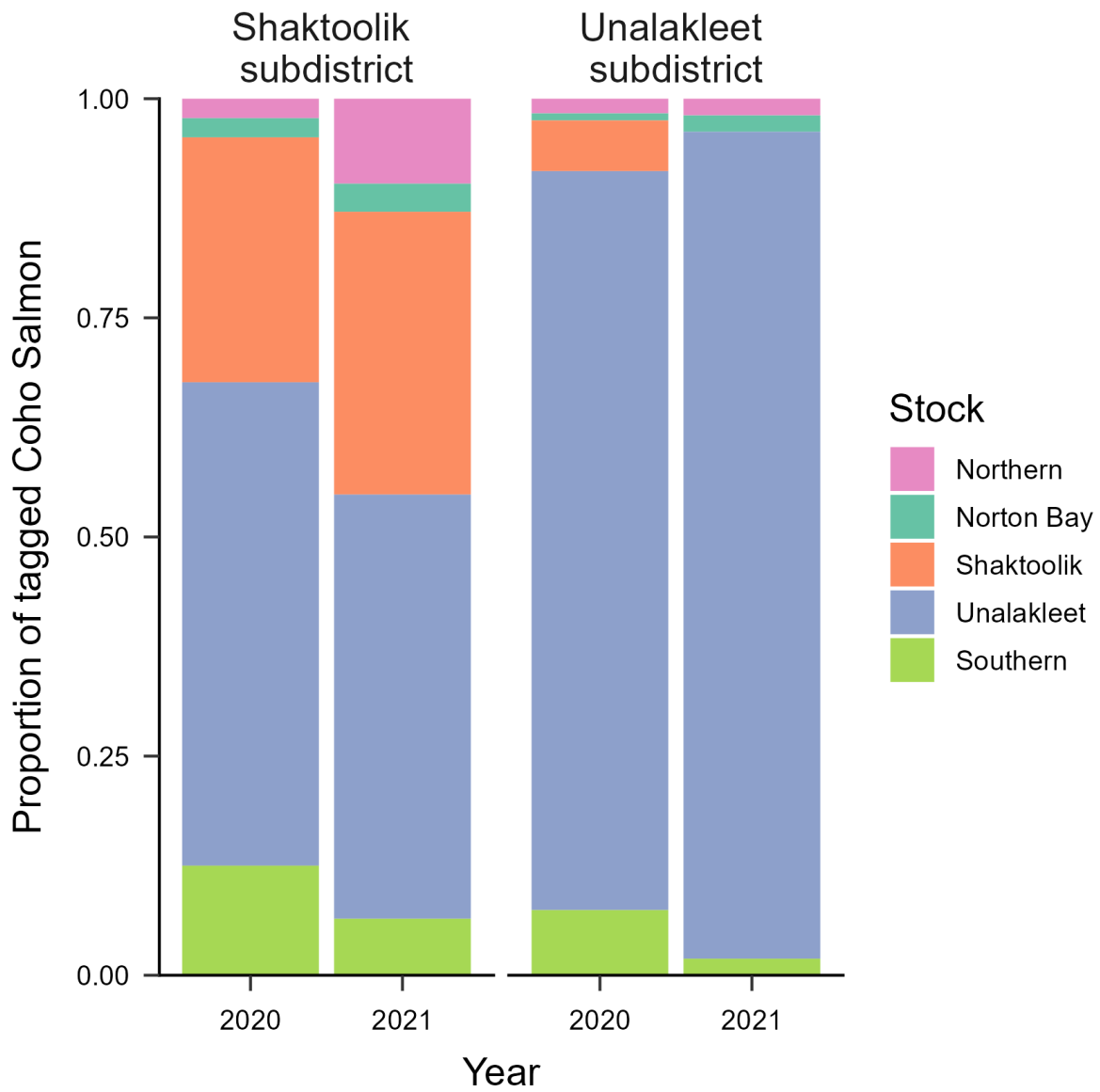


Figure 1.5 Proportion of Coho Salmon stocks tagged in the Shaktoolik and Unalakleet subdistricts of the Norton Sound district of Alaska in project years ($n = 341$).

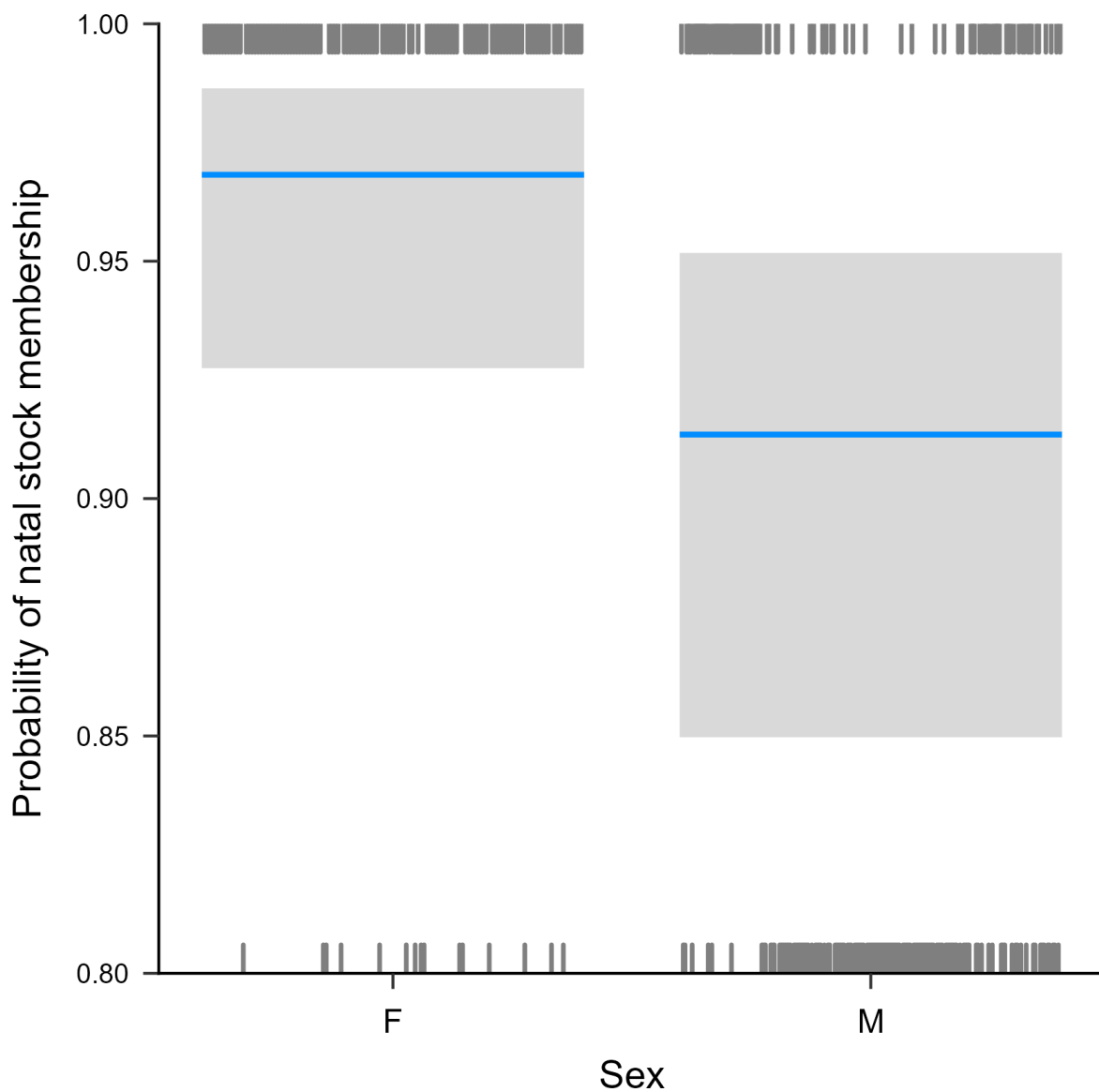


Figure 1.6 Probability of a captured Coho Salmon belonging to the natal stock of the subdistrict of capture by sex in the Shaktoolik and Unalakleet subdistricts of the Norton Sound district of Alaska. Model conditions are for a fish caught in 2020 on day of year 225 in Unalakleet subdistrict at 64.04228° latitude. The blue line is the prediction based on the model conditions, the gray envelope is the 95% confidence interval, and the ticks are observed data. Note condensed scale on y-axis.

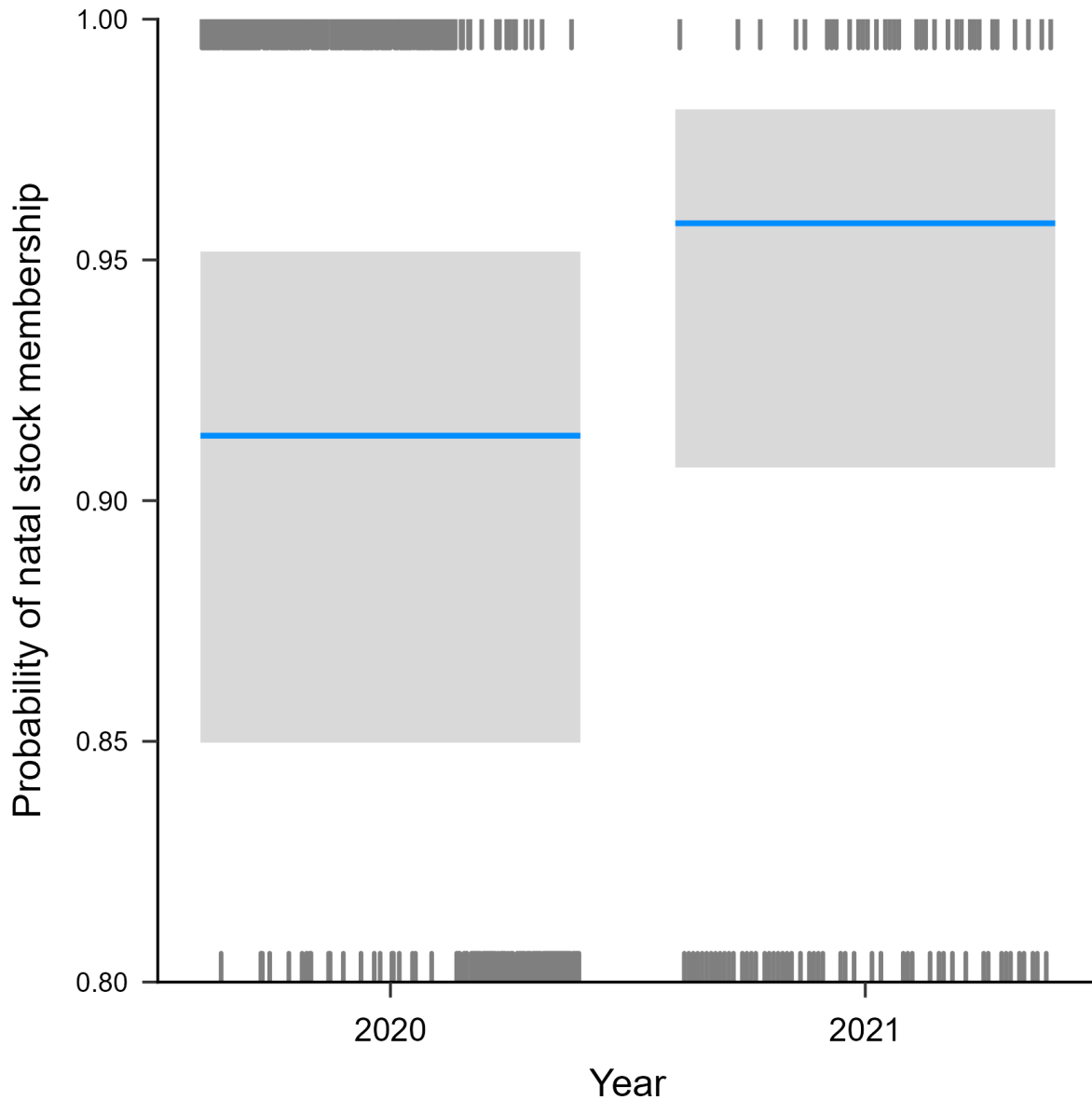


Figure 1.7 Probability of a captured Coho Salmon belonging to the natal stock of the subdistrict of capture by year in the Shaktoolik and Unalakleet subdistricts of the Norton Sound district of Alaska. Model conditions are for a male fish caught on day of year 225 in Unalakleet subdistrict at 64.04228° latitude. The blue line is the prediction based on the model conditions, the gray envelope is the 95% confidence interval, and the ticks are observed data. Note condensed scale on y-axis.

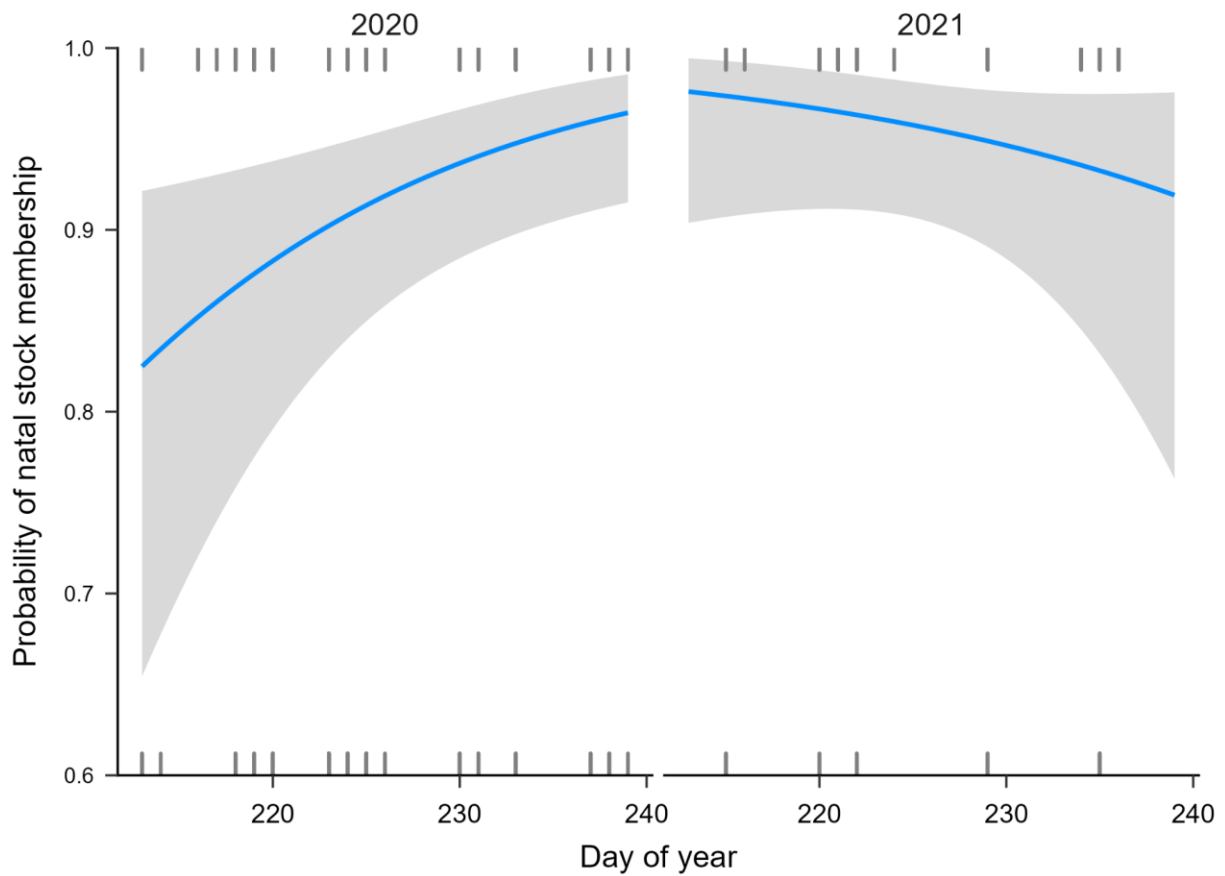


Figure 1.8 Probability of a captured Coho Salmon belonging to the natal stock of the subdistrict of capture by day of year in each project year in the Shaktoolik and Unalakleet subdistricts of the Norton Sound district of Alaska. Model conditions are for a male fish caught in Unalakleet subdistrict at 64.04228° latitude. The blue line is the prediction based on the model conditions, the gray envelope is the 95% confidence interval, and the ticks are observed data. Note condensed scale on y-axis.

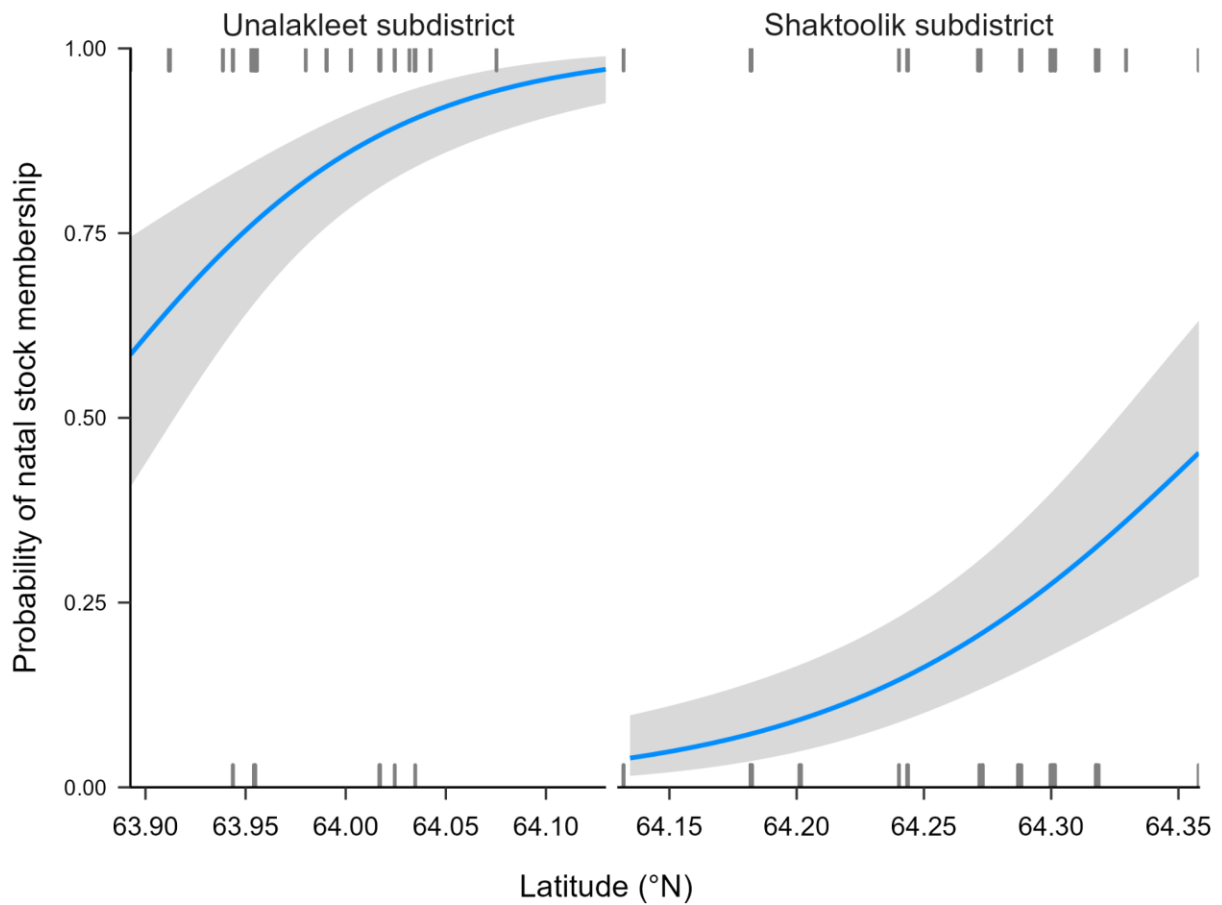


Figure 1.9 Probability of a captured Coho Salmon belonging to the natal stock of the subdistrict of capture by latitude in the Shaktoolik and Unalakleet subdistricts of the Norton Sound district of Alaska. Model conditions are for a male fish caught in 2020 on day of year 225. The blue line is the prediction based on the model conditions, the gray envelope is the 95% confidence interval, and the ticks are observed data.

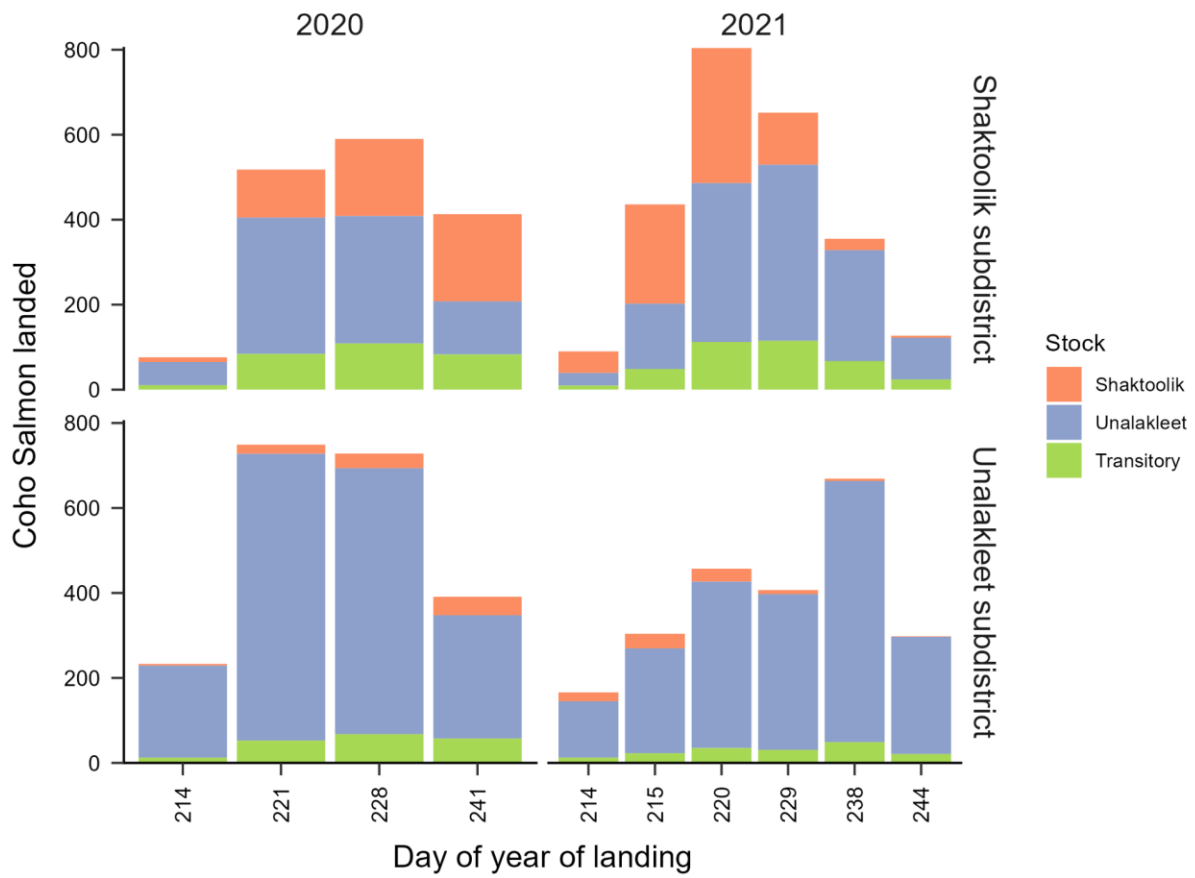


Figure 1.10 Model estimates for the number of Coho Salmon from each stock in commercial landings in Unalakleet and Shaktoolik subdistricts in the Norton Sound district of Alaska in project years by delivery day. Deliveries of < 50 fish are omitted for clarity.

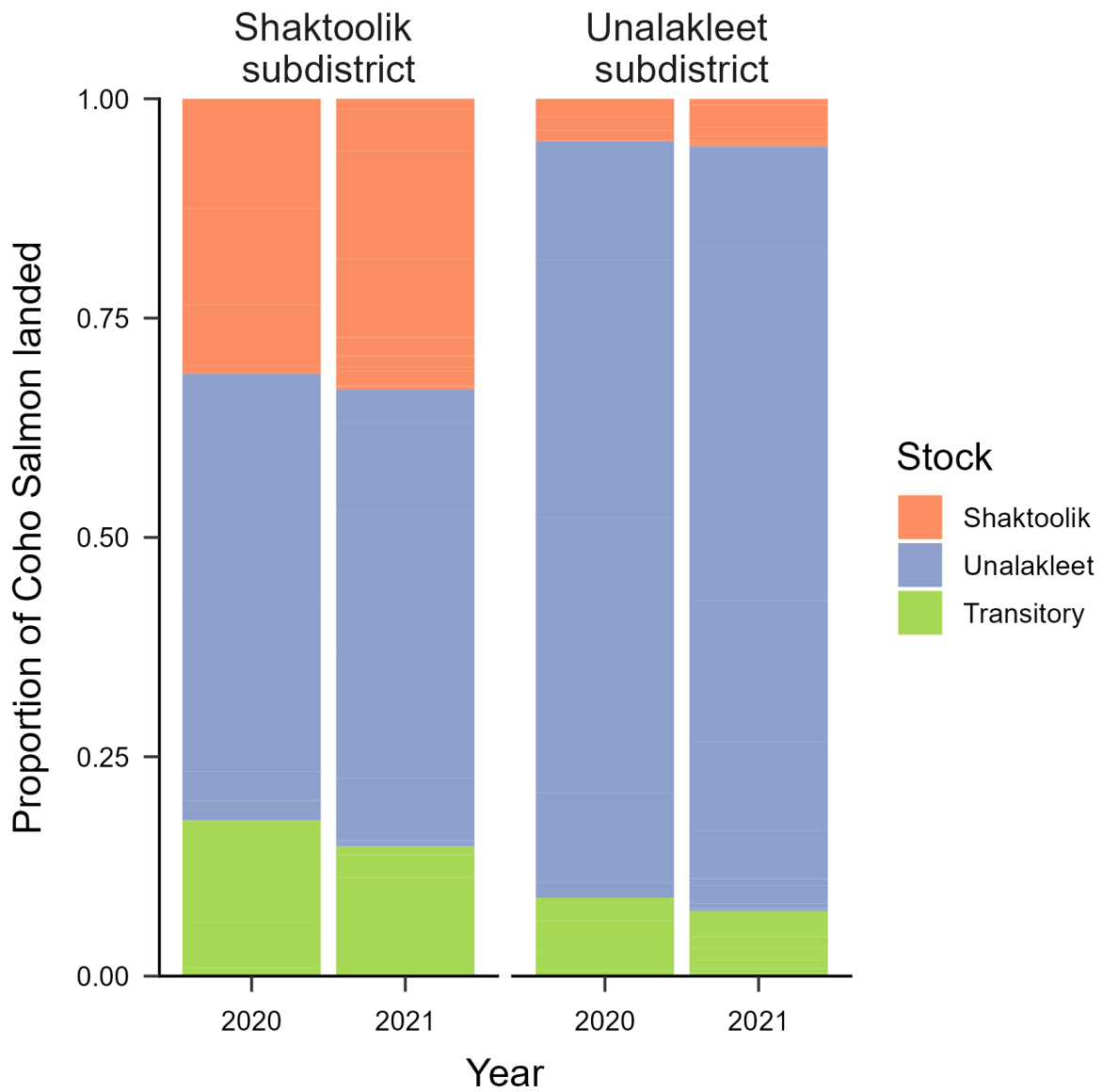


Figure 1.11 Model estimates for the proportion of Coho Salmon from each stock in commercial landings in Shaktoolik and Unalakleet subdistricts in the Norton Sound district of Alaska in project years.

Tables

Table 1.1 Coho salmon harvest by year in project-monitored subdistricts of the Norton Sound.

Acoustic tagging took place in 2020 and 2021.

Year	Elim subdistrict		Norton Bay subdistrict		Shaktoolik subdistrict		Unalakleet subdistrict	
	Harvest	Permits fished	Harvest	Permits fished	Harvest	Permits fished	Harvest	Permits fished
2012	2,003	24	4,376	18	7,827	21	22,188	55
2013	6,651	21	5,485	18	6,890	24	29,366	57
2014	15,821	29	9,560	20	19,749	24	63,270	63
2015	14,095	26	9,468	16	25,632	23	101,640	56
2016	14,141	25	6,652	18	25,849	28	55,090	68
2017	19,405	26	2,989	18	50,299	31	111,830	69
2018	19,987	34	1,513	12	71,468	36	155,578	80
2019	11,446	27	199	9	35,381	36	82,582	77
2020	2,011	25	251	7	1,645	27	2,141	55
2021	883	18	166	9	2,593	25	2,432	64
5-year average	10,746	26	1,024	11	32,277	31	70,913	69
10-year average	10,644	26	4,066	15	24,733	28	62,612	64

Table 1.2 Coho salmon escapement by year in rivers of Norton Sound study area subdistricts. There are no data for Norton Bay subdistrict streams, and years without counts are denoted by a dash. Note that none of these runs are considered completely monitored and numbers reported here should be considered minimum counts.

Year	Elim subdistrict		Shaktoolik subdistrict		Unalakleet subdistrict			
	Kwiniuk River		Shaktoolik River		North River		Unalakleet River	
	Total	Last day of count	Total	Last day of count	Total	Last day of count	Total	Last day of count
2012	781	Aug 16	-	-	3,258	Aug 19	17,548	Aug 15
2013	3,729	Sept 11	-	-	9,115	Sept 2	25,550	Aug 22
2014	14,637	Sept 9	57	July 13	4,995	Sept 1	44,525	Aug 27
2015	6,252	Sept 3	11,025	Aug 21	9,432	Sept 8	40,964	Aug 15
2016	9,210	Sept 16	480	July 18	2,256	Sept 7	132	July 22
2017	13,593	Sept 12	13,107	Sept 11	2,346	Sept 12	21,453	Aug 10
2018	17,172	Sept 16	53,562	Aug 28	20,010	Aug 26	58,755	Aug 8
2019	5,636	Sept 5	5,106	July 31	1,533	Aug 1	10,744	Aug 2
2020	5,373	Sept 7	4,176	Sept 6	1,926	Sept 7	-	-
2021	1,347	Sept 7	579	July 26	204	July 26	1,884	July 29
5-year average	8,624	Sept 9	15,306	Aug 21	5,204	Aug 21	23,209	Aug 5
10-year average	7,773	Sept 7	11,012	Aug 12	5,508	Aug 26	24,617	Aug 10

Table 1.3 Variable groups used for model selection to determine variables influencing Coho Salmon natal stock membership probability.

Variable	Description
Response variable	
‘natal.stock’	Indicates whether a tagged Coho Salmon originated from streams within the subdistrict in which they were captured. A binary response variable with a ‘1’ for natal stock membership and a ‘0’ otherwise.
Spatiotemporal variables	
‘year’	Year of capture. A factor with two levels: ‘2020’ and ‘2021.’
‘DOY’	Day of year of capture. A continuous integer variable.
‘year’ × ‘DOY’	Interaction term between year of capture, and day of year of capture.
‘capture.sd’	Subdistrict of capture. A factor with two levels: ‘Shaktoolik’ and ‘Unalakleet.’
‘latitude’	Latitude of capture. A continuous variable measured in decimal degrees.
Abiotic variables	
‘secchi’	Secchi depth measurement of water turbidity. A continuous variable measured in meters (<i>NA</i> = 24).
‘u.wind’	Vectorized wind measurement parallel to the x-axis (<i>NA</i> = 26).
‘v.wind’	Vectorized wind measurement parallel to the y-axis (<i>NA</i> = 26).
‘water.temp’	Water temperature. A continuous variable measured in °C (<i>NA</i> = 43).
‘cloud.cov’	Percent cloud cover. A continuous variable measured subjectively by eye (<i>NA</i> = 30).
‘tide’	Tide height. A continuous variable measured in meters and scaled by project day.
Demographic variables	
‘sex’	A factor variable with two levels: ‘M’ and ‘F.’
‘length’	Mid-eye to tail fork measured in millimeters. A continuous variable.
‘age’	European age of fish determined by scale pattern analysis. A factor with three levels: ‘1.1,’ ‘2.1,’ and ‘3.1’ (<i>NA</i> = 59).

Table 1.4 Final fate numbers for Coho Salmon tagged in Shaktoolik and Unalakleet subdistricts of the Norton Sound district of Alaska in 2020 and 2021. Fate 1 was fish last detected in spawning streams within the study area, Fate 2 were fish last detected in waters outside the study area, Fate 3 were fish last detected in marine waters within the study area, and Fate 4 not detected after tag deployment.

Year	Shaktoolik subdistrict					Unalakleet subdistrict					Total
	Fate 1	Fate 2	Fate 3	Fate 4	Total	Fate 1	Fate 2	Fate 3	Fate 4	Total	
2020	116	20	39	16	191	110	11	62	11	194	385
2021	26	5	29	13	73	51	2	35	32	120	193
Total	142	25	68	29	264	161	13	97	43	314	578

Table 1.5 Stock proportions of Coho Salmon tagged in Shaktoolik and Unalakleet subdistricts of the Norton Sound district of Alaska.

Each row sums to 100% for Shaktoolik and Unalakleet subdistricts respectively.

Year	Shaktoolik subdistrict						Unalakleet subdistrict					
	North	Elim	Norton Bay	Shaktoolik	Unalakleet	South	North	Elim	Norton Bay	Shaktoolik	Unalakleet	South
2020	2.2%	0.0%	2.2%	27.9%	55.1%	12.5%	1.7%	0.0%	0.8%	5.8%	84.3%	7.4%
2021	10.3%	0.0%	3.4%	34.5%	51.7%	6.9%	1.9%	0.0%	1.9%	0.0%	94.3%	1.9%
Total	3.6%	0.0%	2.4%	28.7%	53.9%	11.4%	1.7%	0.0%	1.1%	4.0%	87.4%	5.7%

Table 1.6 Model selection results for eight candidate logistic regression models estimating the probability of a captured Coho Salmon belonging to the natal stock. The ‘df’ column denotes the degrees of freedom for each model and the ΔAICc column is relative to the most parsimonious candidate model.

Variable groups in model	df	ΔAICc
Spatiotemporal	6	0.00
Spatiotemporal + demographic	11	0.40
Spatiotemporal + abiotic	12	5.51
Spatiotemporal + demographic + abiotic	17	6.88
Demographic	6	45.15
Intercept only	1	45.71
Abiotic	7	46.80
Demographic + abiotic	12	47.92

Table 1.7 Coefficient estimates, standard errors, confidence intervals, and test statistics for the most parsimonious logistic regression model predicting natal stock membership in Shaktoolik and Unalakleet subdistrict Coho Salmon fisheries in the Norton Sound district of Alaska in 2020 and 2021. Standard errors and 95% confidence intervals were estimated using 5,000 bootstrap iterations. Day of year and latitude were centered by subtracting the mean value. Intercept conditions are for a female fish captured in 2020 in Shaktoolik subdistrict at mean day of year and latitude.

Coefficient	Estimate	SE	95% CI	z statistic	p value
Intercept	-17.65	6.67	(-31.72, -5.8)	-2.933	0.003
Year 2021	26.94	10.99	(5.97, 49.52)	2.33	0.020
Day of year	0.067	0.029	(0.015, 0.130)	2.55	0.011
Capture subdistrict Unalakleet	6.79	1.02	(5.21, 9.23)	7.35	< 0.001
Latitude	13.42	3.3	(7.82, 20.80)	4.54	< 0.001
Sex male	-1.059	0.338	(-1.798, -0.464)	-3.19	0.001
Year 2021 x Day of year	-0.116	0.048	(-0.215, -0.023)	-2.28	0.022

Table 1.8 Catch partitioning of Shaktoolik and Unalakleet subdistrict commercial Coho Salmon landings in the Norton Sound district of Alaska in 2020 and 2021 estimated using a predictive multinomial response model. The 95% confidence intervals were estimated using 5,000 bootstrap iterations.

Shaktoolik subdistrict landings										
Year	Shaktoolik stock			Unalakleet stock			Transitory stock			Total
	Estimate	Proportion	95% CI	Estimate	Proportion	95% CI	Estimate	Proportion	95% CI	
2020	522	31.7%	(305, 753)	838	50.9%	(629, 1,053)	286	17.4%	(141, 468)	1,646
2021	873	33.7%	(347, 1,413)	1,345	51.9%	(806, 1,895)	375	14.5%	(60, 865)	2,593
Unalakleet subdistrict landings										
Year	Shaktoolik stock			Unalakleet stock			Transitory stock			Total
	Estimate	Proportion	95% CI	Estimate	Proportion	95% CI	Estimate	Proportion	95% CI	
2020	104	4.8%	(28, 230)	1,856	86.2%	(1,662, 2,006)	192	8.9%	(79, 362)	2,152
2021	136	5.6%	(29, 368)	2,124	87.1%	(1,721, 2,332)	178	7.3%	(24, 476)	2,438

Chapter 2: Coastal migration characteristics of exploited Coho Salmon stocks in the context of commercial fishery boundaries²

Abstract

Although anadromous Pacific salmon *Oncorhynchus* spp. are primarily harvested commercially in coastal waters, little is known about their fine-scale migratory behavior during this final stage of marine migration. This study uses acoustic telemetry to characterize nearshore behavior of 578 adult Coho Salmon *O. kisutch* in the Norton Sound district of Alaska during two fishing seasons. A network of 62 passive hydrophone receivers monitored tagged Coho Salmon swimming speeds and distance from shore, fishery residence time, and movement directionality within the Shaktoolik and Unalakleet commercial subdistricts, and 341 individuals last detected in spawning areas were assigned to a stock of origin based on assumed natal site fidelity. Coho Salmon belonging to local stocks swam slower and further offshore relative to fish bound for spawning streams outside the study area, and residency time within coastal fishery boundaries decreased for all stocks as the season progressed. Multistate models were fit to detection data to estimate movement probabilities among discrete marine and freshwater spatial strata, and model selection by AICc determined that sex and year of migration contributed to model averaged estimates and the Unalakleet stock was more likely than other stocks to explore areas outside of their natal subdistrict before entering freshwater. Results of this study suggest that Coho Salmon display divergent coastal migratory characteristics relative to intraseasonal phenology and proximity to target streams that could be strategically leveraged to optimize both exploitation and conservation.

² Henslee, L. H., P. A. H. Westley, Z. W. Liller, and A. C. Seitz. *In prep for Transactions of the American Fisheries Society*. Coastal migration characteristics of exploited Coho Salmon stocks in the context of commercial fishery boundaries.

Introduction

Anadromous Pacific salmon *Oncorhynchus* spp. (hereafter ‘salmon’) are renowned for vast ocean migrations through diverse habitats while moving from marine feeding areas to freshwater spawning streams. Although the main point of interaction between exploitable salmon populations and commercial fisheries typically occurs in coastal waters, the fine-scale nearshore migratory behavior of salmon in the final stages of their marine migration is poorly understood. This is partly because the coastal phase of adult salmon spawning migration involves complex shifts between navigational mechanisms (Ueda 2019) and physiological states (Crossin et al. 2009; Ueda 2016) as individuals negotiate dynamic coastal environments and prepare to transition to freshwater habitats. Beyond a general deficiency of investigative work characterizing nearshore salmon movement, studies focused on wild populations free of hatchery enhancement in largely intact coastal environments are even more scarce. Controlling for the effects of anthropogenic impacts to nearshore habitats and the potential influence of supplemental populations of hatchery salmon is problematic for disentangling the variables that drive coastal migratory behavior (Jonsson and Jonsson 2017; Knudsen et al. 2021). Investigations aimed at the nearshore adult stage of the wild anadromous salmon life cycle have noted broad variation in movement and phenology (Crossin et al. 2007; Cooke et al. 2008; Davidsen et al. 2013), reflecting the diversity that stabilizes interannual returns of population complexes that are managed as stocks (Schindler et al. 2010). Because diversity among and within exploitable stocks is widely accepted as a hallmark of sustainable salmon fisheries (Dann et al. 2013), characterizing migratory behavior in waters in which fishing effort is managed is important for balancing harvest and conservation.

The migratory characteristics of salmon stocks are ultimately dictated by shared environmental drivers and heritable traits reflecting local adaptations (Mundy and Evenson 2011; Kovach et al. 2012; Thompson et al. 2020) that result in variation of spatiotemporal movements that are often used by managers to regulate harvest and to help conserve diversity (Secor 1999; Boatright et al. 2004; Clark et al. 2015; Moses et al. 2019). For coastal salmon fisheries, availability to harvest is at least partly dictated by swim speeds, migratory distance from shore, and transition timing between marine and fresh waters. These characteristics may be influenced by relative proximity to target streams, as salmon alter swim speeds and vertical movements while homing in on freshwater signals (Quinn et al. 1989; Davidsen et al. 2013; Wilson et al. 2014; Drenner et al. 2015). Additionally, movement behavior variability within stocks may also manifest according to sex (Clark et al. 2015), intraseasonal migration timing (Crossin et al. 2007), and interannual distribution trends (Carey et al. 2017). Therefore, investigations that scrutinize movement characteristics of exploitable salmon stocks should also consider fine spatial and temporal variation in behavior among stock components. Ultimately, fishing effort should be distributed among stocks and their constituent populations to preserve diversity without sacrificing harvest opportunities (Adkison and Cunningham 2015; Gayeski et al. 2018; Freshwater et al. 2020).

Characterizing migration behavior of salmon in fisheries that target a mixture of stocks (i.e., a ‘mixed fishery’) is often achieved by relating stock composition of fishery landings to the spatial and temporal distribution of harvest effort (Cunningham et al. 2018; Whitlock et al. 2018; Svenning et al. 2019), where stocks are identified and partitioned in landings by scrutinizing unique inherited (e.g., genetic) and acquired (e.g., otolith microchemical) markers (Begg and Waldman 1999). However, this method is insufficient to elucidate fine-scale details of coastal movements such as swimming speeds and freshwater entry timing. Mark recapture techniques

have long been used to investigate salmon movement (Gaudet and Schaefer 1982), and acoustic telemetry improves upon this method by using strategically placed passive hydrophone receivers to monitor tagged salmon movement in lieu of recapture events (Bell et al. 2018; Faust et al. 2019; Harris et al. 2022). Although tagging studies can be relatively costly and time-consuming, these techniques are able to provide high-resolution movement data compared to other methods (Goethel et al. 2019).

In the Norton Sound of northwest Alaska, residents rely on salmon for food security, cultural well-being, and economic livelihood (Magdanz et al. 2009; Menard et al. 2009). The marine waters of the region's commercial salmon fishing district are divided into six subdistricts (Figure 2.1) that are managed by the Alaska Department of Fish and Game (ADF&G) based on comparative catch statistics, escapement abundance (number of fish that escape fisheries to spawn), and weather conditions (Menard et al. 2022). Most of the harvest pressure in the region is based in the Shaktoolik and Unalakleet subdistricts (locally referred to as 'southern' Norton Sound), where commercial fisheries consistently attract buyers for Coho Salmon *O. kisutch*. Methods of catch partitioning based on acquired and inherited biological identification markers are unable to classify mixtures of exploitable stocks within subdistrict fisheries, likely due to similarities in spawning and rearing habitats and maintained gene flow among stocks (Beacham et al. 2011; Zimmerman et al. 2013). Previously, acoustic telemetry was used to identify Coho Salmon stocks available for harvest in southern Norton Sound by assuming natal site fidelity of tagged salmon last detected within discrete spawning areas, and model selection methods suggested divergent spatiotemporal characteristics are useful for stock classification (Chapter 1). Although it appears that migratory behavior is an important distinction among stocks transitioning through coastal environments,

fine-scale movement variation relative to fishery boundaries and intraseasonal timing remains obscure.

This investigation makes use of acoustic detection histories of Coho Salmon tagged in the Shaktoolik and Unalakleet subdistricts of the Norton Sound in northwest Alaska to 1) characterize swim speeds and lateral migration distance relative to the shoreline, 2) summarize residency time within fishery boundaries, and 3) estimate movement probabilities among discrete fishery subdistricts and spawning areas. Capture events were conducted throughout the 2020 and 2021 fishing seasons in each subdistrict by mimicking local commercial methods, and tagged fish were tracked through coastal waters to characterize migratory movements. Swim speeds and migratory distance from shore were analyzed by stock and by relative proximity to the target stream for fish bound for the Unalakleet River. Differences in residency times and movement probabilities were examined among stocks, and among sexes and temporal strata (i.e., week of capture, year). Multistate models were fit to detection data to estimate movement probabilities among discrete marine and freshwater spatial strata, and nested candidate models were compared to test the significance of demographic and temporal effects that may influence migratory behavior. Results of this study document complex nearshore Coho Salmon migration at fine scales and are intended to uncover divergent movement characteristics among stocks and their components that could be leveraged to conserve diversity while taking full advantage of harvestable surpluses.

Methods

Study area

Adult Coho Salmon were captured and tagged in the coastal waters of the contiguous Shaktoolik and Unalakleet subdistricts (hereafter ‘study area’) in the Norton Sound commercial management

district (Figure 2.1), which includes approximately 56.1 km and 85.5 km of linear coastline, respectively. Tagged Coho Salmon movement was monitored throughout the region by a network of marine and inriver passive acoustic receivers. Marine receiver arrays were placed to detect tagged Coho Salmon movement at the eastern boundary of Elim subdistrict and the boundaries of the Norton Bay, Shaktoolik, and Unalakleet subdistricts, as well as two additional arrays within the Unalakleet subdistrict (Figure 2.2). The nearshore environment in southern Norton Sound is characterized by shallow water depths (generally < 20 m), sandy substrate, and a mean tidal range of 0.85 m. Tagged Coho Salmon river entry was monitored in all major spawning streams in the region, including the Kwiniuk and Tubutulik rivers in Elim subdistrict; the Koyuk, Inglutalik, and Ungalik rivers in Norton Bay subdistrict; the Shaktoolik and Tagoomenik rivers in Shaktoolik subdistrict (both drain into Shaktoolik Bay); and Egavik Creek, and the Unalakleet and Golsovia rivers in Unalakleet subdistrict (Figure 2.2). Rivers within the study area experience highly variable water levels depending on tides, watershed precipitation, and the previous winters' snowfall.

Tagging and tracking

Adult Coho Salmon were captured using gillnets at fishing sites within 200 m of shore by two crews operating in Shaktoolik and Unalakleet subdistricts, respectively. Fishing effort resembled commercial fishing methods as closely as possible in gear size, seasonal timing, and fishing locations. Fishing sites were advised by communicating with local harvesters and by directly observing commercial fishing operations throughout the season. Coordination with local fishery experts confirmed that gillnets are operated throughout the coastal waters of the Shaktoolik and Unalakleet subdistricts, although commercial fishing activity north of the mouth of Shaktoolik Bay and south of the Unalakleet River is relatively uncommon during Coho Salmon fishing season.

Therefore, the location of fishing sites was not fixed, and an effort was made to evenly distribute fishing effort throughout the area (Figure 2.3). A single site per day was fished unless conditions necessitated relocating (e.g., inclement weather, absence of target species).

Nets were continuously monitored while deployed and fish were immediately attended after becoming entangled in the mesh. Captured Coho Salmon were carefully removed from the net by cutting the web as needed and placed in a tote of circulating sea water. Body length was measured to the nearest millimeter from mid-eye to tail fork (to control for sexual dimorphism), three scales were removed for age determination, and sex was determined using external characteristics such as body symmetry, kype development, and presence of an ovipositor (Eaton 2015). Species identification confirmation was conducted postseason by analysis of scale patterns and fish determined not to be Coho Salmon were removed from the dataset ($n = 15$ in 2020 and $n = 0$ in 2021).

Acoustic tags were attached by inserting two stainless steel 14-gauge darts through the dorsal musculature, between proximal pterygiophores approximately 1.5 cm laterally from the dorsal fin and then threading the wire ends of the tag mount assembly through the darts. This technique prevents muscle damage and premature rejection of the tag caused by tearing through muscle tissue due to hydrodynamic drag and has minimal effect on fish movement and behavior (Bridger and Booth 2003). Coho Salmon were allowed to recover in a tote of circulating seawater (*sensu* Portz et al. 2006) before being released away from the net. The sampling and tagging process from retrieval to release took an average of 7.5 min (SD = 3.6 min). Animal handling and care were approved by the University of Alaska Fairbanks Institutional Animal Care and Use Committee (Protocol 1556023; Appendix B).

Fishing schedules were based on ADF&G statistical weeks and occurred over the 5-year average duration of the commercial Coho Salmon fishing season (2015–2019). Captures began in the last week of July (stat week 31) and continued through the last week of August (stat week 35). Field crews fished in each statistical week of the schedule with the goal of deploying 40 tags per week, and a total of 200 tags deployed in each subdistrict, in each year (800 tags throughout the project). Any tags that were not deployed during a week were added to the tags to be deployed during the next week. Coho Salmon capture was timed to occur between commercial fishing periods (i.e., during fishery closures) and when possible, crews deployed tags immediately following a fishery closure to allow tagged fish time to reach spawning destinations before being subjected to harvest pressure in the subsequent opener. Informational fliers were posted in public places in the communities of Elim, Koyuk, Shaktoolik, and Unalakleet, AK and included instructions on how to recognize and return acoustic tags from recaptured Coho Salmon, and harvesters reporting recaptures were asked to provide the timing and location of recapture.

The acoustic transponders used for this study were Lotek MM-M-11-28 tags with a transmitting frequency of 76 kHz, dimensions of 12 x 60 mm, a weight of 11 g in air, and a battery life expectancy of 111 days at a transmission interval of 7 seconds. Each tag transmitted a unique code to be detected by strategically placed passive acoustic hydrophone receivers (Lotek WHS 3250). Marine arrays were composed of six receivers deployed perpendicular to shore (Table C.1 and C.2), suspended 1.5 m above the sea floor with 50 kg concrete anchors deployed at depths less than 50 m. Receivers were suspended with subsurface and surface buoys to maintain vertical orientation and allow for fluctuations in water level (Figure C.1). Inriver acoustic receivers were mounted on rebar driven into the riverbed in an area that provided the greatest chance of detecting tagged fish while minimizing disturbance to the receiver (Table C.3 and C.4). Two receivers were

placed above tidal influence in all monitored rivers with one receiver ≥ 500 m upstream of the other to confirm movement directionality and for redundancy.

Passive acoustic receivers' ability to detect tag transmissions varies greatly with distance between transmitter and receiver (Hobday and Pincock 2011), and with environmental sources of acoustic interference such as rain, wind, waves, boat traffic, and substrate disturbance (Mathies et al. 2014). Systematic range testing in the presence of environmental variables was used to determine appropriate spacing between individual receivers deployed in marine arrays and optimal deployment locations in riverine environments. In 2020, linear marine arrays were composed of six receivers placed 300 m apart for a total detection range of about 2.1 km from shore based on optimal detection ranges recorded by previous acoustic studies in the Norton Sound (Bell et al. 2018). In 2021, it was determined that receivers could be spaced further apart to achieve a linear detection range of approximately 3.1 km from shore based on an optimal range of 500 m. Refer to Appendix C for details on receiver hardware and settings, marine and inriver deployment and retrieval methods, and range testing.

Data organization

Telemetry files (.jst) were downloaded from receivers at the end of each season and sorted using acoustic detection conversion and organization software (Lotek WHS Host x64 V1.5.3373.1). As an acoustically tagged Coho Salmon swims past a receiver it is detected multiple times within the dynamic detection range. The best estimate of the exact time a fish passed closest to a receiver was determined by identifying the detection with the greatest 'power,' a unitless measure of relative acoustic signal strength which is directly proportional to the distance between the tag and receiver. In this method, multiple detections of a tag moving past a receiver or an array of receivers were

condensed into one timestamp paired with a geographic coordinate point, and these observations were compiled into detection histories.

Three data types were compiled for each tagged Coho Salmon: 1) tag deployment information including unique tag code, time and location, environmental conditions during capture, and age-sex-length data, 2) acoustic detection history including any detections by marine and/or inriver receivers, and 3) recapture information, if any, reported by commercial, subsistence, and sport harvesters. These data types were integrated in R software (R x64 3.5.1, R Core Team 2021), organized by unique tag codes, and individual detection histories were compiled. Note that in this case, ‘detected’ refers to capture events, acoustic detections, and physical recaptures.

All tagged Coho Salmon were assigned a final fate determinate on individual detection histories.

The four possible final fates were:

1. Last detected in spawning streams within the study area;
2. Last detected in waters outside the study area;
3. Last detected in marine waters within the study area;
4. Not detected after tag deployment.

For cases in which a tagged Coho Salmon was recaptured by subsistence and sport harvesters in freshwater below inriver receivers, it was assumed that the fish was in its natal spawning stream and was assigned to Fate 1 ($n = 10$ in 2020 and $n = 11$ in 2021). All fish assigned to Fate 1 or 2 received one of three stock designations based on the location of final detection. The stock designations are:

Shaktoolik stock: fish bound for spawning streams within Shaktoolik subdistrict;

Unalakleet stock: fish bound for spawning streams within Unalakleet subdistrict; and

Transitory stocks: fish bound for spawning streams outside of the study area.

Stock assignments were based on the assumption that tagged Coho Salmon returned to spawn in their natal streams (i.e., not strays from a donor population). This assumption is supported by studies that have shown that Coho Salmon have relatively low straying rates compared to other salmon species (Labelle 1992; Westley et al. 2013), although all populations experience at least some immigration/emigration effects.

Calculating summary statistics

Migratory distance from shore and swimming speeds were estimated from marine receiver detections of tagged Coho Salmon. Migratory swim speeds were standardized by calculating rates in body lengths per second (BL/s). Differences among groups in migratory distance from shore and log-normalized swimming speeds were determined by analysis of variance using a significance level of $\alpha = 0.05$. The placement of the two additional receiver arrays within the Unalakleet subdistrict allowed for comparison of migratory characteristics relative to proximity to the target stream for Coho Salmon last detected in the Unalakleet River (the main component of the Unalakleet stock complex). For fish last detected in the Unalakleet River, swim speeds and migratory distance from shore were averaged for three spatial strata defined for relative proximity to the mouth of the Unalakleet River. The three strata were labeled as 1) *near*: waters between Blueberry Creek and Point Creek arrays, including the Unalakleet River mouth (<20.4 km from river mouth), 2) *mid*: waters of the Unalakleet subdistrict, excluding the area within the *near* strata (<38.6 km from river mouth), and 3) *far*: waters of the Shaktoolik subdistrict (<67.1 km).

The number of decimal days a tagged Coho Salmon resided within Shaktoolik and Unalakleet subdistrict waters was estimated for all fish assigned to a stock (Fates 1–2). The total time at liberty t_l was simply calculated as the elapsed time between the initial encounter and the final detection. Total residency time t_a was calculated by $t_a = \sum t_s = t_l - (t_r + t_x)$, where t_s is the time spent

in subdistrict s , t_r is the time spent in river r , and t_x is the elapsed time the fish spent in waters outside the study area before reentering the study area. Because inriver receivers were placed well above the river mouth to avoid complications associated with dynamic tides and wave action, the time t that a tagged Coho salmon spent in freshwater of river r was calculated as: $t_r = d_r / m$, where d_r is the distance from the mouth of river r to the inriver receiver, and m is the swim rate of the fish assuming a river migration speed of 1 BL/s (Ellis 1966). Distribution of residency time was log-normalized and significant differences among fish grouped by stock, week of capture, and sex were examined using analysis of variance.

Movement probabilities

A spatial multistate mark-recapture model (*sensu* Hestbeck et al. 1991; Brownie et al. 1993; Perry et al. 2010; Hayden et al. 2014) was used to characterize directional movement of tagged Coho Salmon while accounting for the possibility that a fish could pass through monitored waters undetected. Model structure restricts the progression of movement to a sequence of detections away from the release site to the final detection, and so the study area was demarcated into movement areas defined as the waters outside of the study area (movement area *OUT*), marine waters within Shaktoolik or Unalakleet subdistricts (*SKK* and *UNK* respectively), and Shaktoolik or Unalakleet freshwater (*SFW* and *UFW* respectively). Within each step of a detection history, a tagged Coho Salmon could move from area h to area k with probability $\varphi_{h,k}$, or cease migration in that step with probability $1 - \omega_h$, where $\omega_h = \sum \varphi_{h,k}$ for all possible k . For example, a fish encountered in Shaktoolik subdistrict could move south into Unalakleet subdistrict with probability $\varphi_{SKK,UNK}$, move north out of the study area with probability $\varphi_{SKK,OUT}$, move into the Shaktoolik or Tagoomenik rivers with probability $\varphi_{SKK,SFW}$, or cease movement with probability $1 - (\varphi_{SKK,UNK} + \varphi_{SKK,OUT} + \varphi_{SKK,SFW})$. While the estimate of $1 - \omega_h$ within fishery boundaries

(i.e., *SKK* and *UNK*) indicates a probable mortality or recapture event, movement cessation relative to fish encountered in freshwater or outside the study area (i.e., *SFW*, *UFW*, *OUT*) imply that a Coho Salmon has reached the last step of movement progression to a spawning area. Direct transitions between certain movement areas are not possible (e.g., $\varphi_{SKK,UFW}$ or $\varphi_{SFW,OUT}$) and so these parameters were fixed to equal zero in the design matrix of the multistate model. Detection of fish by the Norton Sound acoustic receiver network or by recapture beyond a movement area enabled estimation of area-specific detection probabilities (p_h), defined as the probability that a fish was detected moving through movement area h given that it passed through that area. Detection probabilities at the boundaries of the Norton Sound acoustic network were not estimable in this manner, and so a ‘recovery rate’ ($\lambda_{h,k}$) was calculated as the joint probability of movement between sites h and k and detection at k .

Program MARK (White and Burnham 1999) was used to estimate survival (S), detection (p), and transition (ψ) parameters of the multistate model described by Hestbeck et al. (1991) and Brownie et al. (1993). Movement probabilities (φ) among movement areas were derived from these models as the product of survival and transition probabilities within each step. The R package RMark (Laake 2011) was used to construct models for MARK and the delta method (Seber 1982) was used to estimate standard error for all derived parameters, including movement probabilities, using the R package msm (Jackson 2011).

Estimating Coho Salmon movement probabilities was performed in two steps: (1) candidate models ranging from a global model (including group covariates of sex, week of capture, and year of capture) to an intercept-only model were fit to detection history data for all tagged fish, and (2) goodness of fit test results from the previous step were used to estimate model-averaged movement probabilities for (a) all tagged Coho Salmon, without consideration of stock membership, (b)

Shaktoolik stock, (c) Unalakelet stock, and (d) Transitory stock. For step one, the effects of group covariates were tested by estimating the overdispersion parameter (\hat{C}) for the full model using Fletcher goodness of fit procedures in RMark (Fletcher 2011). Results of \hat{C} were used to adjust values and variances of Corrected Akaike's Information Criterion (AICc). Models within two likelihood/AICc units were determined to be comparable in evidence and models more than four units from the most parsimonious model have a much lower weight of evidence (Burnham and Anderson 2004). Parameter estimates were averaged across candidate models based on AICc weights representing the relative likelihood of each model (Symonds and Moussalli 2011). For the second step, candidate models were fit to the full detection history data set to estimate movement probabilities for all tagged Coho Salmon ($n = 578$), and stock-specific movement was estimated by fitting candidate models to data sets constricted to respective Shaktoolik stock ($n = 55$), Unalakelet stock ($n = 242$), and Transitory stock ($n = 44$) detection histories.

Because stock assignment is conditional on survival to escapement, survival parameters for stock-specific multistate models were fixed at one in the design matrix. Movement probabilities for fish assigned to Shaktoolik or Unalakelet stock were constrained to estimate the next likely move of a fish encountered within its natal subdistrict only. This was done because a stock member encountered outside of its natal subdistrict waters will move toward that subdistrict with a probability near one, causing model convergence issues. For example, a Shaktoolik stock Coho Salmon encountered in the *OUT* or the *UNK* movement areas would move into the *SKK* movement area ($\varphi_{OUT,SKK} \approx \varphi_{UNK,SKK} \approx 1$), since it eventually must enter *SFW* contingent on its stock assignment.

Results

Tag deployment and acoustic detections

In 2020, 385 Coho Salmon were captured and tagged in both subdistricts combined. Of those fish, 257 were tracked to spawning regions (Fates 1 and 2), 101 were last detected in marine waters within the study area (Fate 3), and 27 were not detected after deployment (Fate 4). Of the fish assigned to stocks in 2020, 45 were Shaktoolik stock, 177 were Unalakleet stock, and 35 were Transitory stocks. Inclement weather, low Coho Salmon abundance, and logistical constraints resulted in much lower sample sizes in 2021 when 193 Coho Salmon were captured and tagged. Of those fish, 84 were tracked to spawning regions, 64 were last detected in marine waters within the study area, and 45 tags were not detected. In 2021, there were 10 fish assigned to Shaktoolik stock, 65 were Unalakleet stock, and 9 were Transitory stocks. The number of tags deployed in each statistical week varied widely (mean = 32.1, SD = 25.1) and was mostly dictated by Coho Salmon abundance and weather conditions. The number of unique marine detections of tagged Coho Salmon per day (for days that there were marine detections) ranged from 1 to 86 (Figure 2.4) and varied relative to distance from shore (Figure 2.5). The number of river detections varied from 0 in the Kwiniuk and Tubutulik rivers, to 192 in the Unalakleet River (Figure 2.6).

Summary statistics and stock-specific movement characteristics

The mean length of all tagged Coho Salmon was 541 mm (SD = 36.7), the mean age was 4 years (SD = 0.5), and the proportion of fish that was female was 0.42 (95% CI = 0.38, 0.46). There were no significant differences in age ($F = 0.75, p = 0.47$), sex ($\chi^2 = 1.16, p = 0.56$), or length ($F = 2.65, p = 0.07$) composition among fish assigned to stocks. The mean distance of detection from shore was 1,064 m (SD = 605.0). Stocks differed significantly in their detected distance from shore ($F = 13.26, p < 0.001$), with the Shaktoolik stock detected 1,077 m (SD = 602.3) from shore, the

Unalakleet stock detected 1,162 m (SD = 615.5) from shore, and Transitory stocks detected 861 m (SD = 585.4) from shore on average (Figure 2.7). Coho Salmon bound for the Unalakleet River showed significant variation in migratory distance from shore relative to target stream proximity ($F = 38.8, p < 0.001$), traveling an average of 1,377 m offshore (SD = 561.5) in *near* waters outside the river mouth, 799 m offshore (SD = 500.4) in *mid* waters outside the mouth but still within Unalakleet subdistrict, and 900 m offshore (SD = 709.9) in *far* waters of the Shaktoolik subdistrict (Figure 2.8).

The average marine swim speed of all tagged Coho Salmon within the study area was 0.21 BL/s (SD = 0.14) and varied widely among individuals (min = 0.44×10^{-3} , max = 3.80). Swim speeds varied significantly among stocks ($F = 1900, p < 0.001$), with Transitory stocks traveling the fastest at an average of 0.46 BL/s (SD = 21.2). Shaktoolik stock had an average swim speed of 0.12 BL/s (SD = 5.73), and Unalakleet stock migrated at an average of 0.20 BL/s (SD = 13.8, Figure 2.9). Coho Salmon bound for the Unalakleet River showed significant variation in mean swimming speeds relative to target stream proximity ($F = 726.9, p < 0.001$), moving 0.20 BL/s (SD = 3.14) in *near* waters, 0.29 BL/s (SD = 0.37) in *mid* waters, and 0.20 BL/s (SD = 0.22) in *far* waters (Figure 2.10).

The average amount of time tagged Coho Salmon of all fates resided in the contiguous Shaktoolik and Unalakleet subdistricts was 2.37 days (SD = 2.82, min = 0.01, max = 19.8) and did not vary significantly between the two study years ($F = 0.17, p = 0.68$) or between sexes ($F = 0.90, p = 0.34$). The mean residence time varied between subdistricts ($F = 4.64, p = 0.03$) with Coho Salmon spending an average of 2.03 days (SD = 2.18) in Shaktoolik subdistrict waters and 2.58 days (SD = 3.14) in Unalakleet subdistrict (Figure 2.11). Residence time varied significantly by stock ($F = 8.48, p < 0.001$), with Shaktoolik stock Coho Salmon residing in study area waters for 3.19 days

(SD = 2.48), Unalakleet stock for 2.24 days (SD = 2.93) on average, and Transitory stocks for 2.21 days (SD = 2.41, Figure 2.12). There was significant variation in residence time among stocks within each subdistrict ($F = 8.80, p < 0.001$). Shaktoolik stock Coho Salmon resided for an average of 3.20 days (SD = 2.09) in Shaktoolik subdistrict waters and 3.14 days (SD = 4.16) in Unalakleet subdistrict. Unalakleet stock Coho Salmon resided for 1.34 days (SD = 1.71) in Shaktoolik subdistrict waters and 2.58 days (SD = 3.22) in Unalakleet subdistrict. Transitory stocks resided for an average of 2.00 days (SD = 2.67) in Shaktoolik subdistrict waters and 2.40 days (SD = 2.15) in Unalakleet subdistrict waters (Figure 2.13). Coho salmon residence time varied by statistical week of capture ($F = 3.21, p = 0.01$), with salmon residing for the greatest amount of time in the first week of sampling (statistical week 31, mean = 3.03 days, SD = 2.02) and the least amount of time in the last week of sampling (statistical week 35, mean = 1.95 days, SD = 2.76, Figure 2.14).

Movement and detection probabilities

Detection probabilities for all marine receiver arrays within the study area were > 0.9 in 2020 and > 0.5 in 2021 (Table 2.1). Few fish moved undetected through any of the discrete marine movement areas ($p_{SKK} = 0.94, p_{UNK} = 0.96, p_{OUT} = 0.95$), and while Shaktoolik subdistrict streams had perfect detection probabilities ($p_{SFW} = 1$), the loss of Egavik River receivers in inclement weather in 2021 reduced Unalakleet subdistrict stream detection probabilities to $p_{UFW} = 0.92$. Goodness of fit tests suggest the intercept-only model to be the most parsimonious among multistate mark-recapture candidate models fit to detection history data of all tagged Coho Salmon. However, models including the group covariates of sex and year, respectively, were within four AICc units of the intercept-only model and contributed to model averages (Table 2.2).

Movement probability estimates should be interpreted as the next likely move among discrete movement areas for a salmon first encountered within the study area. In this context, a Coho

Salmon encountered in Shaktoolik subdistrict would probably move into Unalakleet subdistrict ($\varphi_{SKK,UNK} = 0.62$, CI: 0.60, 0.67), and would be less likely to move into Shaktoolik subdistrict freshwater ($\varphi_{SKK,SFW} = 0.16$, CI: 0.12, 0.20), exit the study area ($\varphi_{SKK,OUT} = 0.07$, CI: 0.05, 0.10), or to cease movement ($1 - \omega_{SKK} = 0.15$, CI: 0.11, 0.18). A Coho Salmon encountered in the Unalakleet subdistrict would have about a 50% chance of moving into Unalakleet subdistrict freshwater streams ($\varphi_{UNK,UFW} = 0.48$, CI: 0.43, 0.52), and would be less likely to move to Shaktoolik subdistrict ($\varphi_{UNK,SKK} = 0.14$, CI: 0.09, 0.18), exit the study area ($\varphi_{UNK,OUT} = 0.06$, CI: 0.04, 0.09), or to cease migration ($1 - \omega_{UNK} = 0.32$, CI: 0.28, 0.37). Coho Salmon that were first encountered within the study area that then move outside of the study area would probably continue migration outside the study area ($1 - \omega_{OUT} = 0.69$, CI: 0.57, 0.82) and would be less likely to move into Shaktoolik subdistrict ($\varphi_{OUT,SKK} = 0.06$, CI: 0.02, 0.10) or Unalakleet subdistrict waters ($\varphi_{OUT,UNK} = 0.25$, CI: 0.14, 0.35). Most, but not all, Coho Salmon encountered in freshwater would not be detected subsequently on marine receivers ($1 - \omega_{SFW} = 0.998$ CI: 0.996, 1, and $1 - \omega_{UFW} = 0.983$ CI: 0.977, 0.988). Movement probability estimates from model averages fit to detection history data of all tagged Coho Salmon can be visualized in Figure 2.15.

Shaktoolik stock Coho Salmon encountered in their natal subdistrict would be highly likely to move directly into Shaktoolik subdistrict spawning streams ($\varphi_{SKK,SFW} = 0.93$, CI: 0.86, 0.97), and would be unlikely to move into Unalakleet subdistrict ($\varphi_{SKK,UNK} = 0.04$, CI: 0.01, 0.10) or to move out of the study area ($\varphi_{SKK,OUT} = 0.03$, CI: 0.01, 0.11, Figure 2.16) before eventually moving into a Shaktoolik subdistrict spawning stream. A Unalakleet stock Coho Salmon encountered in its natal subdistrict would be very likely to move directly into Unalakleet subdistrict spawning streams ($\varphi_{UNK,UFW} = 0.88$, CI: 0.83, 0.92), and would not be very likely to move outside the

project area ($\varphi_{UNK,OUT} = 0.02$, CI: 0.01, 0.04). However, Unalakleet stock Coho Salmon would move from their natal subdistrict into Shaktoolik subdistrict with probability $\varphi_{UNK,SKK} = 0.10$ (CI: 0.07, 0.16) before eventually moving into Unalakleet subdistrict spawning streams (Figure 2.17). Because fish assigned to Transitory stocks were ultimately detected at the bounds of the study area, movement probabilities should be considered in the context of a series of steps in a movement history that ultimately takes the fish outside of the study area. Transitory stock Coho Salmon encountered in Shaktoolik subdistrict would have approximately an even chance of moving north and exiting the study area ($\varphi_{SKK,OUT} = 0.43$, CI: 0.28, 0.59) or moving south to the Unalakleet subdistrict ($\varphi_{SKK,UNK} = 0.51$, CI: 0.35, 0.67), and would explore Shaktoolik subdistrict spawning streams with a probability of $\varphi_{SKK,SFW} = 0.06$ (CI: 0, 0.13). A Transitory stock Coho Salmon encountered in Unalakleet subdistrict would move outside the study area with a probability of $\varphi_{UNK,OUT} = 0.78$ (CI: 0.65, 0.92), but may also move to Shaktoolik subdistrict ($\varphi_{UNK,SKK} = 0.22$, CI: 0.08, 0.35) before ultimately exiting the study area. Finally, Transitory stocks that were first encountered within the Shaktoolik or Unalakleet subdistricts and subsequently moved outside of the study area would not be likely to return to the study area ($\varphi_{OUT,SKK} = 0.01$, CI: 0, 0.03, $\varphi_{OUT,UNK} = 0.04$, CI: 0, 0.10), but would continue to distant spawning areas ($1 - \omega_{OUT} = 0.95$, CI: 0.87, 1, Figure 2.18).

Discussion

This study makes use of acoustic detection histories of tagged Coho Salmon in the southern Norton Sound of Alaska to investigate poorly understood salmon migratory characteristics in nearshore coastal waters. Results suggest that: 1) Coho Salmon stocks display divergent movement characteristics that vary relative to proximity to natal waters, 2) residence time within marine

waters of the study area depended on stock membership and the intraseasonal timing of migration, with fish tagged later in the season spending less time in marine waters before moving to spawning areas, and 3) Coho Salmon encountered in Shaktoolik subdistrict were likely to migrate into Unalakleet subdistrict, and were then likely to enter spawning streams, and Unalakleet stock members were more likely than other stocks to explore non-natal waters before entering freshwater. There were no significant differences in movement characteristics and study area residency times between sexes or years. Results highlight complex nearshore migration of wild Coho Salmon stocks in functionally intact nearshore ecosystems at the northern extent of their range.

Migration distance from shore varied significantly among stocks, but generally averaged > 1 km from the beach. Considering that the capture/tagging events took place ~ 200 m from shore, fish concentrating near the beach must have subsequently moved offshore. This is consistent with the results of acoustic tracking studies that document other salmon species reversing direction after encountering land rather than simply following the shoreline during spawning migrations, suggesting this is a general navigational strategy in salmon (Quinn et al. 1989; Candy and Quinn 1999). Previous investigations focusing on fine-scale migratory behavior of salmon during late stages of marine spawning migrations have largely focused on populations maneuvering through convoluted estuaries to reach relatively large drainages (Crossin et al. 2007; Davidsen et al. 2013; Wilson et al. 2014), but there is little documented behavior of salmon stocks navigating open coastline to locate natal watersheds (but see Welch et al. 2014). This is an important distinction since a salmon navigating through a large bay or fjord orients into an increasing gradient of freshwater signals, while a salmon traveling along an open coast may be required to make exploratory movements to encounter familiar target stream cues (Davidsen et al. 2013; Drenner et

al. 2015). Waterborne olfactory signals carried by river plumes move offshore from the point of discharge and disperse horizontally, and depending on water volume, wind, and ocean currents, thus a salmon may be more likely to encounter olfactory cues by traveling further from the coast (Jurisa et al. 2016; Lemos et al. 2022). Transitory stocks would of course not be familiar with local freshwater olfactory signals, and indeed may avoid them (Pascual and Quinn 1991), preferring to follow compass and ocean current cues or continue interacting with the coast (Thomson et al. 1992; Putman et al. 2014).

Consistent with previous studies, results show that fish in close proximity to their target stream travel far slower than fish further away from potential freshwater signals (Crossin et al. 2007; Davidsen et al. 2013; Wilson et al. 2014). Relatively slow swim speeds and longer residency times are likely indicative of vertical and horizontal searching behavior prior to freshwater entry (Doving et al. 1985), and may also suggest feeding, or milling behavior, which is the tendency of salmon to hold in waters just outside target streams before river entry. Milling behavior is well documented, and there is evidence that salmon may use this holding time to undergo physiological processes (Crossin et al. 2007), assess conspecific cues (Berdahl et al. 2017), or await optimal upstream migration conditions (Carey et al. 2017). Milling prior to river entry may also be linked to later reproductive success (Crossin et al. 2009). Although there were no significant differences in body sizes among stocks, Shaktoolik stock Coho Salmon traveled at especially low swimming speeds and had relatively high residency times, which could indicate difficulty homing on weak or diluted freshwater olfactory signals, a navigational challenge that has been observed in salmon migrating through dendritic or artificially constrained river waters (Keefer et al. 2008; Middleton et al. 2018).

Estimating residency of Coho Salmon within coastal fisheries boundaries revealed that Shaktoolik and Unalakleet stocks spend more coastal residency time on average in waters adjacent to their natal streams, and this is consistent with the slower swimming speeds observed in stocks within their respective subdistricts. There is a pronounced divergence in residency times within study area waters by statistical week of capture for all Coho Salmon stocks, with fish tagged earlier in the season spending longer in coastal waters on average than individuals marked later in the season. This may be due to an increase in the concentration of recognizable conspecific cues due to greater numbers of spawning adults within freshwater streams later in the season (Nordeng 1971; Berdahl et al. 2017). Although tagged salmon had occupied study area waters prior to capture, the distribution of estimates should resemble actual residency times due to the indiscriminate nature of the sampling design.

Movement probabilities estimated by the multistate model should be considered in the context of stepwise migrations and represent the likelihood of the next directional step in a fish's migration to its spawning area. Generally, Coho Salmon encountered anywhere within the study area were likely bound for Unalakleet subdistrict and its spawning streams, which could be a numerical effect of the more abundant Unalakleet stock (see Chapter 1, Table 1.2). The low probability of northern movement estimated by the model indicates that Coho Salmon migrating through study area waters make coastal landfall between the outlets of Shaktoolik Bay and Unalakleet River and may orient against prevailing northward ocean currents (i.e., positive rheotaxis, Døving and Stabell 2008). Small proportions of fish encountered in both subdistricts were bound for waters outside the study area. However, the model estimated that almost a quarter of the fish that exited the study area through the southern boundary reenter the Unalakleet subdistrict, probably a signal from several tagged Coho Salmon bound for Golsovia River that displayed searching behavior beyond the

southern array. Very few fish leaving the study area from the northern boundary of the Shaktoolik subdistrict reentered the study area, perhaps indicating that these fish were using navigational cues that do not necessitate searching for water-borne signals (e.g., geomagnetic or visual cues). Interestingly, the model detected evidence of fish reentering marine waters from both Shaktoolik and Unalakeet subdistrict spawning streams, suggestive of behavioral thermoregulation or mistaken navigational cues (Keefer et al. 2008; Frechette et al. 2021).

Models investigating stock-specific movement probabilities suggest that some stocks may be more likely to explore non-natal waters rather than homing directly to target streams. Very small proportions of Shaktoolik stock fish were estimated to move outside their natal subdistrict before transitioning to spawning streams, but Unalakeet stock Coho Salmon were relatively likely to explore Shaktoolik subdistrict waters prior to entering Unalakeet subdistrict spawning streams. It is possible that individuals originating from the Unalakeet River may have colonized Shaktoolik subdistrict freshwater streams as climates allowed northern expansion (Abdul-Aziz et al. 2011; Dunmall et al. 2016), and results of this investigation could reflect ongoing emigration of the Unalakeet stock to proximal habitats. This could also help explain the lack of perceptible genetic divergence between the two stocks, as the degree of geographic and temporal distance (i.e., genetic isolation) is not great enough to be investigated on evolutionary timescales (Quinn et al. 2000; Habicht et al. 2007).

The multistate model that estimated movement probabilities of transitory stocks gave interesting insight into the migration characteristics of fish bound for spawning regions north and south of the study area. A Transitory stock Coho Salmon encountered in the Shaktoolik subdistrict had about an even chance of moving north out of the study area or moving south to Unalakeet subdistrict. This might suggest that Transitory stocks making landfall in the Shaktoolik movement area are

almost equally composed of stocks bound for the north and south of the study area. Additionally, there was a single fish from a Transitory stock detected in Shaktoolik subdistrict spawning streams before migrating out the study area through the northern boundary. The majority of Transitory stocks encountered in the Unalakleet subdistrict were headed south out of the study area, probably representative of Coho Salmon migrating through southern Norton Sound waters *en route* to other western Alaska spawning streams such as the Yukon and Kuskokwim rivers. Once out of the study area, Transitory stocks presumably continue on to respective spawning regions, likely continuing to follow geomagnetic signals or other navigation cues. Salmon may be encountered in coastal habitats far from targeted spawning streams due to dynamic ocean currents, secular variation of geomagnetic fields, and strength of freshwater inputs from rivers (Keefer and Caudill 2014).

Models containing sex and year as group covariates contributed to model averaged parameter estimates, although model selection methods did not find significant differences in movement probabilities among these groups. Other studies have also failed to detect sex effects on spatial movement characteristics (Davidsen et al. 2013), although phenological differences between males and females have been documented in salmonids (e.g., river-entry timing, Dahl et al. 2004; Eldøy et al. 2021). There were no significant differences in movement probabilities and residency time within the study area of Coho Salmon between years, although annual variation in migratory behavior almost certainly does exist (Carey et al. 2017), but may not be detectable over short time scales. While this investigation was able to describe movement patterns during study years, relevance to future Coho Salmon migrations will depend on shifts in relative stock abundance, coastal harvest pressure, interannual environmental trends, and other variables that could influence nearshore salmon behavior. Application of these findings to future salmon returns to the Norton

Sound or to fisheries in other regions should deliberately consider the effects of these drivers to fine-scale migratory behavior and directional movement probabilities.

This study demonstrates the assessment of salmon stock migratory behavior using telemetry techniques and provides information that could influence management decisions based on expectations of stock harvest availability and movement probabilities. Especially in Norton Sound salmon fisheries where management relies on commercial catch metrics for relative abundance, a detailed understanding of Coho Salmon movement could clarify interpretation of these indices. Fine-scale movement divergences that are described here could potentially be leveraged by managers to conserve diversity without sacrificing harvest opportunities by distributing fishing pressure among salmon stocks and their components according to unique sustainable harvest levels. Salmon movement and behavior in coastal environments seems to vary greatly among populations relative to intraseasonal timing and proximity to target streams, although the complex interaction of environmental, physiological, demographic, and social variables makes pinpointing cause and effect of coastal spawning migration dynamics difficult. Salmon fishery managers should promote investigations that investigate specific migratory and movement behavior relative to fishery boundaries on stocks available in their region, especially when convenient stock markers are not available for analysis of inseason availability from commercial landings.

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Figures

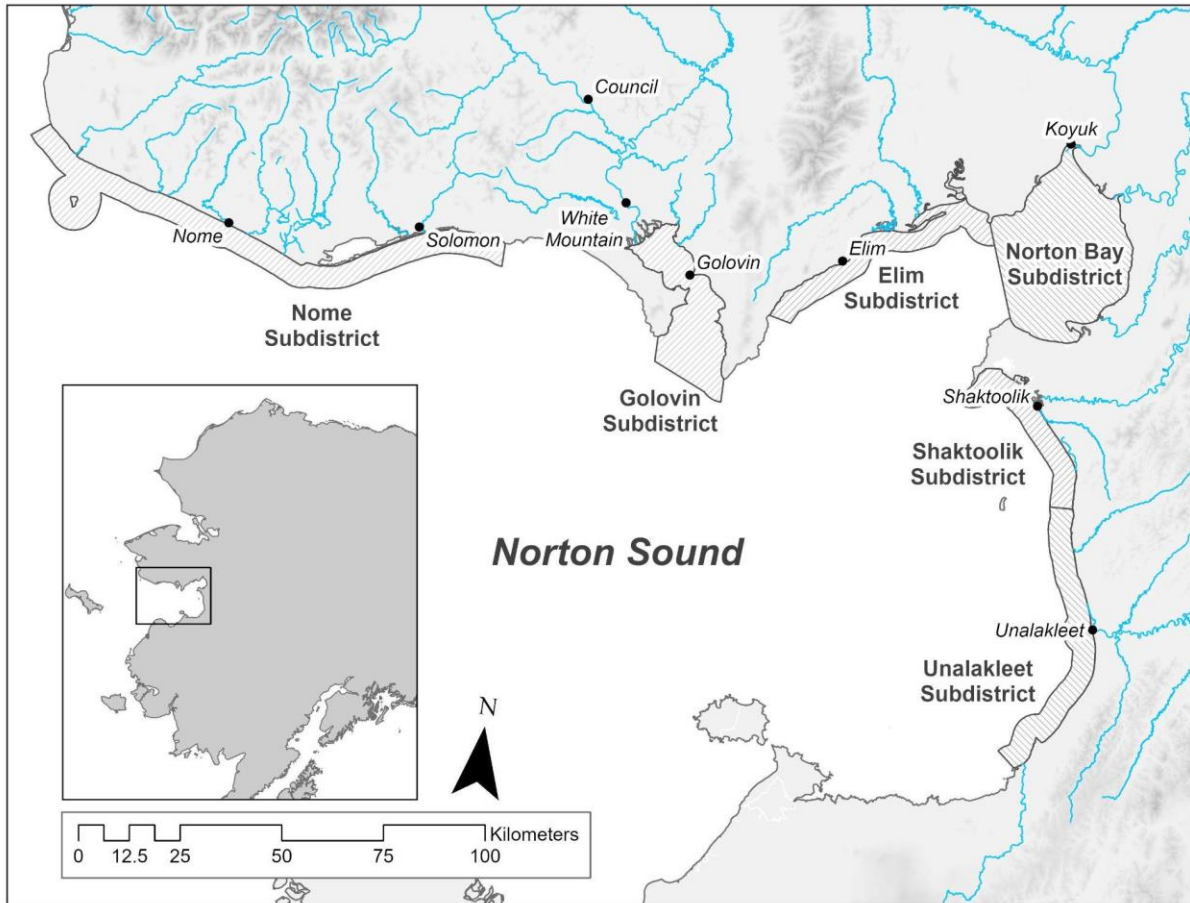


Figure 2.1 Communities and commercial fishing subdistricts of the Norton Sound district in western Alaska. Hatched areas represent waters within subdistrict boundaries.

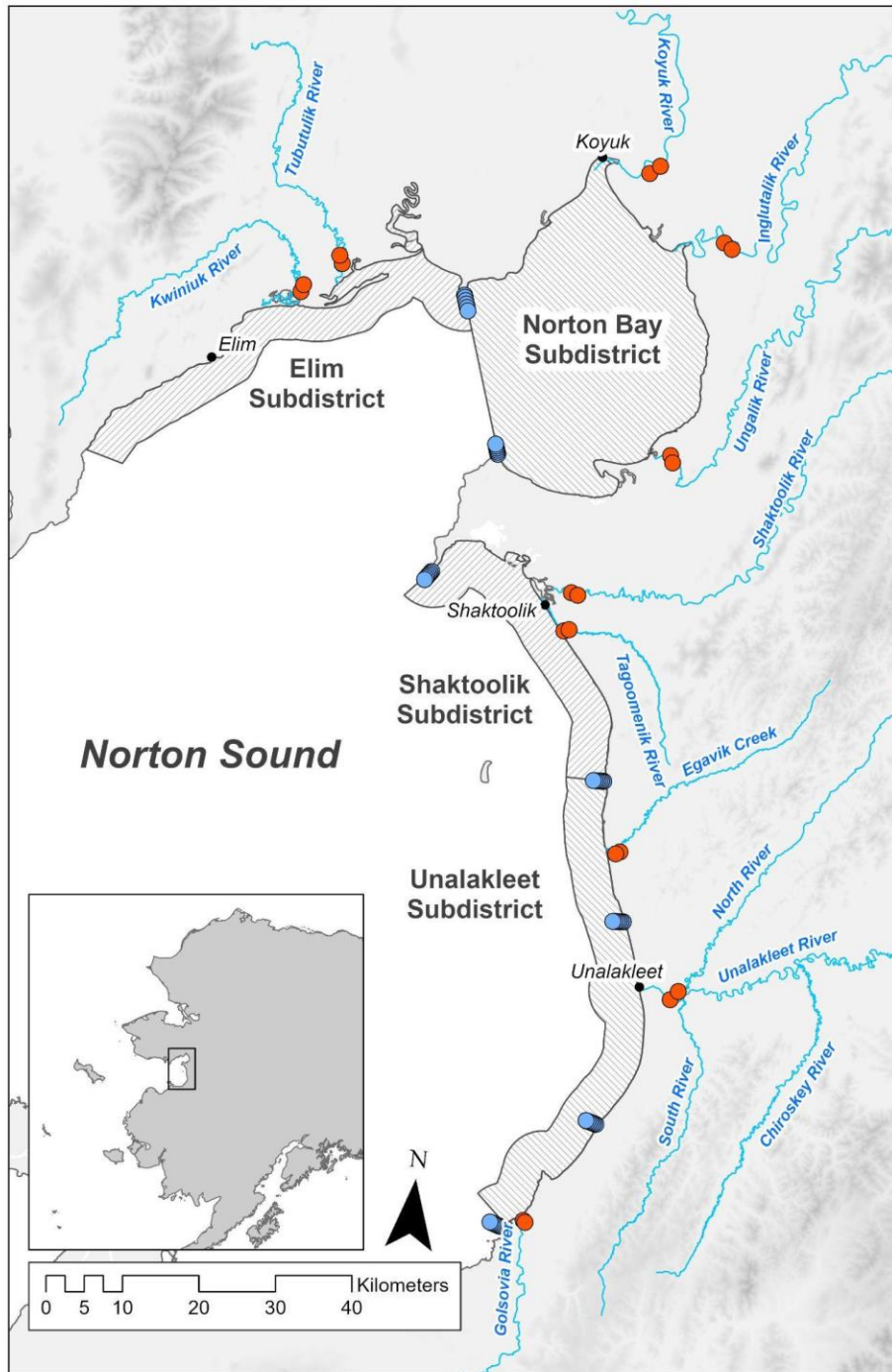


Figure 2.2 Acoustic receiver placement in Norton Sound district of Alaska. Blue points show marine receiver locations and red points are inriver receiver locations. From north to south, the marine receiver arrays are: Bald Head, Point Dexter, Cape Denbeigh, Junction Creek, Blueberry Creek, Point Creek, and Black Point.

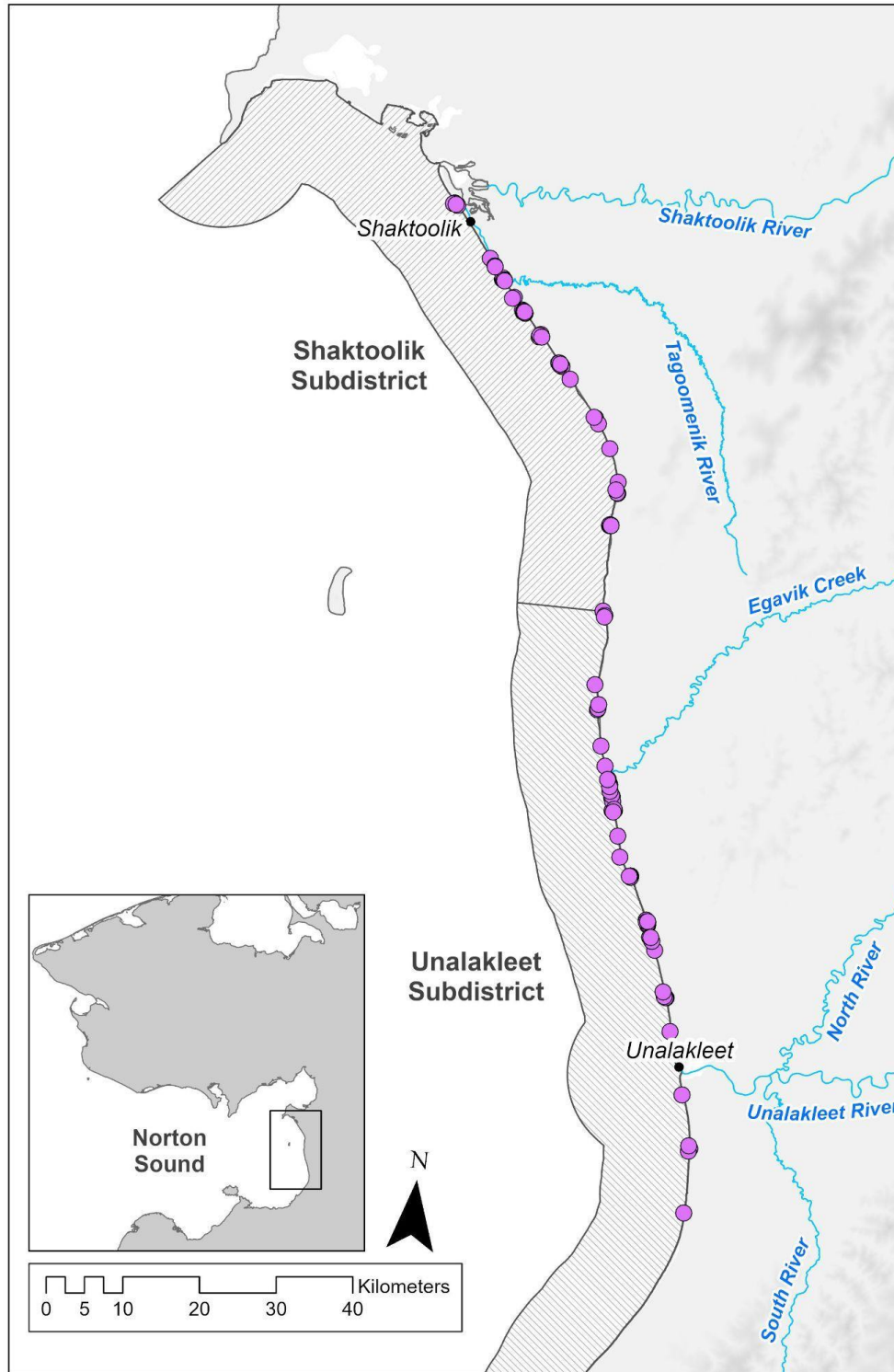


Figure 2.3 Coho Salmon capture locations within the study area in Norton Sound district of western Alaska.

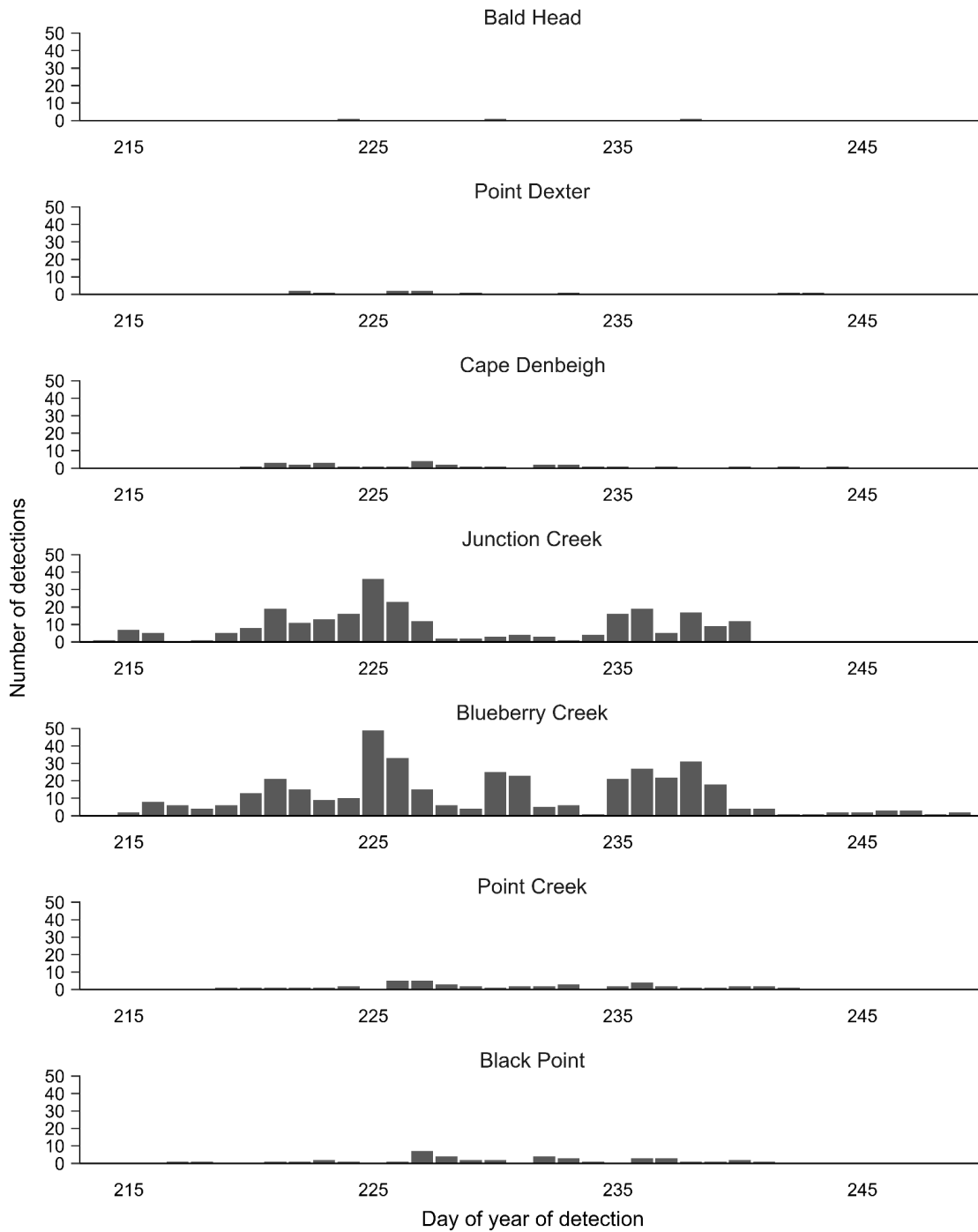


Figure 2.4 Number of detections of tagged Coho Salmon in 2020 and 2021 by day of year for each marine receiver array in Norton Sound district of Alaska. Each panel represents detections at an individual array, arranged geographically from north to south.

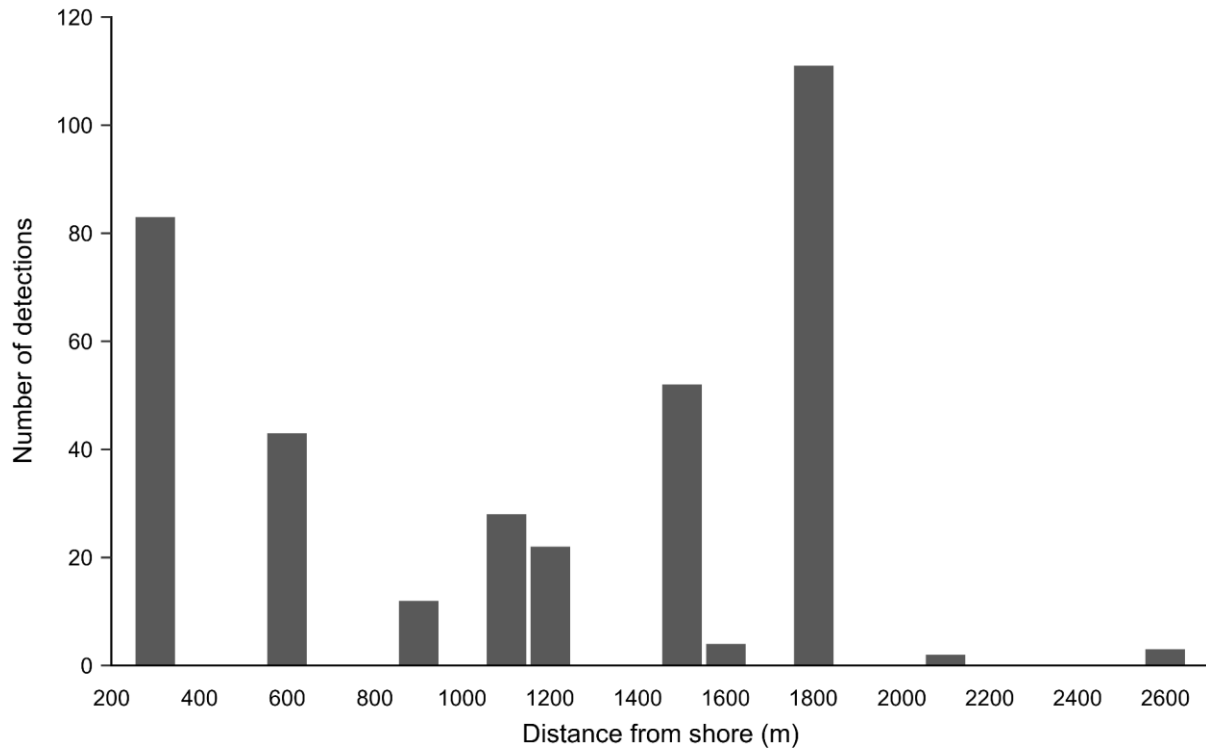


Figure 2.5 Number of detections of tagged Coho Salmon by receiver distance from shore for marine receivers in Norton Sound district of Alaska.

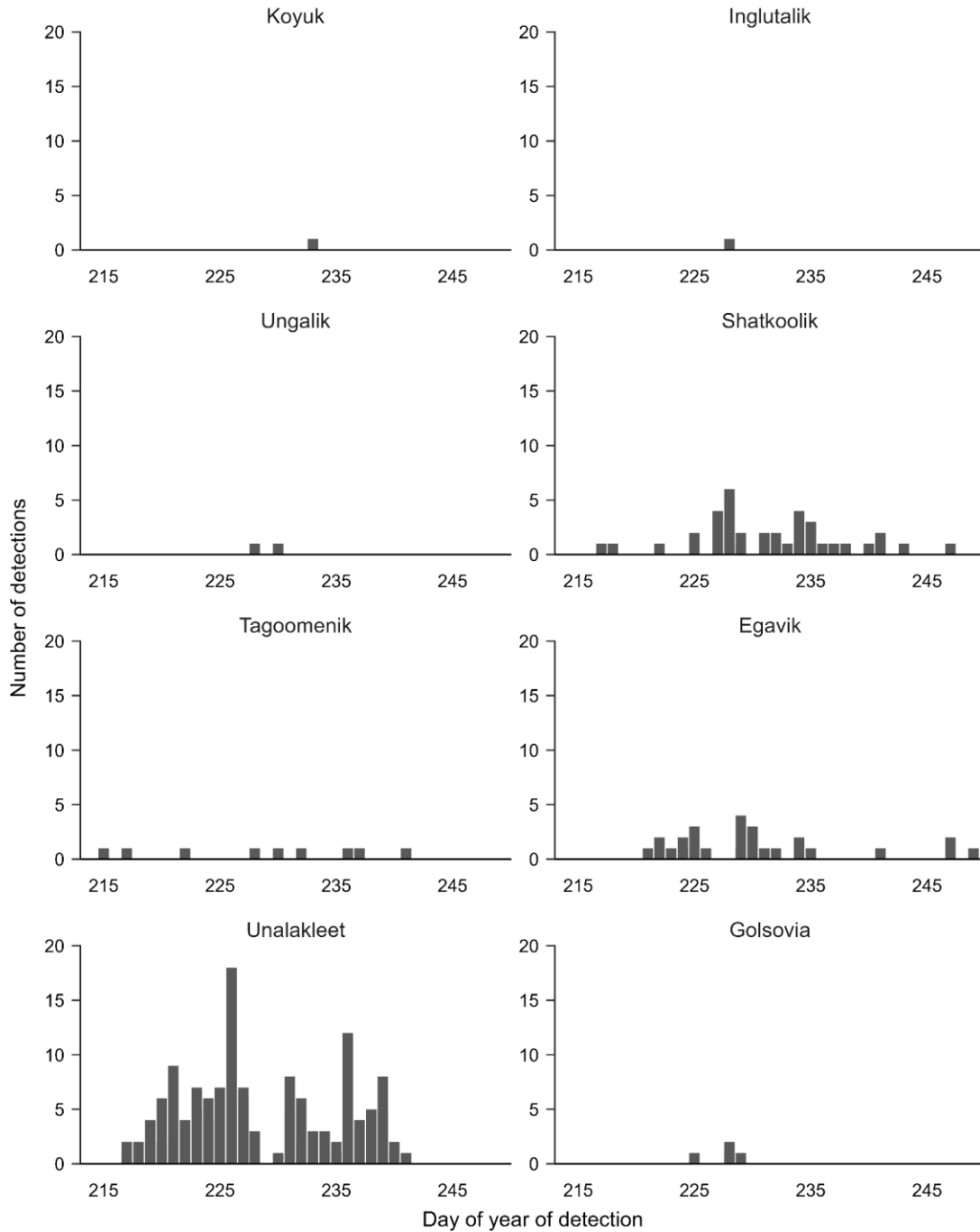


Figure 2.6 Number of detections of tagged Coho Salmon in 2020 and 2021 by day of year for inriver receivers in Norton Sound district of Alaska. Each panel represents detections in an individual river, arranged geographically from north to south.

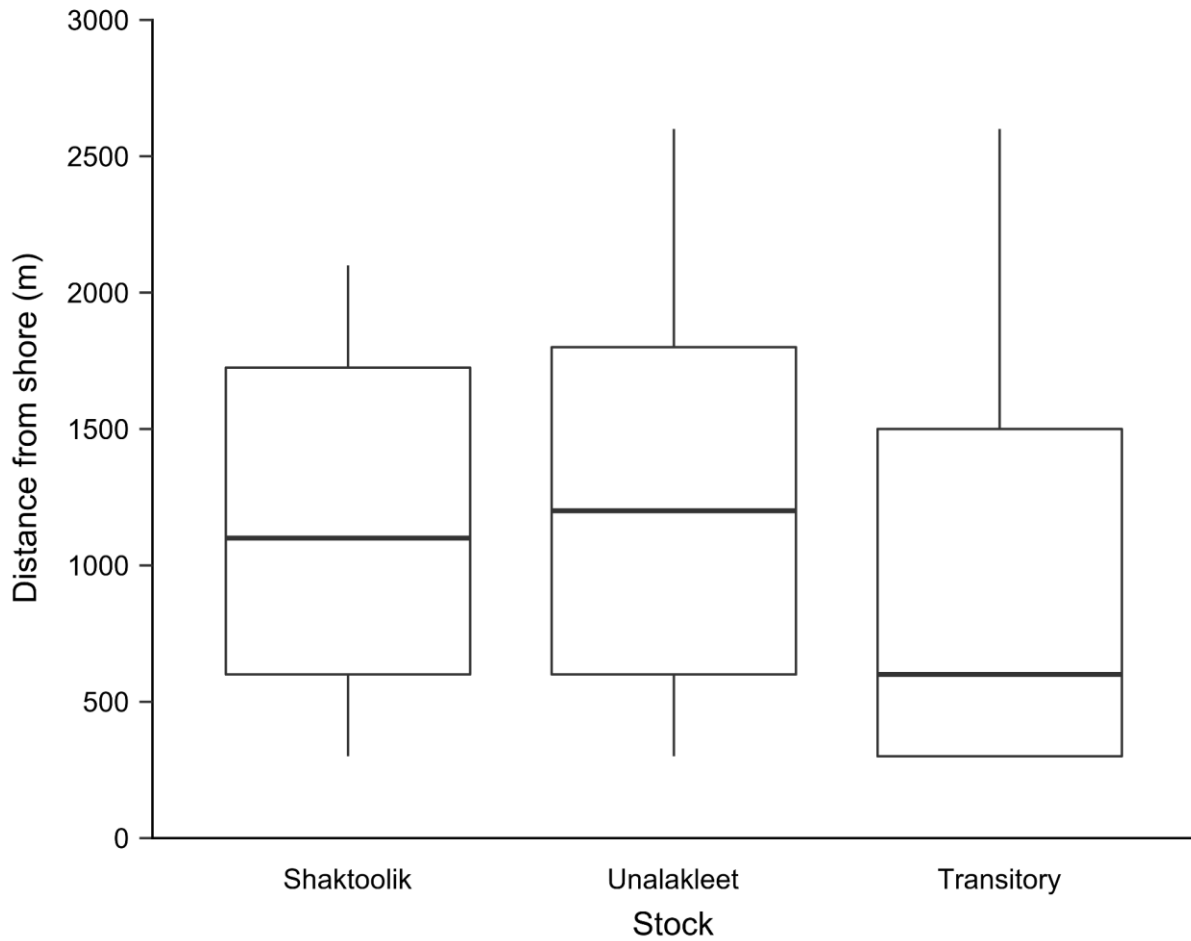


Figure 2.7 Migratory distance from shore for Coho Salmon by stock in the Norton Sound district of Alaska in 2020 and 2021. Box hinges represent the first and third quartile, the bold bar is the median value, and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

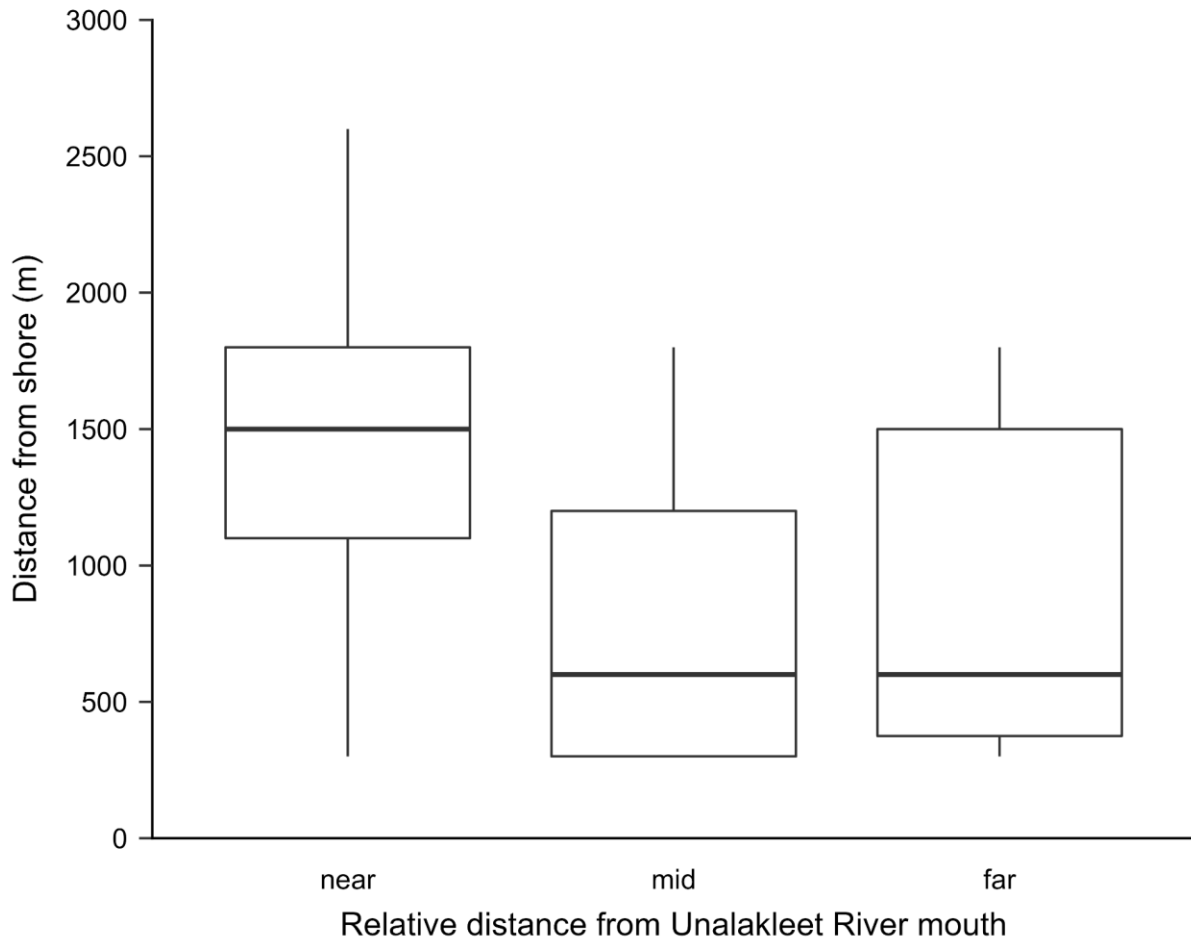


Figure 2.8 Migratory distance from shore for Coho Salmon by relative distance from the river mouth for Coho Salmon bound for the Unalakleet River in the Norton Sound district of Alaska in 2020 and 2021. Box hinges represent the first and third quartile, the bold bar is the median value, and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

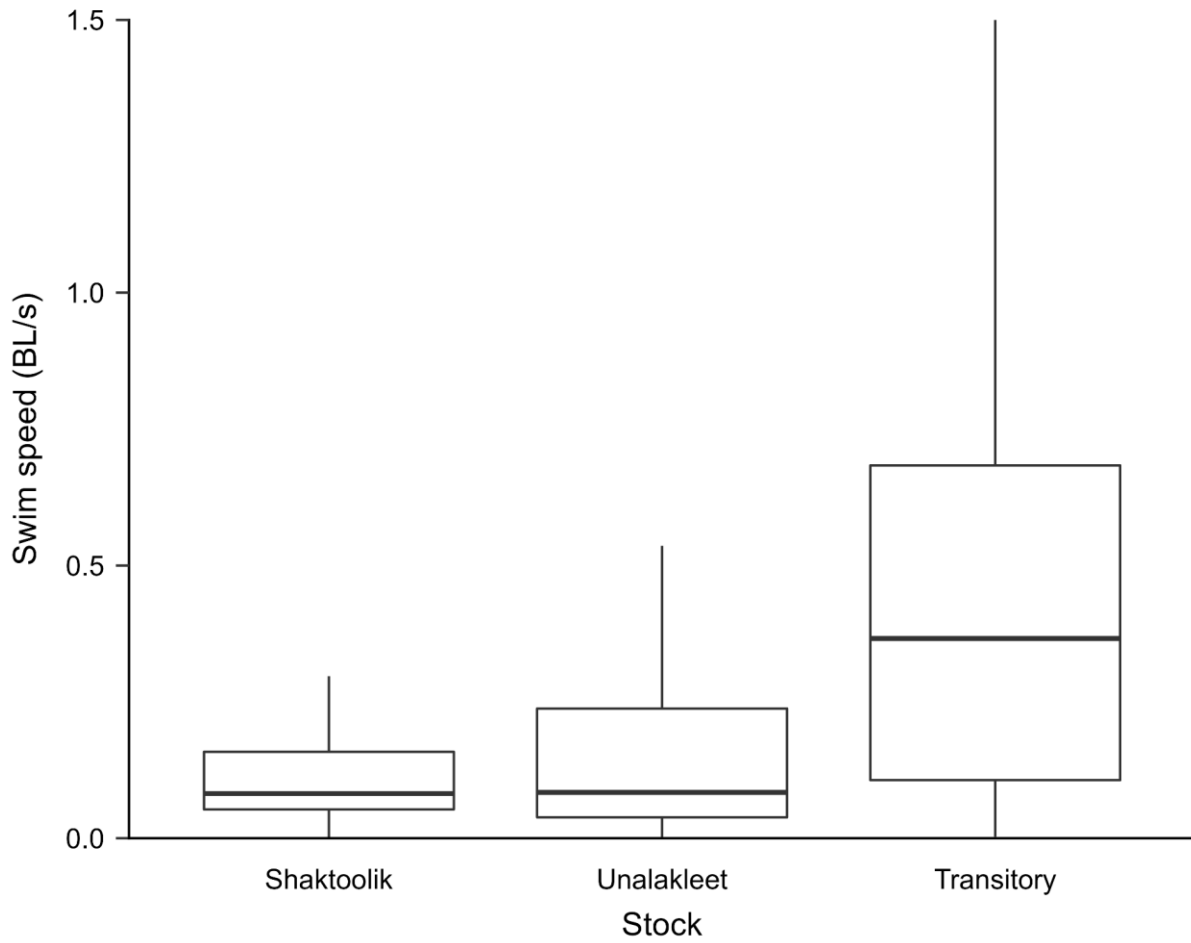


Figure 2.9 Swim speeds for Coho Salmon by stock in the Norton Sound district of Alaska in 2020 and 2021. Box hinges represent the first and third quartile, the bold bar is the median value, and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

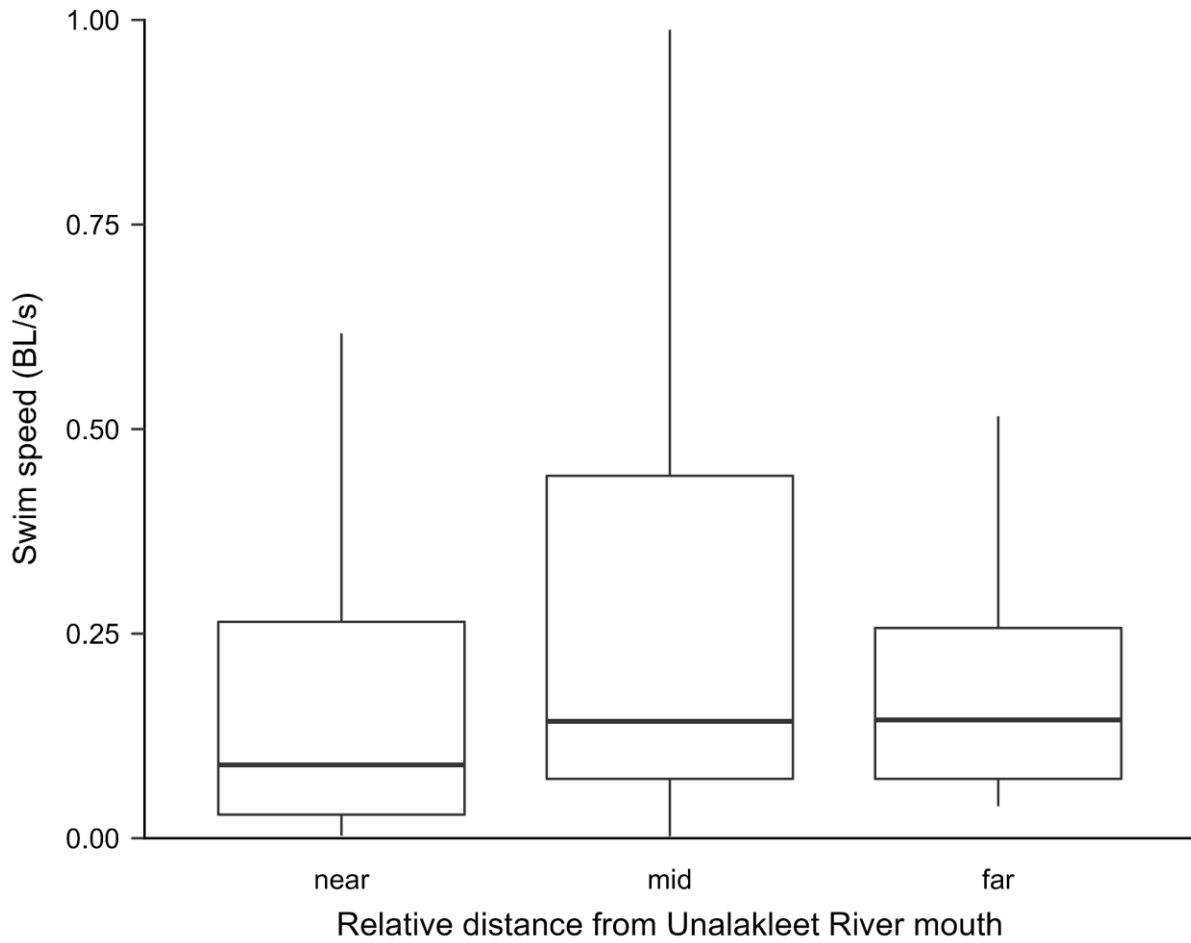


Figure 2.10 Swim speeds by relative distance from the river mouth for Coho Salmon bound for the Unalakleet River in the Norton Sound district of Alaska in 2020 and 2021. Box hinges represent the first and third quartile, the bold bar is the median value, and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

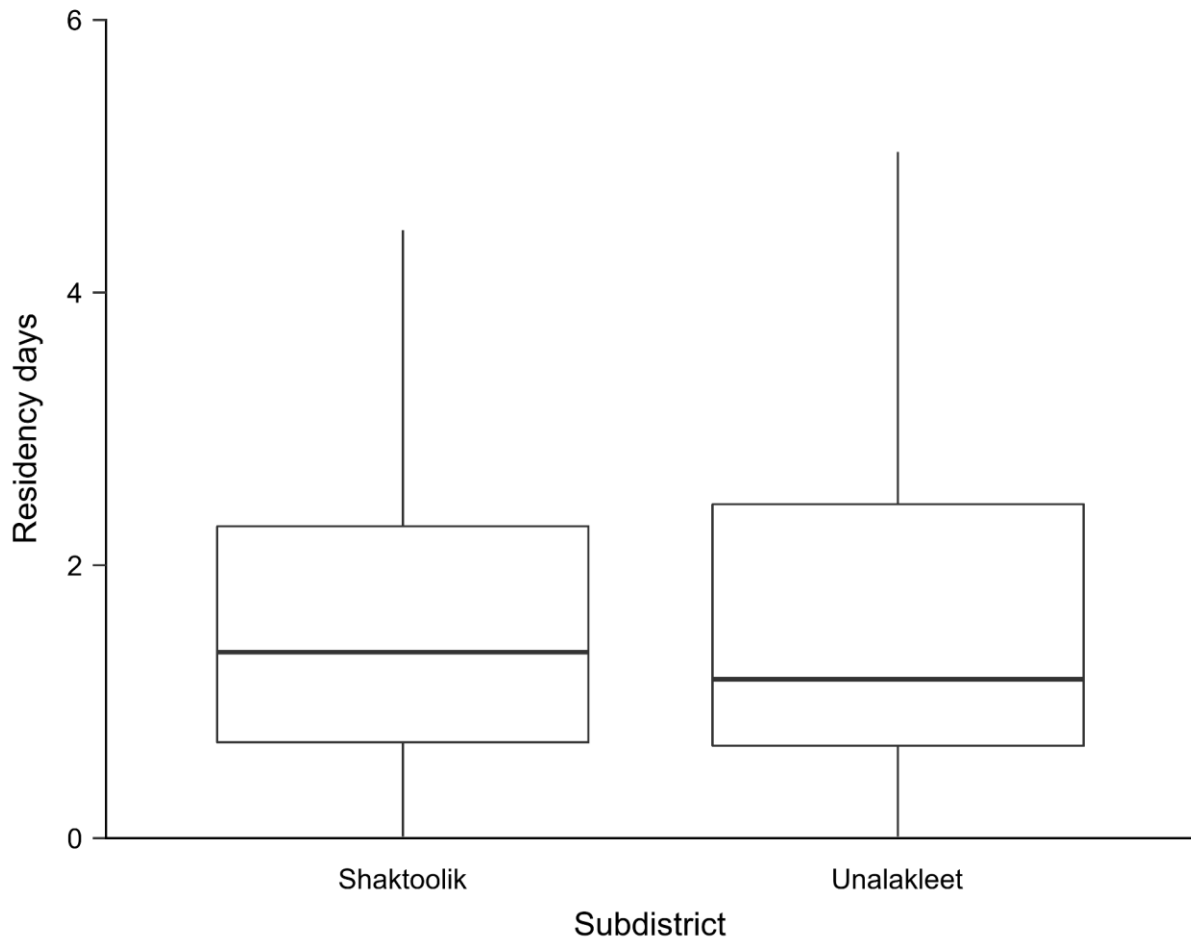


Figure 2.11 Residence time within each study area subdistrict for all tagged Coho Salmon. Box hinges represent the first and third quartile, the bold bar is the median value, and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

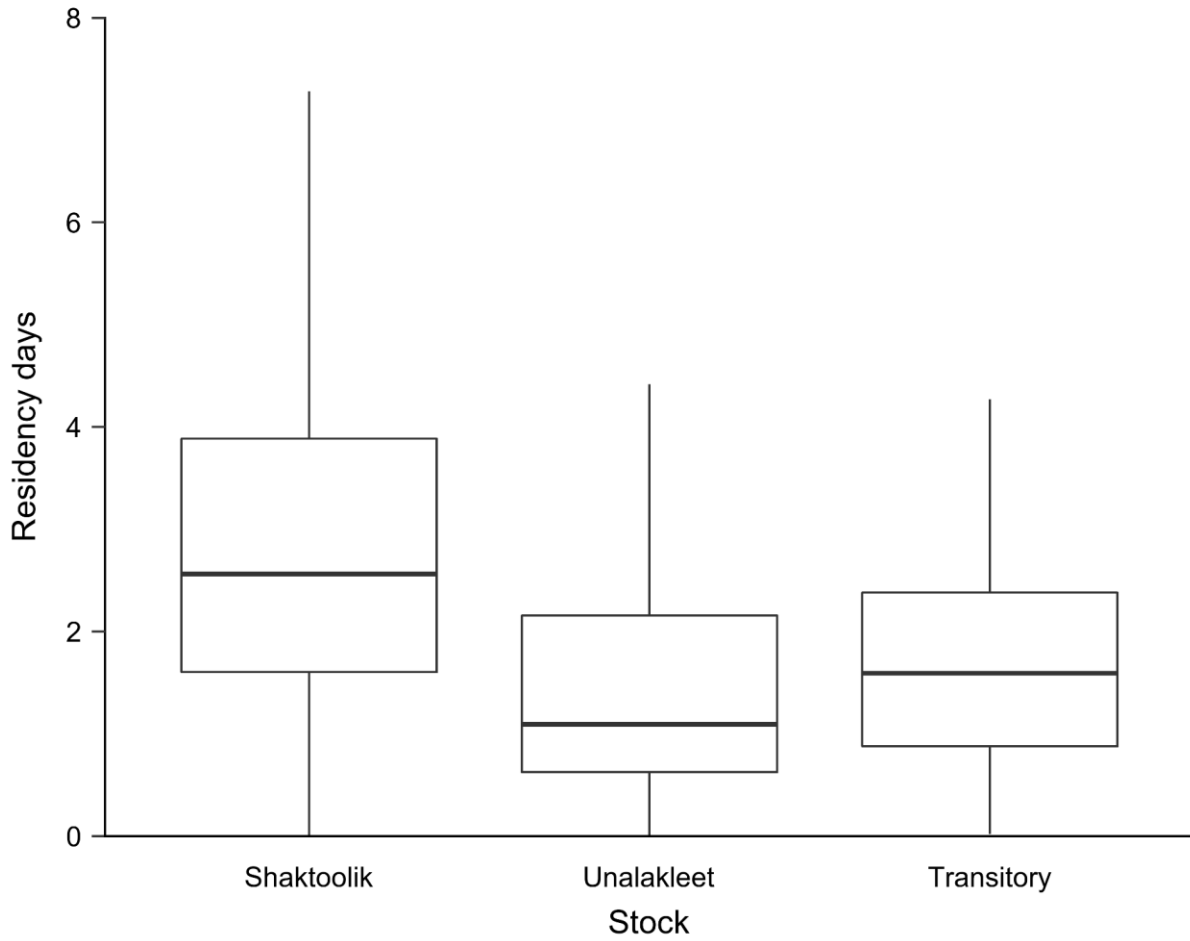


Figure 2.12 Residence time within the study area for Coho Salmon by stock. Box hinges represent the first and third quartile, the bold bar is the median value and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

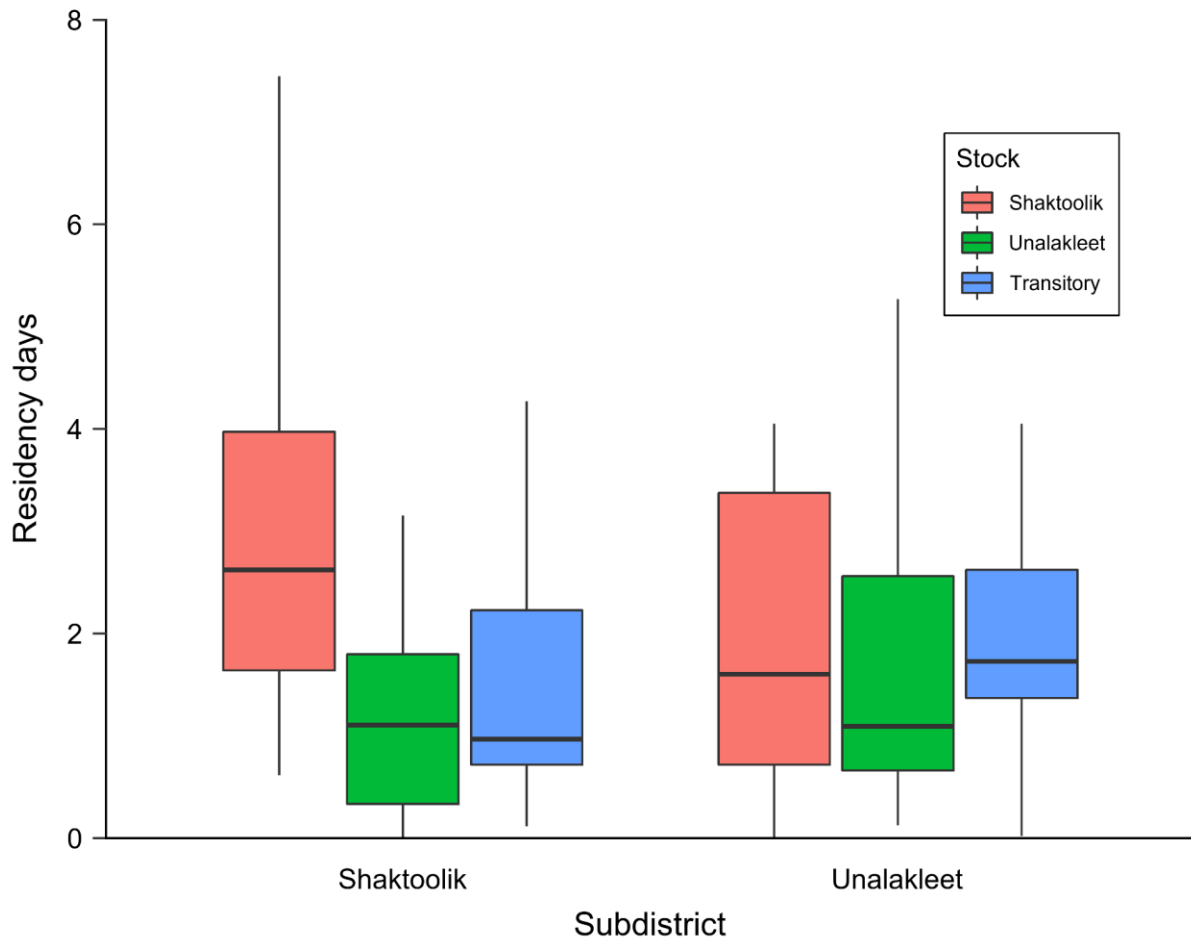


Figure 2.13 Residence time within each study area subdistrict for Coho Salmon by stock. Box hinges represent the first and third quartile, the bold bar is the median value and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

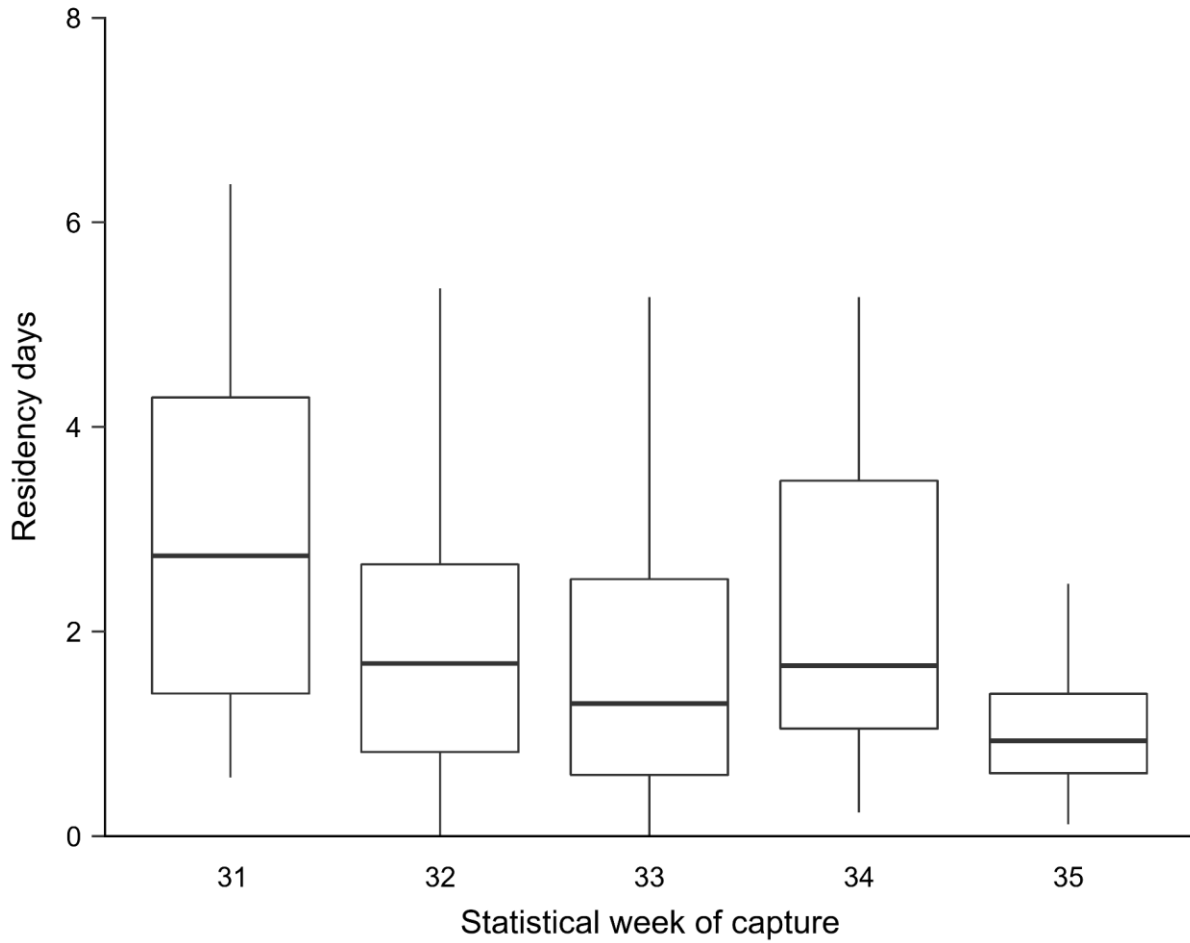


Figure 2.14 Residence time within the study area for all tagged Coho Salmon by statistical week of capture. Box hinges represent the first and third quartile, the bold bar is the median value and whiskers extend 1.5 times the interquartile range. Outliers were not plotted to clarify interquartile range.

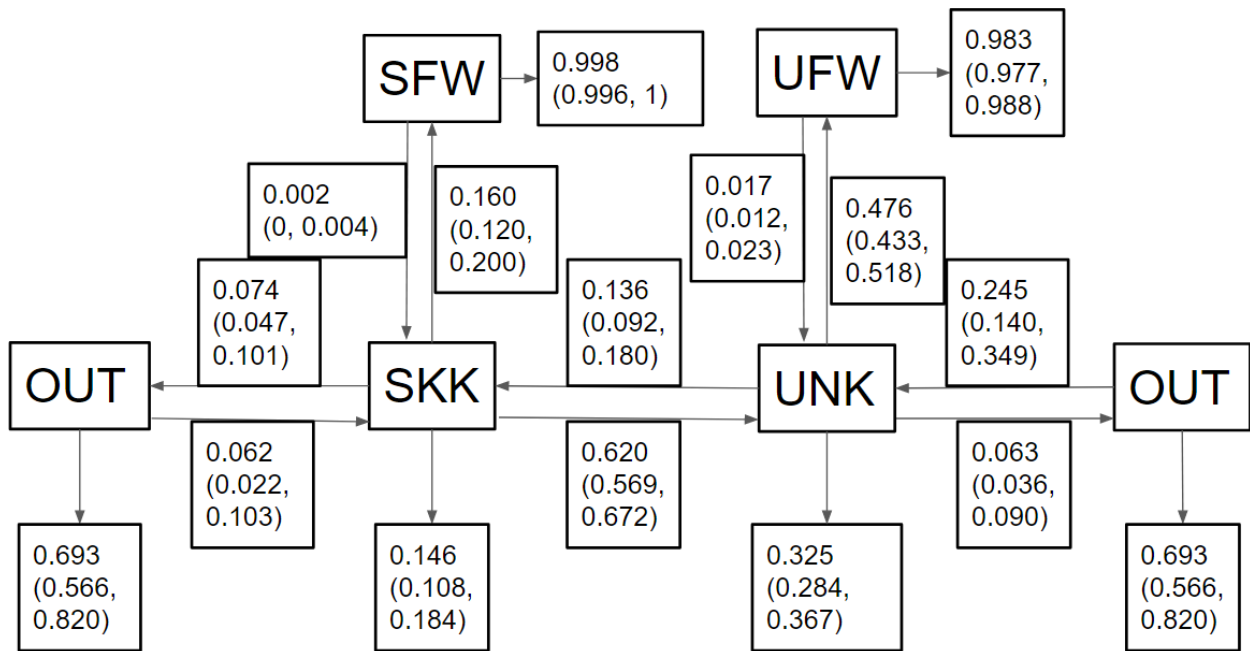


Figure 2.15 Movement probabilities for tagged Coho Salmon among discrete movement areas. The *SKK* and *UNK* movement areas represent the Shaktolik and Unalakleet subdistricts respectively, while *SFW* and *UFW* represent freshwater streams in those subdistricts. The *OUT* movement area represents waters outside the study area. Numbers within parentheses indicate 95% confidence intervals.

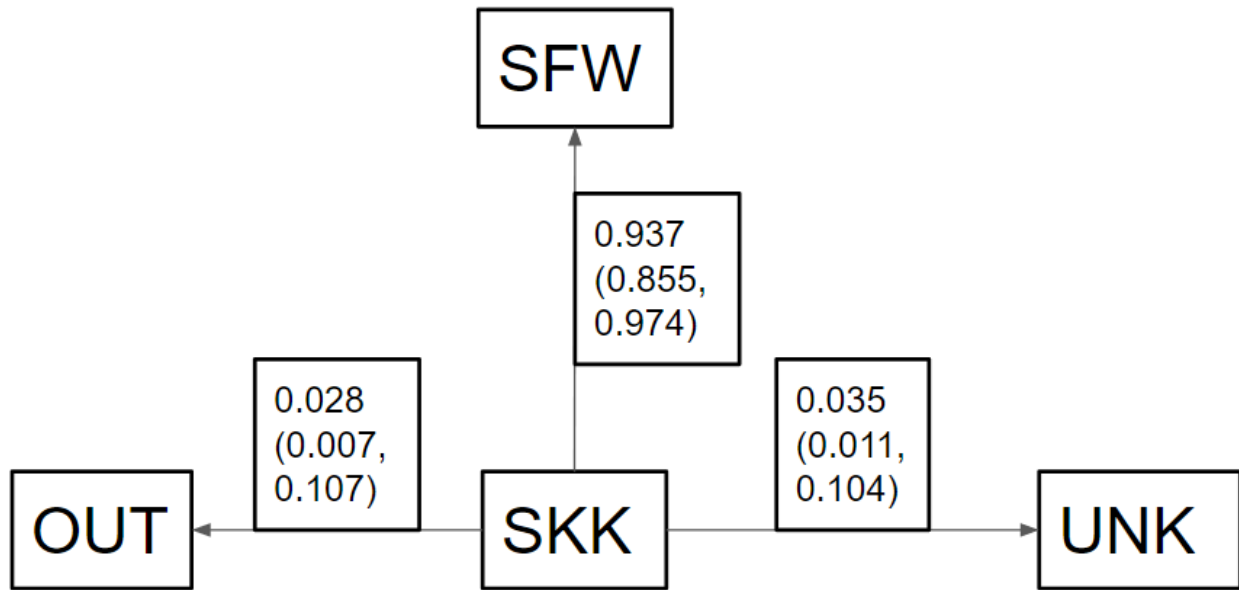


Figure 2.16 Movement probabilities for Shaktolik stock Coho Salmon among discrete movement areas. The *SKK* and *UNK* movement areas represent the Shaktolik and Unalakleet subdistricts respectively, while *SFW* and *UFW* represent freshwater streams in those subdistricts. The *OUT* movement area represents waters outside the study area. Numbers within parentheses indicate 95% confidence intervals.

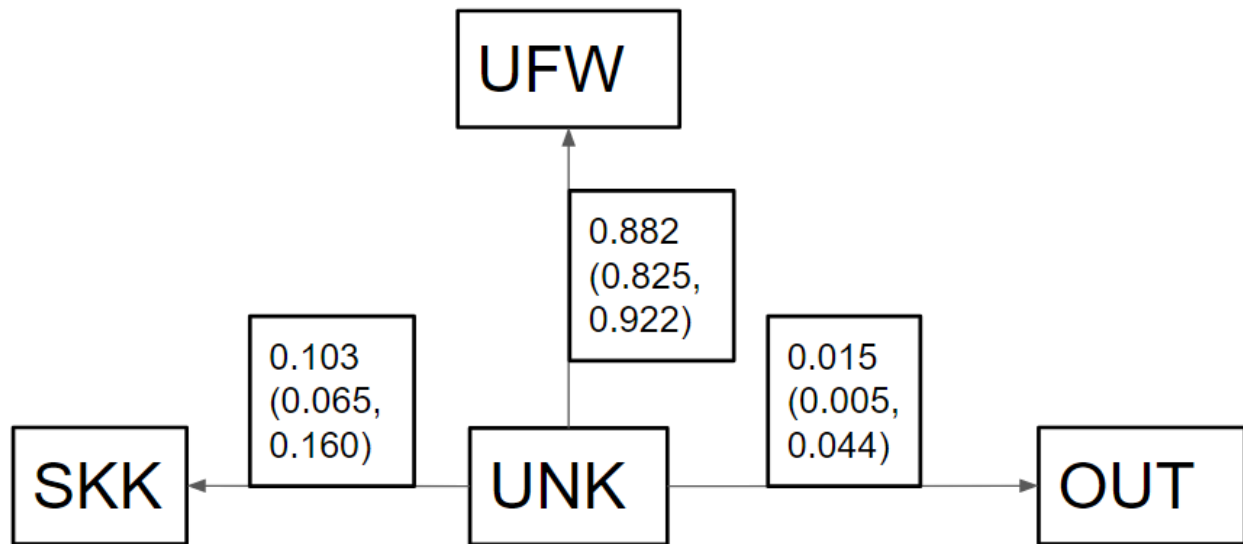


Figure 2.17 Movement probabilities for Unalakelet stock Coho Salmon among discrete movement areas. The *SKK* and *UNK* movement areas represent the Shaktoolik and Unalakelet subdistricts respectively, while *SFW* and *UFW* represent freshwater streams in those subdistricts. The *OUT* movement area represents waters outside the study area. Numbers within parentheses indicate 95% confidence intervals.

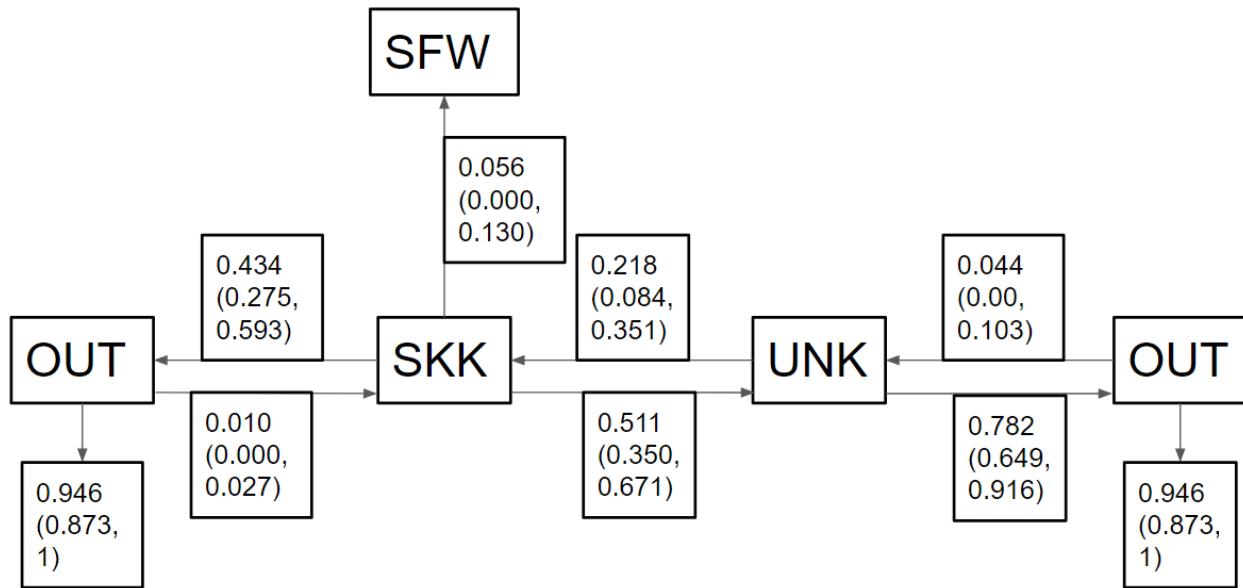


Figure 2. 18 Movement probabilities for Transitory stock Coho Salmon among discrete movement areas. The *SKK* and *UNK* movement areas represent the Shaktoolik and Unalakleet subdistricts respectively, while *SFW* and *UFW* represent freshwater streams in those subdistricts. The *OUT* movement area represents waters outside the study area. Numbers within parentheses indicate 95% confidence intervals.

Tables

Table 2.1 Detection probabilities (p) and standard errors (SE) for marine arrays of the Norton Sound acoustic receiver network.

Array	Year	p	SE
Bald Head	2020	0.143	0.118
Point Dexter	2020	1.000	–
Cape Denbeigh	2020	1.000	–
Junction Creek	2020	0.917	0.062
Blueberry Creek	2020	0.932	0.061
Point Creek	2020	0.939	0.090
Black Point	2020	0.909	0.051
Bald Head	2021	1.000	–
Point Dexter	2021	0.467	0.125
Cape Denbeigh	2021	0.500	0.577
Junction Creek	2021	0.900	0.171
Blueberry Creek	2021	0.826	0.153
Point Creek	2021	0.833	0.234
Black Point	2021	0.833	0.234
Bald Head	averaged	0.572	–
Point Dexter	averaged	0.734	0.125
Cape Denbeigh	averaged	0.750	0.577
Junction Creek	averaged	0.909	0.171
Blueberry Creek	averaged	0.879	0.153
Point Creek	averaged	0.886	0.234
Black Point	averaged	0.871	0.234

Table 2.2 Model selection results for eight candidate multistate models estimating movement probabilities of Coho Salmon in southern Norton Sound. The ΔAICc column values are relative to the most parsimonious candidate model.

Group covariates in model	Δ parameters	ΔAICc	Weight
-	0	0.00	0.54
sex	1	2.05	0.19
year	1	2.05	0.19
sex + year	2	4.10	0.07
week	4	8.21	0.00
sex + week	5	10.27	0.01
week + year	5	10.27	0.00
sex + week + year	6	12.34	0.00

Discussion

This thesis elucidates the composition and distribution of Coho Salmon *Oncorhynchus kisutch* stocks available for harvest in the Shaktoolik and Unalakleet subdistricts in southern Norton Sound. Telemetry techniques and subsequent statistical analyses revealed two key findings: 1) distinct spatiotemporal and demographic characteristics can be leveraged for assignment of Coho Salmon to distinct stocks in commercial landings, and 2) these differences manifest in divergent coastal movements of Coho Salmon that appear to be related to proximity to target streams. This approach provides a model that uses unique characteristics for distinguishing among stocks in commercial fishery landings when other identification methods, such as inherited genetic markers, are not sufficient for classification. Divergent behaviors among fish stocks such as differences in migratory routes and phenology, responses to abiotic drivers, and diverse life-histories likely reflect underlying inherited and acquired markers typically used for stock identification.

Beyond applicability to management, techniques that describe characteristics of Pacific Salmon in coastal habitats are useful for investigating a poorly understood phase of dynamic transition between physiological states and navigational sensory inputs for homing adults. The complex interactions between migratory behavior and ecological correlates makes identification of the important factors that drive nearshore movement difficult, and this study focuses more on documentation of behavior rather than causes. However, results suggest that proximity to target stream is a major influencer of Coho Salmon coastal migratory movements, which has also been observed in studies focusing on other salmon species (Crossin et al. 2009, Davidsen et al. 2013, Welch et al. 2014). This investigation revealed large differences in swimming speeds, distances from shore, and fishery residency times relative to distance from natal freshwater signals at fine scales in coastal waters. These findings are ecologically interesting and could provide another tool

for managers to focus harvest pressure on specific stocks.

In Chapter 1, results indicate that 1) southern Norton Sound subdistricts provide harvest access to a dynamic mixture of local and transitory stocks, 2) spatiotemporal and demographic variables are able to classify stocks relative to fishery boundaries, and 3) these characteristics can be used as *de facto* stock markers to partition commercial landings. Catch partitioning revealed dissimilar degrees of stock mixing in the study subdistricts, with landings in the Shaktoolik subdistrict consisting of a diverse combination of local and transitory stocks while those in the Unalakleet subdistrict were mainly from the natal Unalakleet stock. During the study years, the Unalakleet subdistrict primarily had access to a single stock, but diversity still exists within constituent components that make up this stock complex. For instance, previous studies investigating Unalakleet River Coho Salmon found temporal structure among components, with later-arriving fish more likely to spawn in the lower mainstem compared to earlier arrivals that were bound for the upper river and tributaries (Joy et al. 2005). Therefore, component groups that comprise the Unalakleet stock complex may need to be scrutinized, and harvest pressure distributed to ensure that undue fishing pressure is not disproportionately placed upon one or the other of these groups to conserve diversity within the Unalakleet stock complex.

Distributing appropriate harvest pressure among stocks and their components requires a thorough knowledge of productivity and sustainable harvest rates, which necessitates careful accounting of stock-specific harvest and escapement. This practice is currently deficient for Coho Salmon stocks in the southern Norton Sound, where traditional enumeration methods tend not to be practical due to late-season precipitation, and a lack of convenient stock markers has hindered estimation of stock proportions in commercial landings. Further studies should focus on elucidating spawner-recruit relationships of exploited stocks by effectively monitoring escapement and continuing to

develop catch partitioning methods such as those described in this study. While it may not be feasible to run full-scale telemetry projects in coastal waters in every commercial fishery season to fit the catch partitioning models presented here, there are practical approaches to inferring inseason spatiotemporal and demographic stock characteristics. Spatial habitat use is probably relatively consistent between years compared to interannual temporal trends and catch location reporting from harvesters could provide important clues for stock classification. Further, relating stock-specific escapement abundance to previous same-season landings could clarify annual temporal trends and ASL catch sampling could continue to provide real-time demographic information also useful for informing the partitioning models used in this study.

The knowledge gained from analysis in Chapter 1 suggests that increased spatial demarcation could aid in high-resolution management. For instance, the effect of latitude of capture on natal stock membership probabilities in the Shaktoolik subdistrict suggests that Shaktoolik stock Coho Salmon are increasingly more likely to be harvested in closer proximity to the mouth of Shaktoolik Bay (Chapter 1) and demarcating a management area around these waters could offer a further degree of control on spatiotemporal fishery openers. This method would also add additional harvest location information to commercial harvests which could then be used for catch partitioning using statistical techniques described in this study. Obvious coastal breaks created by large bluffs between popular fishing locations near Shaktoolik Bay, Junction Creek, Egavik Creek, and Unalakleet River mouth could be useful for spatial demarcation in the Shaktoolik and Unalakleet subdistricts.

A further practical application of the results from Chapter 1 in other salmon fisheries could be the use of behavioral characteristics as a complementary stock identification technique to be used in conjunction with traditional classification methods in a holistic approach to catch partitioning, or

as a short-term alternative method. For instance, many Alaskan salmon fisheries use genetic stock identification to account for stock proportions in fishery landings to glean information on inseason spatiotemporal stock availability, but these data are often not available in real-time as samples must be shipped to laboratories and managers must wait for results before enacting appropriate harvest strategies. In cases when management decisions come under time constraints, prior knowledge of characteristic stock movement behavior could be used to direct commercial harvest in the short term in lieu of genetic stock identification. In fact, comparing genetic data to behavioral expectations could continually refine managers' understanding of stock-specific harvest availability, increasing the practicality of this technique.

In Chapter 2, analysis of spatiotemporal detections of tagged Coho Salmon provided evidence that 1) Coho Salmon stocks display divergent movement characteristics that vary relative to proximity to natal waters, and fish encountered closer to target streams swim relatively slower and further offshore, 2) residence time within marine waters of the study area depended on stock membership and the intraseasonal timing of migration, with fish tagged later in the season spending less time in marine waters before moving to spawning areas, and 3) Coho Salmon encountered in southern Norton Sound were most likely to migrate into Unalakleet subdistrict, and were then likely to enter spawning streams. This analysis provides novel insights into fine-scale Coho Salmon behavior and coastal movement probabilities in the final stages of marine spawning migrations.

While other studies have demonstrated adult salmon movements in coastal environments in the final phases of marine spawning migration, this may be the first study to document specific behavior of Coho Salmon homing in on relatively small drainages along an open coastline. Investigations taking place near the mouth of the Fraser River in British Columbia document Sockeye Salmon *O. nerka* funneling through convoluted coastline into increasing concentrations

of freshwater signals (Crossin et al. 2007; 2009) and studies of Atlantic Salmon *Salmo salar* in Norway (Davidsen et al. 2013) and Sweden (Whitlock et al. 2018) describe nearshore homing behavior of adults that takes place in elongated bays and fjords where fish could be oriented head-first into spawning stream olfactory cues. The investigation presented here observes Coho Salmon that must make an abrupt transition from open-water navigational behavior to olfactory homing on potentially elusive and highly diluted freshwater-borne chemicals. The differences in habitat characteristics between this study and previous studies could manifest in specific behaviors that might not be seen in populations returning to large streams draining into contained bays and estuaries with convoluted coastlines. For instance, the movement offshore displayed by Coho Salmon in southern Norton Sound as they approach spawning streams has not been observed in previous studies in response to proximity to target streams and could be related to coastal geographies. Future research should expressly incorporate coastline features to investigate the influence on freshwater olfactory signal dynamics on salmon behavior across a range of nearshore geographies.

In accordance with findings that fish swim slower as they near the mouth of target spawning streams, evidence shows Coho Salmon stocks spend relatively prolonged periods of time in natal coastal waters prior to freshwater entry. This behavior has been previously observed in Chinook Salmon *O. tshawytscha* targeting the Cook Inlet in southcentral Alaska, where individuals spent up to 19 days paralleling the beach in nearshore waters before moving into streams (Welch et al. 2014). Beyond the fact that river mouths are compression points for fish targeting those tributaries, this finding suggests that natal stocks may be more vulnerable to capture as they display milling behavior. However, as the season progressed, residency times in fishery waters declined, and individuals that were encountered relatively late in the season spent less time available to harvest

in coastal waters. This represents an additional level of divergent migratory behavior among stocks and their components that could potentially be incorporated into high-resolution harvest strategies.

Multistate models provided evidence that most stock members make movements that progress directly toward target streams, but there are a proportion that tend to explore non-natal waters prior to freshwater entry, especially members of the Unalakleet stock. Exploration of novel habitat is a characteristic trait in Pacific salmon and is essential for range expansion (Anderson and Quinn 2007; Frechette et al. 2021; Pitman et al. 2020), but it is interesting to observe stocks that display differing degrees of this behavior relative to neighboring groups. This could be a numeric effect as a larger proportion of tagged Coho Salmon were determined to be Unalakleet stock, and the likelihood of monitoring stock members that display exploratory behavior could be higher. Several studies have focused on straying rates and their causes among populations in various habitats (Keefer and Caudill 2014), but most of these analyses were conducted within a riverine setting and might not accurately reflect stray rates among coastal streams (but see Labelle 1992). Further, causes and consequences of straying have mainly been investigated in a setting where hatchery populations are returning to spawning streams alongside wild Pacific salmon, further obscuring drivers of natural exploratory behavior (Jonsson and Jonsson 2017). Analysis in Chapter 1 provided evidence that male Coho Salmon are more available for harvest outside of natal subdistricts than females, suggesting there could be a sex effect on straying among southern Norton Sound stocks, as has been observed in other studies (Hard and Heard 1999; Anderson and Quinn 2007). Future research should focus on exploratory behavior in coastal ecologies among unenhanced wild populations to disentangle the variables influencing homing at these scales.

Taken together, the findings of this investigation provide evidence that spatiotemporal and demographic characteristics could be used to identify stock proportions in commercial landings,

and divergent movement behaviors based on proximity to target spawning streams could allow managers to develop harvest strategies that distribute exploitation in a manner that preserves diversity among stocks and their constituent populations in salmon fisheries. This study also highlights several areas of future research concerning adult salmon in the coastal phase of spawning migration, such as the relationship between movement behaviors and underlying inherited and acquired characteristics, the influence of natural geographic features on salmon orientation, and the dynamics of homing and straying among unenhanced populations in intact habitats. Elucidating basic life-history traits and behavior of exploited salmon often reveals characteristics that could allow development of management strategies that are specifically tailored to respective stocks, such as leveraging the observed tendency for salmon in southern Norton Sound to have higher residency times in natal subdistricts and therefore be more available to harvest. While this study emphasizes some key nearshore behaviors of Coho Salmon available for harvest in the southern Norton Sound district of Alaska, managers of other salmon fisheries should advocate for research that specifically focuses on exploitable groups in their waters, as these behaviors may manifest differently depending on unique demographic, abiotic, and geographic variables. As understanding of coastal behavior of salmon across a range of populations and ecologies expands, so too should the ability to maximize sustainable harvests while preserving diversity.

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Appendix A: Environmental observations

Fishing crews observed and recorded environmental conditions during capture events to investigate potential relationships between abiotic variables and stock-specific migration characteristics and harvest availability. Measurements were taken immediately after setting the net in a new location and recorded on sampling forms, along with the time, date, and coordinates of the fishing site. All environmental observations were measured while the boat was clipped to the offshore end of the net, which varied in distance from the beach according to net placement. Along with abiotic measurements, local weather observations were recorded in a comments section of the data form (e.g., precipitation, wave action, etc.).

Temperature

Air temperature was measured with a Kestrel 2000 Weather Meter and recorded in degrees Celsius. Water temperature was measured using a Garmin GT54UHD-Transom Mount Transducer connected to the ECHOMAP Ultra 106sv 25.4 cm display plotter and recorded in degrees Celsius. A liquid-in-glass thermometer was included in sample kits as a backup. In cases when the backup method was needed, air temperature was recorded before submerging the thermometer to take water temperature so that moisture on the glass would not interfere with air temperature measurements.

Wind and cloud cover

Wind speed was measured as a 3-second rolling average with the Kestrel 2000 Weather Meter and recorded in meters per second. Direction of wind origination was inferred by positioning the anemometer to achieve maximum speed. Wind direction was determined by referencing the compass function of a handheld GPS unit and recorded as one of eight factor variables: N, NE, E, SE, S, SW, W, NW. Wind speed and direction were converted to u and v component vectors by

assigning a direction based on a two-dimensional polar coordinate plane (e.g., W = 0°, SW = 45°, S = 90°, etc.), where u winds run parallel to the x axis and v winds run parallel to the y axis (i.e., a positive u wind is from the west and positive v wind is from the south). Wind components were then calculated as:

$$u = ws \times \cos(\theta),$$

$$v = ws \times \sin(\theta),$$

where θ is the polar coordinate wind direction in radians and ws is the wind speed. This conversion was necessary to reduce the degrees of freedom taken up by the wind direction factor variable. Cloud cover was simply measured as a subjective observation by the recorder based on a visual scan.

Water turbidity

Water turbidity at sample sites was measured using a Secchi disc. A measuring line with 25-cm demarcations was attached to the center of the disc and lowered into the water until it just disappeared from sight, at which point the depth of the disc was recorded. The disc was then raised until it was again visible and the average of the two depths was recorded as the Secchi disc transparency (SD). Measurements were taken on the lee and/or shaded side of the boat and the observer removed polarized sunglasses prior to taking measurements.

Tides

Hourly water height observations were downloaded from the National Oceanic and Atmospheric Administration Tides and Currents website (which continuously records relative water depth at the Unalakleet River mouth (Station ID: 9468333). Values were scaled by date by subtracting the daily mean height from hourly observations and dividing by the daily standard deviation.

Appendix B: IACUC Approval



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Institutional Animal Care and Use Committee

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

March 25, 2020

To: Andrew Seitz

Principal Investigator

From: University of Alaska Fairbanks IACUC

Re: [1556023-2] Investigating nearshore marine migration and stocks of origin of commercial salmon species in eastern Norton Sound fisheries

The IACUC reviewed and approved the New Project referenced above by Designated Member Review.

Received: March 23, 2020

Approval Date: March 25, 2020

Initial Approval Date: March 25, 2020

Expiration Date: March 25, 2021

This action is included on the April 9, 2020 IACUC Agenda.

PI responsibilities:

- *Acquire and maintain all necessary permits and permissions prior to beginning work on this protocol. Failure to obtain or maintain valid permits is considered a violation of an IACUC protocol and could result in revocation of IACUC approval.*
- *Ensure the protocol is up-to-date and submit modifications to the IACUC when necessary (see form 006 "Significant changes requiring IACUC review" in the IRBNet Forms and Templates)*
- *Inform research personnel that only activities described in the approved IACUC protocol can be performed. Ensure personnel have been appropriately trained to perform their duties.*
- *Be aware of status of other packages in IRBNet; this approval only applies to this package and the documents it contains; it does not imply approval for other revisions or renewals you may have submitted to the IACUC previously.*
- *Ensure animal research personnel are aware of the reporting procedures on the following page.*

(The following information is also available in a printable format in the IRBNet Forms and Templates) **HOW DO I REPORT CONCERNS ABOUT ANIMALS IN A UAF RESEARCH**

FACILITY?

- All "live" animal concerns related to care and use should be reported to the IACUC
- Email: uaf-iacuc@alaska.edu Phone: 474-7800
- Report form: www.uaf.edu/iacuc/report-concerns/
- IACUC Committee Members: www.uaf.edu/iacuc/iacuc-info/
- Additional information: www.uaf.edu/ori/responsible-conduct/research-misconduct/ and www.uaf.edu/ori/responsible-conduct/conflict-of-interest/

WHAT SHOULD I DO IF AN ACCIDENT OR INCIDENT OCCURS IN AN UAF ANIMAL FACILITY?

- **For all immediate human emergencies call 911** or UAF Dispatch at 474-7721 for less immediate emergencies.
- If you have **suffered an animal bite or other injury**, complete an "Accident/Incident Investigation form" (personal injury) form available at <https://uaf.edu/safety/occupational-safety/accident-reporting.php>.
- If an accident such as a **chemical spill** occurs, contact the Environmental Health, Safety, and Risk Management (EHSandRM) Supervisor at 474-5617 or the Hazmat Coordinator at 474-7889.

WHO DO I CONTACT IF I FIND A DEAD, INJURED, OR DISTRESSED ANIMAL IN A UAF RESEARCH FACILITY?

- During regular business hours, immediately contact facility staff and/or Veterinary Services Staff at 474-7020.
- After hours or on weekends, immediately contact facility staff and/or Veterinary Services Staff using the contact numbers posted on the "Emergency Contact Information" in the facility or call UAF Dispatch at 474-7721.
- Contact the IACUC at 474-7800 or uaf-iacuc@alaska.edu if an "Emergency Contact Information" sign is NOT posted in the facility.
 - Contact the IACUC if you are not satisfied with the response from Vet Services.

HOW DO I REPORT ANY CONCERNS REGARDING WORK HAZARDS OR ANY GENERAL UNSAFE CONDITIONS?

- Complete an "Unsafe Condition Reporting Program" form, available at the EHSandRM website: www.uaf.edu/safety/unsafe-condition/

WHERE CAN I OBTAIN GENERAL OCCUPATIONAL SAFETY INFORMATION? •

<https://www.uaf.edu/iacuc/uaf-policies-procedures/occupational-health-safety/>

America's Arctic University

Appendix C: Acoustic receiver deployment, retrieval, and range testing

Receiver deployment

Hardware and settings

Passive acoustic hydrophone receivers were used to monitor tagged Coho Salmon movement through nearshore marine waters and into spawning streams. The receiver used for this investigation was the Lotek Wireless Hydrophone System (WHS) model 3250D acoustic autonomous receiver, which has dimensions of 60-mm diameter, 430-mm length, and weighs 1.2 kg in air. The receiver is powered by two lithium primary D-cell batteries with a lifespan of ~84 days. This system has the ability to transmit a beacon with a unique receiver ID code at a preset frequency that can be detected by other receivers to ensure seasonal functionality. Before deployment, each receiver was connected to a field computer, the internal clock was set to Alaska Standard Time (AKTC, -9:00 Coordinated Universal Time correction), the beacon was set to transmit every 60 seconds, and the schedule was set for continuous recording of acoustic detections. Each receiver was labeled with return information for the Alaska Department of Fish and Game in Nome, AK in the event that the device became unmoored and was recovered.

Mooring

A mooring system was configured to anchor marine receivers in place, with a subsurface buoy to maintain vertical orientation and a surface buoy for retrieval (Figure C.1). The mooring had a total weight of approximately 50 kg and the subsurface and surface floats provided approximately 40 kg of buoyancy. Inriver receivers were attached with hose clamps to 2-m rebar posts driven into river substrate using a post pounder. Lengths of rubber hose were fit around the rebar at the receiver attachment site to prevent chafing resulting from dynamic river levels and discharge. All inriver

rebar posts were deployed with bright flagging and small surface buoys to aid in visibility for boaters.

Marine receiver placement

Marine receiver arrays were formed by placing six receivers in a perpendicular line from shore to detect tagged Coho Salmon migrating along the coast toward spawning destinations. Receiver arrays were placed at the regulatory boundaries of the Norton Bay, Shaktoolik, and Unalakleet commercial subdistricts, along with two additional receiver arrays within Unalakleet subdistrict placed at the mouths of Blueberry and Point creeks to monitor tagged fish nearshore marine movement (Tables C.1 and C.2). Overlapping detection ranges among receivers in an array to account for dynamic acoustic interference is preferred for detecting migratory fishes with stationary receivers (Hobday and Pincock 2011). During a feasibility study for a previous telemetry project in the region, range testing was conducted by Alaska Department Fish and Game (ADF&G) and Lotek Wireless Inc. in the nearshore marine waters of the Nome subdistrict in northern Norton Sound (Bell et al. 2018). The results suggested that detection range optimality formed a donut shape around the acoustic receiver within the marine environment with increasing proportions of tag transmissions detected until ~400 m. These data were used to inform receiver placement for marine arrays used in this study. In 2020, it was determined that the first (nearshore) receiver in marine arrays would be placed 300 m from shore and each subsequent receiver would be placed 300 m apart (Table C.1) to ensure overlapping acoustic detection ranges for a total linear detection range of 2.1 km from shore, assuming an optimum detection range of 300 m. For the initial field season, receivers were deployed from the 9.75 m ADF&G Research Vessel Peter Joel and from Norton Sound Economic Development Corporation (NSEDCC) tender vessels during 14–22 July 2020. At all array sites, the sea floor sloped gradually downward so that the outermost

receiver from shore was in the deepest water. The minimum receiver depth was 3.05 m (receiver 5.1), and the maximum depth was 10.36 m (receiver 7.6), with a mean depth of 6.40 m (SD = 2.39).

Preliminary data from tagged Coho Salmon detection histories in 2020 suggested that some fish moved offshore after being tagged and were out of the detection range of the marine receiver arrays. It was also determined that the original spacing of the receivers in the array produced multiple overlapping detection ranges, evidenced by range testing in 2020 and by the number of tagged Coho Salmon detected by more than two individual receivers in an array. Therefore, the spacing between receivers was adjusted in 2021 to extend the linear detection range from shore by moving the outer four receivers to 500 m from the preceding receiver (Table C.2), increasing the total optimal detection range to 3.1 km assuming an optimum detection range of 500 m. Receivers were deployed from NSEDC tender vessels on 25 June 2021. The minimum receiver depth was 3.05 m (receiver 5.1), and the maximum depth was 11.28 m (receiver 5.6), with a mean depth of 6.40 m (SD = 2.60). In both seasons, the first receiver in each array (most nearshore receiver) was deployed along with a HOBO temperature logger attached to the steel cable, just above the attachment point of the acoustic receiver (Figure C.1).

Inriver receiver placement

Inriver receivers were placed in all major spawning streams in Norton Bay, Shaktoolik, and Unalakleet subdistricts. Receivers were also placed in Elim subdistrict streams to test whether tagged Coho Salmon might be spawning in distant fishery subdistricts (Tables C.3 and C.4). Two receivers were placed in each river at a relative distance to remove line of sight (usually on either side of a river bend) to ensure that a tagged Coho Salmon would not be simultaneously detected by both receivers so directionality of tagged fish entering and exiting freshwater could be

confirmed. Range testing by Bell et al. (2018) in Nome, AK area streams demonstrated that a single receiver placed near the riverbank was able to detect acoustic transmissions from up to 300 m away in streams up to 150 m wide, and because the surveyed streams were similar in size and substrate to the rivers monitored by this project, it was assumed that this design was applicable. The exception was the Koyuk River which has a width of 300 m at the upstream receiver site, and range testing was performed on 24 July 2020 to ensure detection performance. Receiver sites were accessed by Robinson R44 model helicopters or by river skiffs during 13–17 July 2020. Any stream without an enumeration project that collected water temperature data had a HOBO temperature logger deployed along with the downstream receiver mooring. Receivers were deployed on the cutbank side of the river when possible to ensure that fluctuating river depth would not leave the receiver exposed to air. Inriver detection data in 2020 suggested that some inriver receivers were not placed far enough apart to avoid overlapping ranges and were placed in new sites in 2021 (Table C.4).

Range testing

Marine range testing

Range testing measures the ability of a receiver or an array to detect an acoustic transmission in a field setting and is an important step in any passive telemetry study (Kessel et al. 2014). Marine range testing was performed by two methods: a one-time drift test to measure the effect of continuously increasing distance between the receiver and the transmitter, and a seasonal analysis of receiver beacon transmissions successfully detected by receivers in the same array. In both tests, the proportions of actual to expected transmission detections were modeled as a function of the distance between the acoustic receiver and the point of transmission origination. For the marine receiver arrays, detection proportions were also modeled over time throughout the season to

analyze the influence of dynamic nearshore environmental conditions on acoustic receiver performance.

The drift test was performed on 9 September 2020 in marine waters near the Blueberry Creek array within 1.5 km of shore (63.92504°, -160.86158°), with 1-m swells from the south and a 3 m/s wind from the southeast. A buoyed anchor was deployed with an acoustic transmitting tag attached to the line 3 m above the anchor and ~ 4.5 m beneath the surface (depth at site was 7.62 m). The tag used for the drift test was the same model used to monitor Coho Salmon movement (Lotek MM-M-11-28, transmitting frequency of 76 kHz) and was set to transmit an acoustic signal every 5 seconds. An acoustic hydrophone receiver identical to those used in the study (Lotek WHS 3250) was deployed over the leeward gunwale of the boat attached to a weighted line that allowed the receiver to maintain vertical orientation 3 m beneath the sea surface. The boat motors were turned off immediately after the anchored buoy was deployed and the boat was allowed to drift with the current. Increasing distance from the buoy was recorded once a minute referencing a handheld GPS unit until the boat had reached a distance of 1 km from the buoy, at which point the test was ended. The drift test lasted approximately 41 minutes and resulted in 337 acoustic transmissions decoded by the receiver. Observations from the first 50 m of the drift test were omitted, as the successful proportion of detections exceeded 100%, probably due to a close proximity ‘echo effect’ observed in other environmental acoustic detection range studies (Kessel et al. 2015). A generalized additive model was fit to the data using formula: $p_m \sim s(d)$ using a penalized cubic regression spline, where p_m is the proportion of transmissions detected in minute m and $s(d)$ is a smooth function of distance. The model predicts an increasing proportion of acoustic transmissions detected up to 525 m (observed proportion: 0.958, predicted: 0.936, SE = 0.095), and then a rapid decrease until zero transmissions were detected at 750 m, although transmissions were

intermittently received until the test ended at a distance of 1 km from the transmitter (Figure C.2). These results were consistent with the findings of Bell et al. (2018), who recorded increasing detection proportions until an optimum range in nearshore environments of northern Norton Sound. The less-than optimal proportion of successful detections at closer ranges is most likely due to close proximity detection interference (CPDI) which has been reported in several investigations of acoustic telemetry system performance (Kessel et al. 2015; Scherrer et al. 2018) and demonstrates the ‘donut effect’ of detection performance around the receiver (Figure C.3).

The receiver beacon function transmits a signal at 76 kHz once every minute, and this feature was used to measure hourly successful detection proportions by receivers at various distances from beacon origination throughout the season. In 2020, recovered receivers from marine arrays ($n = 37$) detected 904,083 beacons over 53 days, and 1,063,590 beacons over 72 days in 2021 ($n = 32$). For seasonal receiver performance analysis, any beacon decoded with a frequency greater than 60 detections per hour due to close proximity echo effects were set to a detection proportion of 1. To assess the proportion of beacons originating from various distances detected by any receiver in a marine array, hourly detections were grouped by distance and the mean frequency of decoded beacons was calculated as: $p_d = b_d/B_d$ where d is the distance between the beacon origination point and the receiver, p is the proportion of beacons detected, B is the number of beacons emitted, and b is the detected number of beacons. The hourly proportion of successful detections by distance over the season by year was analyzed by fitting generalized additive models (GAMs) to data using the formula: $p_d \sim s(h)$ with a penalized cubic regression spline, where $s(h)$ is a smooth function of the sequential hour from the beginning of the project. To aid in visualization of detection performance throughout the season, a linear model was fitted for the pooled data from each array in each season using the formula: $p_{a,d} \sim h$, where $p_{a,d}$ is the proportion of beacons detected by

array a at distance d (Figures C.4 and C.5). These same steps were followed to fit GAMs to predict detection performance as a function of distance for each array, with the formula: $p_a \sim s(d)$, where p_a is the proportion of beacons detected by array a (Figure C.4). As expected, marine array acoustic detection performance was highly variable throughout the season in both years, as transmission attenuation is influenced by dynamic interactions between environmental and anthropogenic factors (Gjelland and Hedger 2013). Generally, detection performance decreases with distance between the transmitter and receiver, although some evidence of CPDI exists as evidenced by periods of decreased detection performances from closer beacons. Detection proportions were lower in 2021 for all arrays relative to 2020, probably due to sustained inclement weather during that season. Overlapping detection ranges coupled with high tag transmitting frequencies resulted in very few tagged Coho Salmon passing undetected through marine arrays in both seasons.

Inriver range testing

Inriver range testing was performed in 2020 on the Unalakleet and Koyuk rivers using a method similar to the marine drift test. For the inriver test, however, the receiver was stationary, moored in a cut bank near the shore, and an acoustic tag suspended halfway down the water column by a weighted line was attached to a boat that drifted past the receiver in a downstream direction. The Unalakleet River range test took place near the site of the downstream receiver (63.55776°, -161.05689°) on 22 July under calm conditions and began ~ 400 m upstream of the receiver. The boat drifted for 11 minutes until a point ~ 400 m downstream of the receiver, which detected 259 acoustic transmissions during this time. The Koyuk River range test was performed near the downstream receiver site (64.91696°, -161.01233°) on 24 July under calm conditions and began ~400 m upstream of the receiver. The boat drifted for 8 minutes until ~ 400 m downstream of the

receiver, and there were 116 acoustic transmissions detected. Similar to analysis of the marine test, a GAM was fitted to the data from each test using the formula: $p_m \sim s(d)$ with a penalized cubic regression spline where p_m is the proportion of successfully detected transmissions in minute m .

Inriver receiver tests showed variability in the proportion of transmissions successfully detected over a range of distances. The model predictions for the Unalakleet River range test data have an increasing proportion of detections until 181 m from the receiver (observed proportion: 0.25, predicted: 0.65, SE = 0.08), and then decreasing performance until the test ended at 400 m from the receiver (Figure C.5). Like the marine range test, transmissions were intermittently received until the end of the test. The model predictions for the Koyuk River range test data have highest receiver performance at 90 m (observed proportion detected: 0.50, predicted: 0.54, SE = 0.05) and then a steady decrease until detection proportions stabilize at ~300 m (observed: 0.08, predicted: 0.11, SE = 0.05, Figure C.6). Both tests confirm that it would be highly unlikely for a tagged Coho Salmon to swim past an inriver receiver without being detected.

Receiver retrieval

Marine receivers

In 2020, receivers were retrieved by personnel aboard the Peter Joel and NSEDC tender vessels using hydraulic pot-pullers. Receivers in some locations were found to be heavily biofouled by blue mussels *Mytilus trossulus*, which may have affected receiver performance later in the season. Unfortunately, it was not noted whether receivers retrieved by tender vessels were subject to biofouling, but it is believed that only the most nearshore receivers from arrays 4 and 5 were vulnerable to biofouling since all other locations had deeper water and stronger currents which would discourage attachment by blue mussels. Receiver 1.1 was lost when the buoy line was cut

by the tender vessel propeller and receiver 1.3 was found to have corrupted data (Table C.1). However, overlapping detection should have still been maintained since there were no gaps in coverage > 600 m (Figure C.7). Receivers 3.4 and 3.5 were not able to be located although they were detected throughout the season, indicating the mooring stayed in place while the buoy lines snapped, probably due to strong currents past Cape Denbeigh in the fall, and data were found to be corrupted on receiver 3.2. The missing receiver data most likely had minimal impact on array detection performance, as the receivers recovered from the Cape Denbeigh array with usable data (3.1, 3.3, and 3.6) were not > 600 m apart (Figure C.7). Inclement weather is most likely to blame for the missing receivers in 2021, which saw high precipitation and winds. Overall, nine receivers were lost and three had corrupted data (Table C.2). These resulted in the Bald Head array having a reduced overall linear coverage due to the loss of receiver 1.6 (Figure C.8). Similarly, linear coverage for the Point Dexter array was reduced due to the loss of receiver 2.6 (Figure C.8). Unfortunately, the Cape Denbeigh array had only two usable sources of acoustic detection data in 2021: receivers 3.2 and 3.5 (Table C.2).

Inriver receivers

All receivers were successfully retrieved from rivers in 2020 and were accessed by helicopter or river skiff (Table C.3). Inclement weather in 2021 is most likely to blame for the number of lost receivers in 2021 (Table C.4). In several instances the river levels became so high during the season that cut banks sloughed into the river, burying or otherwise dislodging mooring rebar. Unfortunately, several rivers had only one remaining receiver (Tubutulik, Unalakleet, Golsovia rivers, Table C.4), and for analysis, directionality upriver was assumed unless a tagged Coho Salmon was subsequently detected by another marine or river receiver. Two streams had no surviving receivers (Ungalik and Egavik rivers, Table C.4), and this was accounted for in analysis

by removing those rivers from the dataset. This may have negatively biased the estimated stock proportion represented in the sample for Norton Bay and Unalakleet subdistrict stocks but does not affect the logistic regression of significant variables for determining target stock characteristics or the multinomial response models for predicting stock proportions in commercial catch.

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Figures

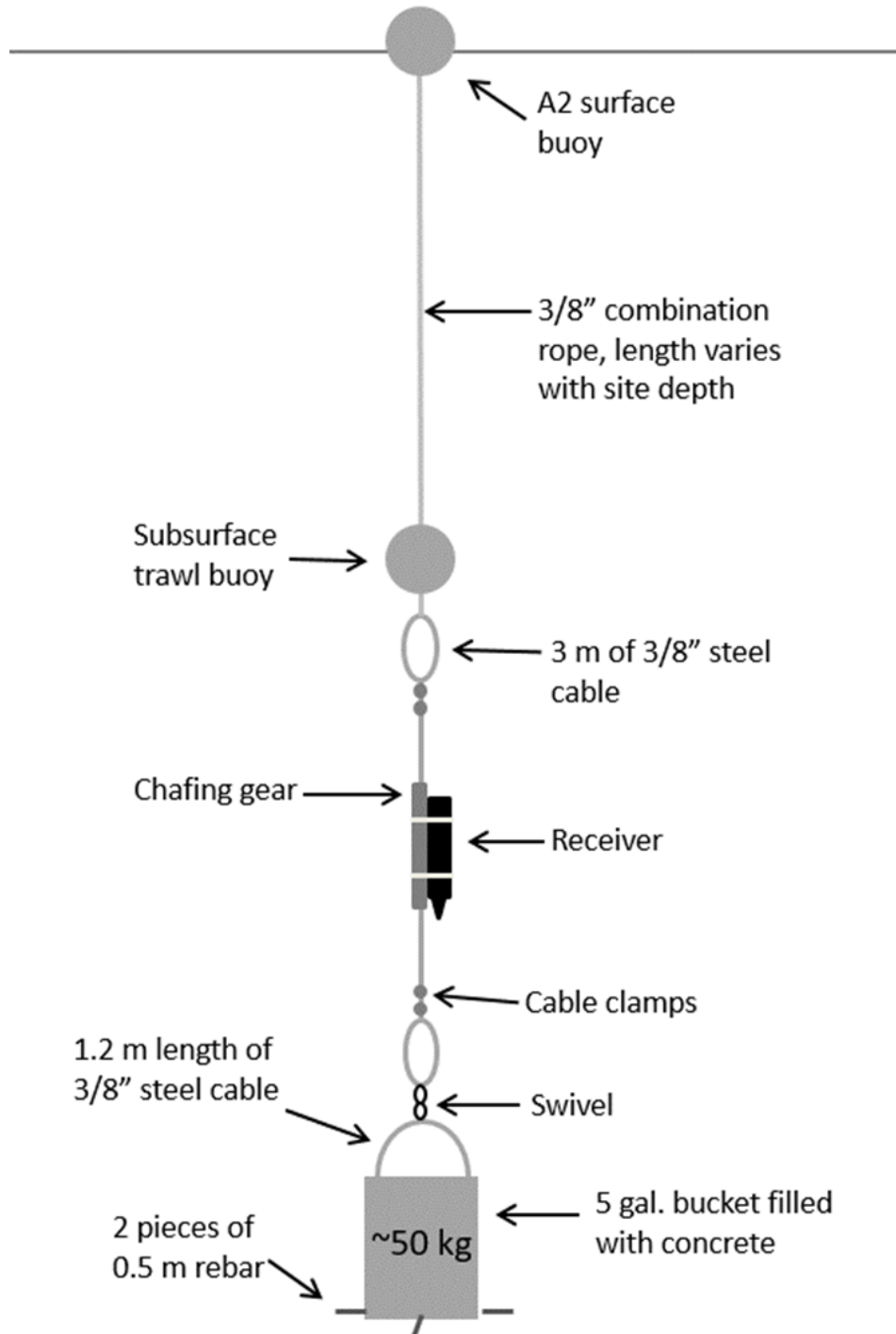


Figure C.1 Mooring assembly schematic for marine acoustic receivers.

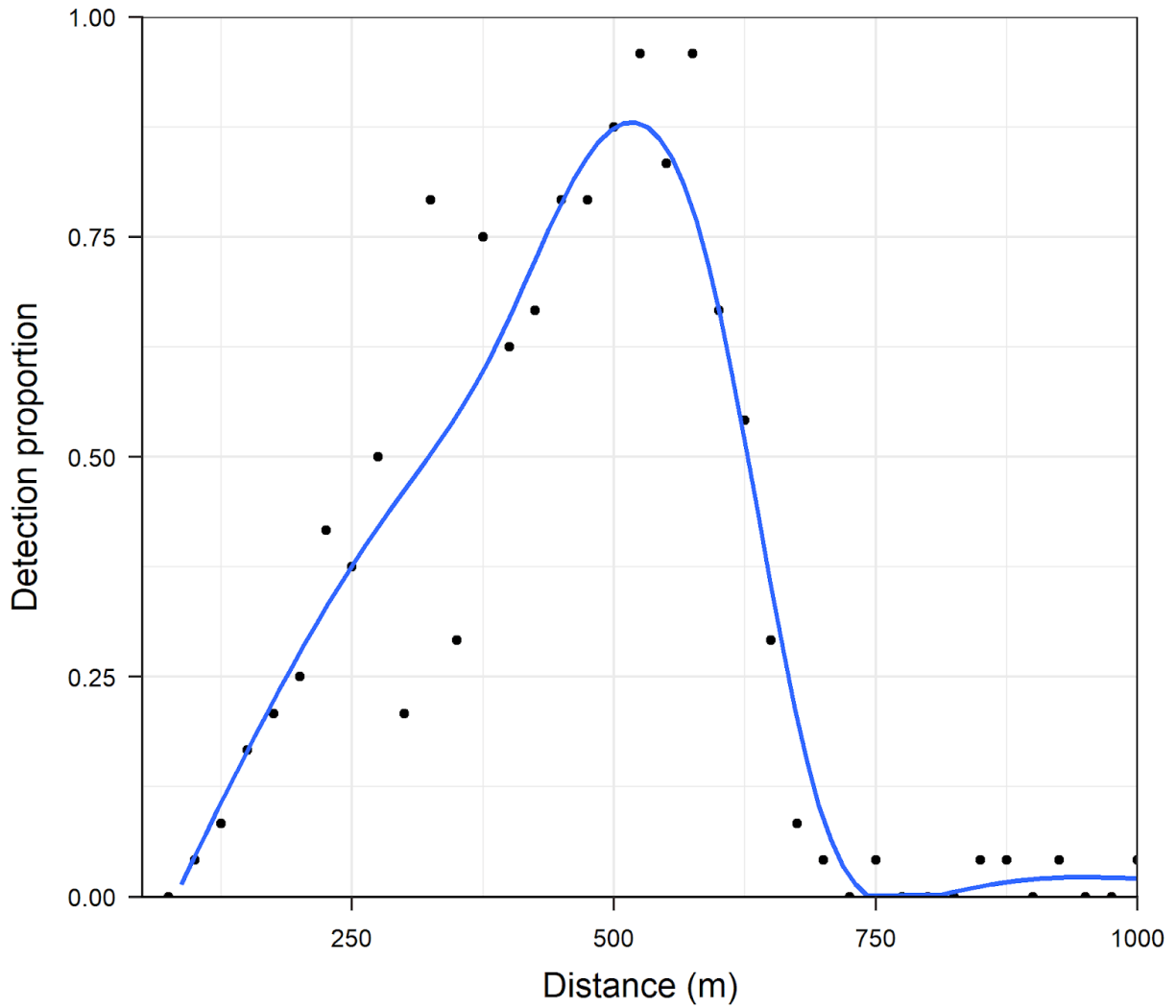


Figure C.2 Results of a marine acoustic range test performed near the Blueberry Creek array in the Unalakleet subdistrict of Norton Sound, Alaska. The proportion of acoustic transmissions successfully detected is plotted as a function of distance. The blue line represents predictions from a generalized additive model using formula: $y \sim s(x)$ with a penalized cubic regression spline.

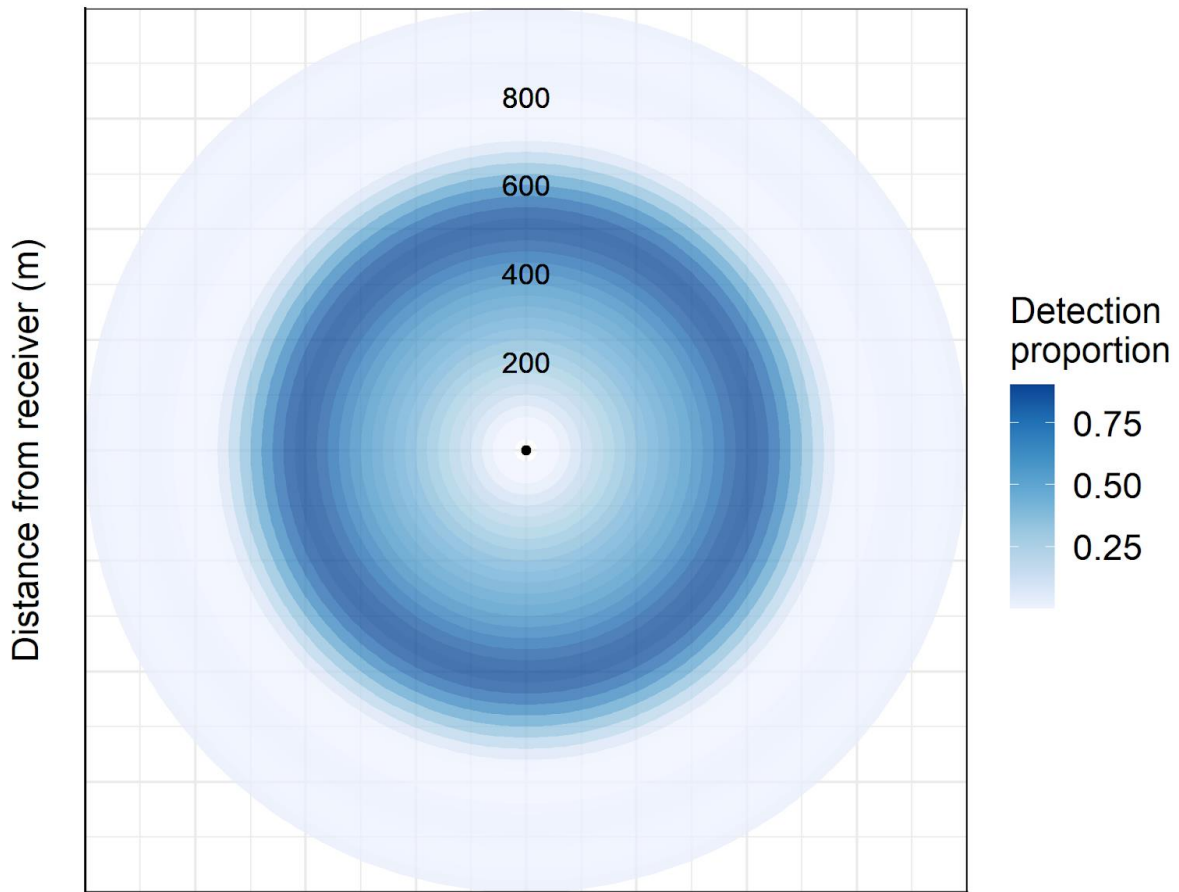


Figure C.3 Visualization of the ‘donut effect’ using model-predicted acoustic tag detection proportions near the Blueberry Creek array in the Unalakleet subdistrict of Norton Sound, Alaska. Detection proportions are plotted as a function of linear distance of signal origination from the receiver, where the center point represents the position of the acoustic receiver.

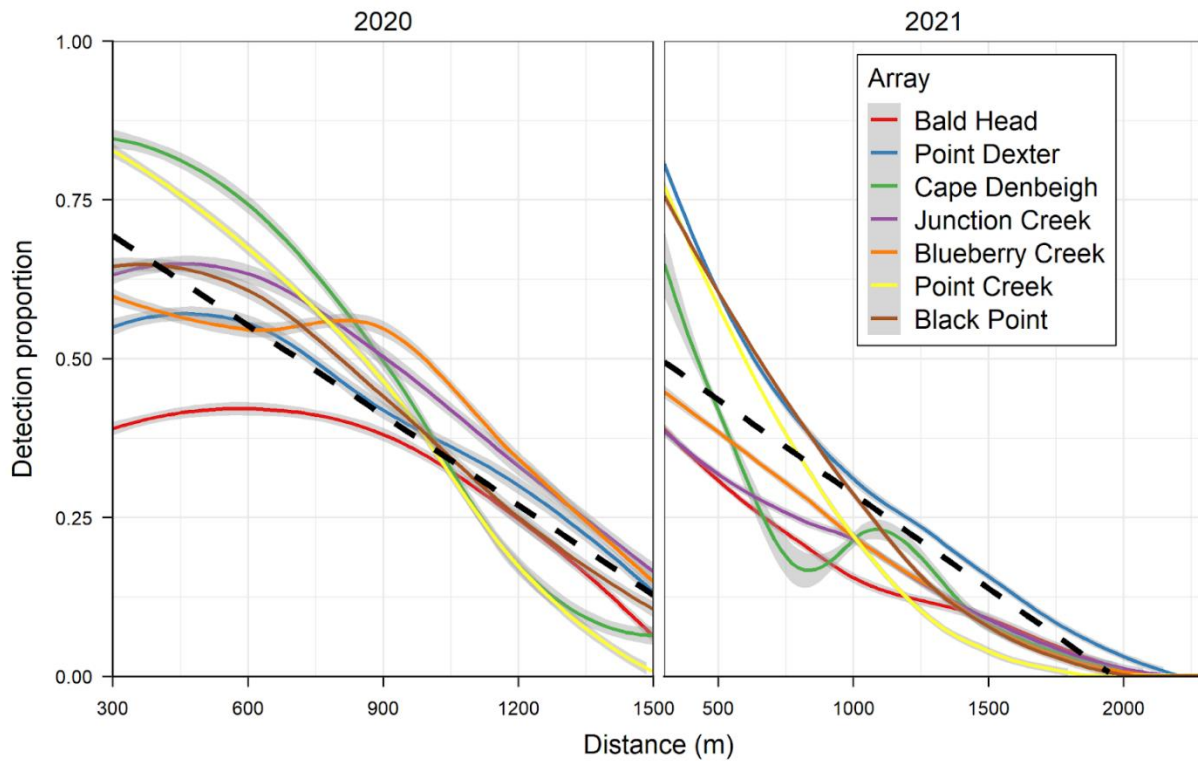


Figure C.4 Model-predicted detection proportions of acoustic transmissions by marine acoustic receiver arrays as a function of distance in 2020 and 2021. The dashed line represents a linear model of the pooled data using formula: $y \sim x$ and the gray envelope represents a 95% confidence interval. Note that x-axis is unfixed due to varied spacing of receivers within arrays between years.

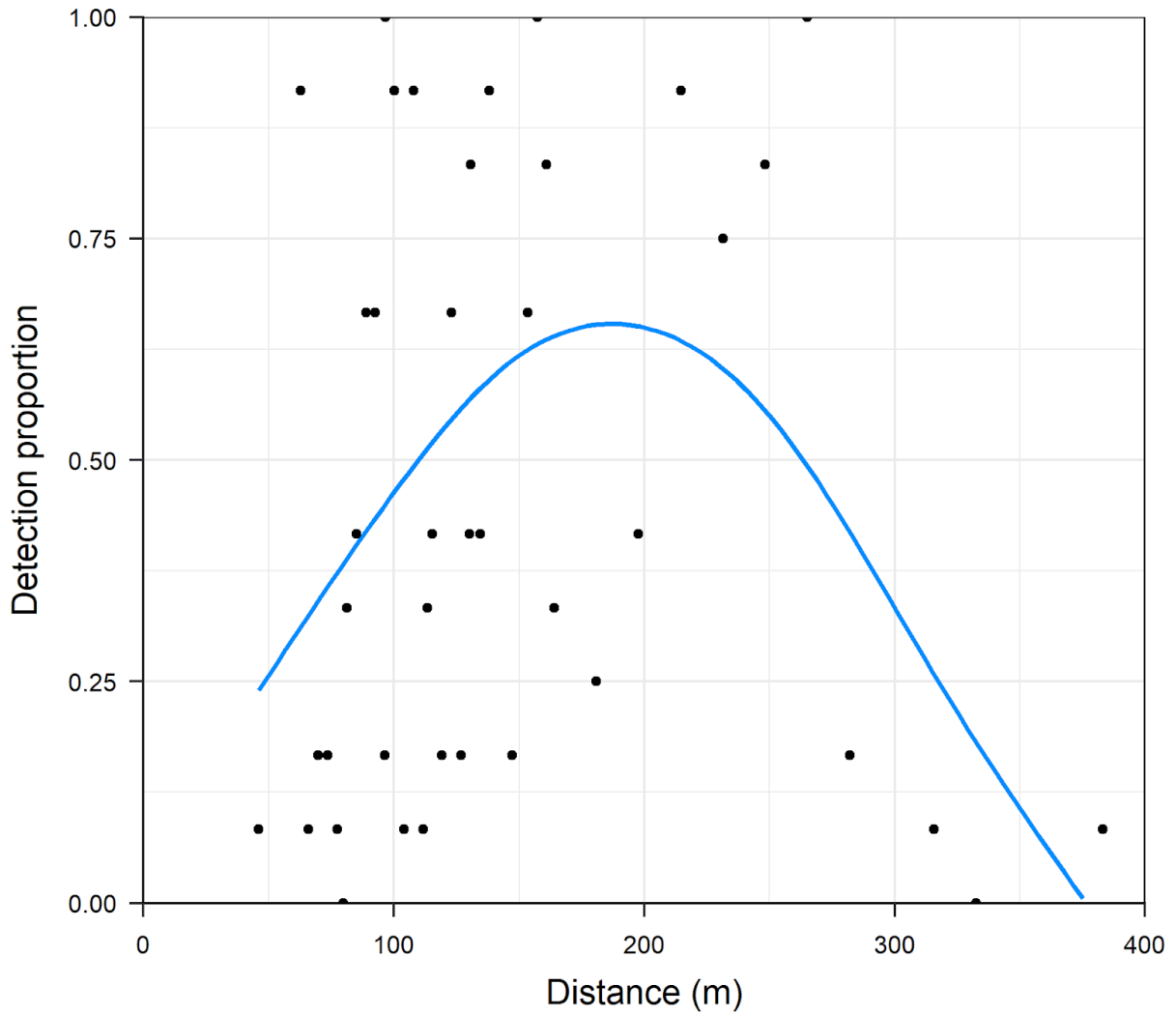


Figure C.5 Results of the Unalakleet River range test in which the proportion of acoustic transmissions successfully detected is plotted as a function of distance. The blue line represents predictions from a generalized additive model using formula: $y \sim s(x)$ with a penalized cubic regression spline.

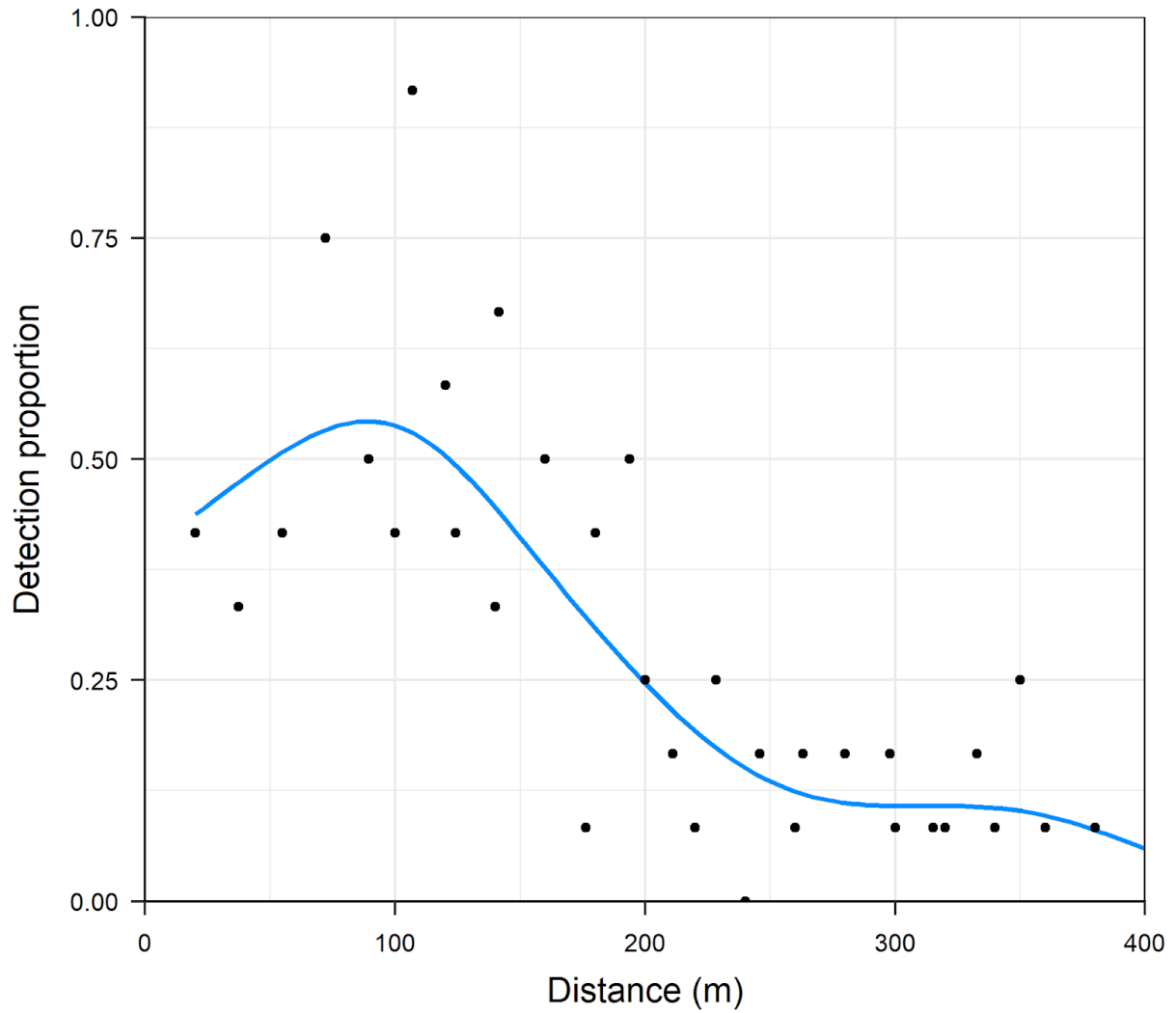


Figure C.6 Results of the Koyuk River range test where the proportion of acoustic transmissions successfully detected is plotted as a function of distance. The blue line represents predictions from a generalized additive model using formula: $y \sim s(x)$ with a penalized cubic regression spline.

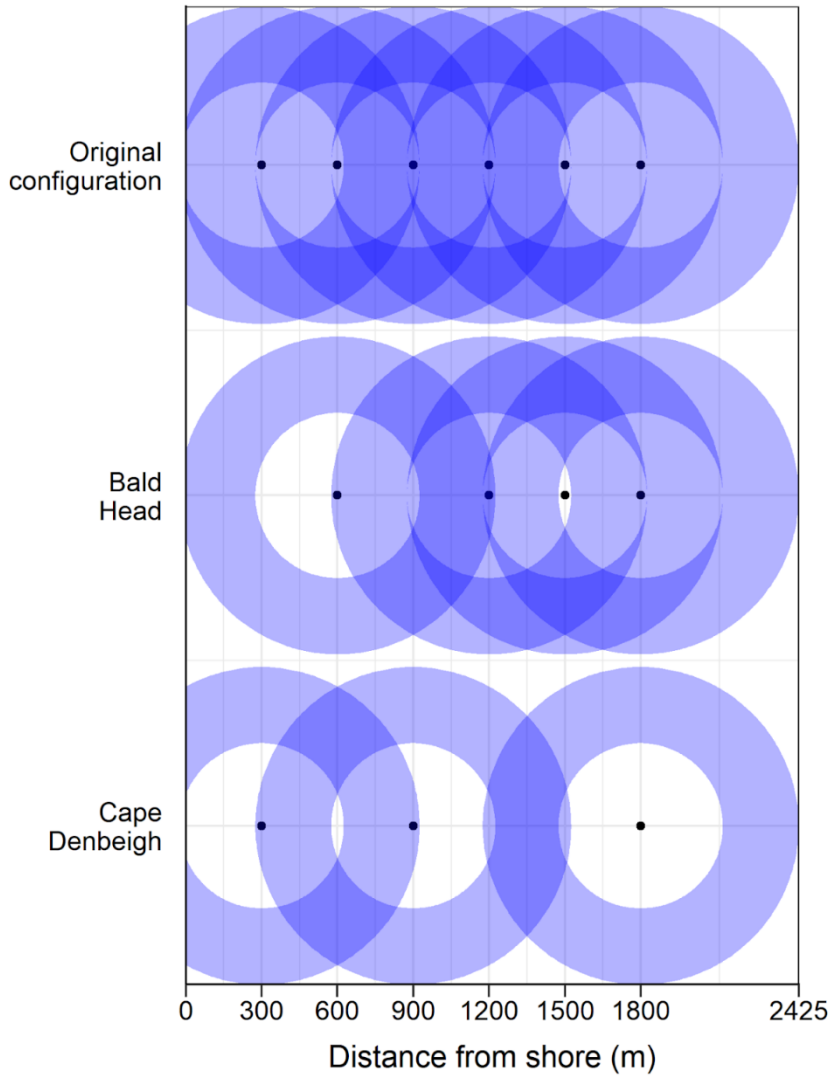


Figure C.7 Visualization of acoustic detection coverage by marine receiver arrays in 2020. Some arrays differ from the original configuration because receivers were lost during the season or data could not be retrieved. The blue donuts represent a model-predicted range of acoustic detection proportions > 0.50 .

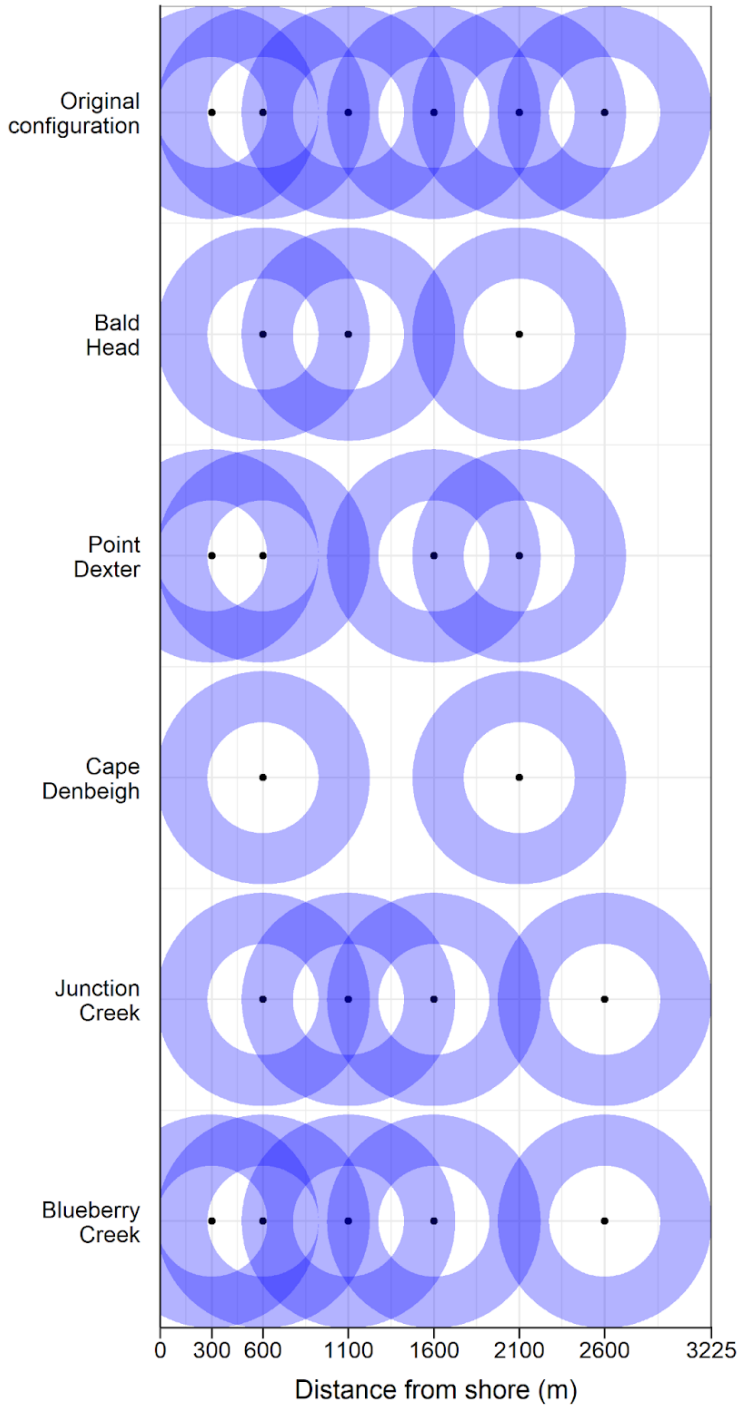


Figure C.8 Visualization of acoustic detection coverage by marine receiver arrays in 2021. Some arrays differ from the original configuration because receivers were lost during the season or data could not be retrieved. The blue donuts represent a model-predicted range of acoustic detection proportions > 0.50 .

Tables

Table C.1 Receiver IDs and associated deployment and retrieval statistics for marine receivers in Norton Sound, AK in 2020. Receivers with no retrieval date were not recovered.

Receiver ID	Latitude	Longitude	Distance from shore (m)	Deployment date	Retrieval date	Notes
Bald Head array						
1.1	64.735038°	-161.529442°	300	7/16/2020	-	Last detected 9/4
1.2	64.732402°	-161.527414°	600	7/16/2020	9/4/2020	
1.3	64.729833°	-161.525338°	900	7/16/2020	9/4/2020	Data corrupted
1.4	64.727261°	-161.523460°	1200	7/16/2020	9/4/2020	
1.5	64.724733°	-161.521433°	1500	7/16/2020	9/4/2020	
1.6	64.722083°	-161.519428°	1800	7/16/2020	9/4/2020	
Point Dexter array						
2.1	64.535826°	-161.376410°	300	7/16/2020	9/4/2020	
2.2	64.538388°	-161.378270°	600	7/16/2020	9/4/2020	
2.3	64.540824°	-161.380421°	900	7/16/2020	9/4/2020	
2.4	64.543390°	-161.382232°	1200	7/16/2020	9/4/2020	
2.5	64.545967°	-161.384115°	1500	7/16/2020	9/4/2020	
2.6	64.548512°	-161.386132°	1800	7/16/2020	9/4/2020	
Cape Denbeigh array						
3.1	64.376093°	-161.533817°	300	7/22/2020	9/4/2020	
3.2	64.373826°	-161.537393°	600	7/22/2020	9/4/2020	Data corrupted
3.3	64.371604°	-161.541044°	900	7/22/2020	9/4/2020	
3.4	64.369362°	-161.544582°	1200	7/22/2020	-	Last detected 9/4
3.5	64.367045°	-161.548138°	1500	7/22/2020	-	Last detected 9/4
3.6	64.364748°	-161.551676°	1800	7/22/2020	9/4/2020	

Junction Creek array					
4.1	64.131287°	-160.957982°	300	7/22/2020	9/5/2020
4.2	64.131239°	-160.964123°	600	7/22/2020	9/5/2020
4.3	64.131144°	-160.970255°	900	7/22/2020	9/5/2020
4.4	64.131052°	-160.976405°	1200	7/22/2020	9/5/2020
4.5	64.130941°	-160.982481°	1500	7/22/2020	9/5/2020
4.6	64.130854°	-160.988610°	1800	7/22/2020	9/5/2020
Blueberry Creek array					
5.1	63.953841°	-160.857668°	300	7/14/2020	9/5/2020
5.2	63.953644°	-160.863799°	600	7/14/2020	9/5/2020
5.3	63.953475°	-160.869926°	900	7/14/2020	9/5/2020
5.4	63.953337°	-160.876021°	1200	7/14/2020	9/5/2020
5.5	63.953142°	-160.882113°	1500	7/14/2020	9/5/2020
5.6	63.952990°	-160.888171°	1800	7/14/2020	9/5/2020
Point Creek array					
6.1	63.690645°	-160.876555°	300	7/16/2020	9/5/2020
6.2	63.691418°	-160.882280°	600	7/16/2020	9/5/2020
6.3	63.692109°	-160.888144°	900	7/16/2020	9/5/2020
6.4	63.692845°	-160.893966°	1200	7/16/2020	9/5/2020
6.5	63.693551°	-160.899800°	1500	7/16/2020	9/5/2020
6.6	63.694258°	-160.905669°	1800	7/16/2020	9/5/2020
Black Point array					
7.1	63.547179°	-161.123543°	300	7/17/2020	9/5/2020
7.2	63.548007°	-161.129208°	600	7/17/2020	9/5/2020
7.3	63.548826°	-161.134898°	900	7/17/2020	9/5/2020
7.4	63.549665°	-161.140528°	1200	7/17/2020	9/5/2020
7.5	63.550473°	-161.146236°	1500	7/17/2020	9/5/2020
7.6	63.551293°	-161.151899°	1800	7/17/2020	9/5/2020

Table C.2 Receiver IDs and associated deployment and retrieval statistics for marine receivers in Norton Sound, AK 2021. Receivers with no retrieval date were not recovered.

Receiver ID	Latitude	Longitude	Distance from shore (m)	Deployment date	Retrieval date	Notes
Bald Head array						
1.1	64.735038°	-161.529442°	300	6/25/2021	-	Last detected 8/29
1.2	64.732402°	-161.527414°	600	6/25/2021	9/9/2021	
1.3	64.728134°	-161.524096°	1100	6/25/2021	9/9/2021	
1.4	64.723868°	-161.520787°	1600	6/25/2021	-	Last detected 8/24
1.5	64.719596°	-161.517487°	2100	6/25/2021	9/9/2021	
1.6	64.715320°	-161.514191°	2600	6/25/2021	-	Last detected 8/24
Point Dexter array						
2.1	64.535826°	-161.376410°	300	6/25/2021	9/9/2021	
2.2	64.538388°	-161.378270°	600	6/25/2021	9/9/2021	
2.3	64.540824°	-161.380421°	1100	6/25/2021	9/9/2021	Data corrupted
2.4	64.543390°	-161.382232°	1600	6/25/2021	9/9/2021	
2.5	64.545967°	-161.384115°	2100	6/25/2021	9/9/2021	
2.6	64.548512°	-161.386132°	2600	6/25/2021	-	Last detected 8/14
Cape Denbeigh array						
3.1	64.376093°	-161.533817°	300	6/25/2021	9/9/2021	Data corrupted
3.2	64.373826°	-161.537393°	600	6/25/2021	9/9/2021	
3.3	64.371604°	-161.541044°	1100	6/25/2021	-	Last detected 7/27
3.4	64.369362°	-161.544582°	1600	6/25/2021	-	Last detected 6/25
3.5	64.367045°	-161.548138°	2100	6/25/2021	9/9/2021	
3.6	64.364748°	-161.551676°	2600	6/25/2021	9/9/2021	Data corrupted

Junction Creek array						
4.1	64.131287°	-160.957982°	300	6/25/2021	-	Last detected 8/28
4.2	64.131239°	-160.964123°	600	6/25/2021	9/9/2021	
4.3	64.131144°	-160.970255°	1100	6/25/2021	9/9/2021	
4.4	64.131052°	-160.976405°	1600	6/25/2021	9/9/2021	
4.5	64.130941°	-160.982481°	2100	6/25/2021	-	Last detected 8/31
4.6	64.130854°	-160.988610°	2600	6/25/2021	9/9/2021	
Blueberry Creek array						
5.1	63.953841°	-160.857668°	300	6/25/2021	9/9/2021	
5.2	63.953644°	-160.863799°	600	6/25/2021	9/9/2021	
5.3	63.953475°	-160.869926°	1100	6/25/2021	9/9/2021	
5.4	63.953337°	-160.876021°	1600	6/25/2021	9/9/2021	
5.5	63.953142°	-160.882113°	2100	6/25/2021	-	Last detected 9/5
5.6	63.952990°	-160.888171°	2600	6/25/2021	9/9/2021	
Point Creek array						
6.1	63.690645°	-160.876555°	300	6/25/2021	9/9/2021	
6.2	63.691418°	-160.882280°	600	6/25/2021	9/9/2021	
6.3	63.692109°	-160.888144°	1100	6/25/2021	9/9/2021	
6.4	63.692845°	-160.893966°	1600	6/25/2021	9/9/2021	
6.5	63.693551°	-160.899800°	2100	6/25/2021	9/9/2021	
6.6	63.694258°	-160.905669°	2600	6/25/2021	9/9/2021	
Black Point array						
7.1	63.547179°	-161.123543°	300	6/25/2021	9/9/2021	
7.2	63.548007°	-161.129208°	600	6/25/2021	9/9/2021	
7.3	63.548826°	-161.134898°	1100	6/25/2021	9/9/2021	
7.4	63.549665°	-161.140528°	1600	6/25/2021	9/9/2021	
7.5	63.550473°	-161.146236°	2100	6/25/2021	9/9/2021	
7.6	63.551293°	-161.151899°	2600	6/25/2021	9/9/2021	

Table C.3 Receiver IDs and associated deployment and retrieval statistics for inriver receivers adjacent to Norton Sound, AK in 2020. Note that receiver IDs with a ‘1’ were downstream relative to receiver IDs with a ‘2.’

Stream	Receiver ID	Latitude	Longitude	River width (m)	Deployment date	Retrieval date
Elim subdistrict						
Kwiniuk River	W1	64.714890°	-162.021235°	51	7/15/2020	10/12/2020
	W2	64.724167°	-162.015833°	50	7/15/2020	10/12/2020
Tubutulik River	B1	64.757215°	-161.907372°	48	7/15/2020	10/12/2020
	B2	64.767315°	-161.917887°	47	7/15/2020	10/12/2020
Norton Bay subdistrict						
Koyuk River	K1	64.916964°	-161.012332°	275	7/15/2020	9/13/2020
	K2	64.927713°	-160.982101°	300	7/15/2020	9/13/2020
Inglutalik River	I1	64.837735°	-160.765534°	115	7/15/2020	9/13/2020
	I2	64.830505°	-160.740074°	162	7/15/2020	9/13/2020
Ungalik River	N1	64.557998°	-160.860689°	52	7/15/2020	9/14/2020
	N2	64.548801°	-160.852381°	41	7/15/2020	9/14/2020
Shaktoolik subdistrict						
Shaktoolik River	S1	64.368624°	-161.112718°	60	7/15/2020	10/12/2020
	S2	64.366297°	-161.093039°	52	7/15/2020	10/12/2020
Tagoomenik River	T1	64.318634°	-161.122722°	24	7/15/2020	10/12/2020
	T2	64.320926°	-161.107788°	22	7/15/2020	10/12/2020
Unalakleet subdistrict						
Egavik Creek	E1	64.042944°	-160.888673°	28	7/15/2020	10/12/2020
	E2	64.039991°	-160.900489°	31	7/15/2020	10/12/2020
Unalakleet River	U1	63.557764°	-161.056892°	156	7/13/2020	9/5/2020
	U2	63.555623°	-161.051248°	114	7/13/2020	9/5/2020
Golsovia River	G1	63.860209°	-160.697523°	39	7/17/2020	9/5/2020
	G2	63.871681°	-160.676135°	37	7/17/2020	9/5/2020

Table C.4 Receiver IDs and associated deployment and retrieval statistics for inriver receivers adjacent to Norton Sound, AK in 2021. Note that receiver IDs with a ‘1’ were downstream relative to receiver IDs with a ‘2.’ Receivers with no retrieval date were not recovered.

Stream	Receiver ID	Latitude	Longitude	River width (m)	Deployment date	Retrieval date
Elim subdistrict						
Kwiniuk River	W1	64.714890°	-162.021235°	51	6/23/2021	9/17/2021
	W2	64.724167°	-162.015833°	50	6/23/2021	9/17/2021
Tubutulik River	B1	64.757215°	-161.907372°	48	6/23/2021	-
	B2	64.767315°	-161.917887°	47	6/23/2021	9/26/2021
Norton Bay subdistrict						
Koyuk River	K1	64.916964°	-161.012332°	275	6/23/2021	9/9/2021
	K2	64.927713°	-160.982101°	300	6/23/2021	9/9/2021
Inglutalik River	I1	64.837735°	-160.765534°	115	6/23/2021	9/9/2021
	I2	64.830505°	-160.740074°	162	6/23/2021	9/9/2021
Ungalik River	N1	64.557998°	-160.860689°	52	6/23/2021	-
	N2	64.548801°	-160.852381°	41	6/23/2021	-
Shaktoolik subdistrict						
Shaktoolik River	S1	64.368624°	-161.112718°	60	6/23/2021	9/26/2021
	S2	64.366297°	-161.093039°	52	6/23/2021	9/26/2021
Tagoomenik River	T1	64.318634°	-161.122722°	24	6/23/2021	9/26/2021
	T2	64.320926°	-161.107788°	22	6/23/2021	9/26/2021
Unalakleet subdistrict						
Egavik Creek	E1	64.042944°	-160.888673°	28	6/23/2021	-
	E2	64.039991°	-160.900489°	31	6/23/2021	-
Unalakleet River	U1	63.557764°	-161.056892°	156	6/25/2021	9/27/2021
	U2	63.555623°	-161.051248°	114	6/25/2021	-
Golsovia River	G1	63.860209°	-160.697523°	39	6/23/2021	9/26/2021
	G2	63.871681°	-160.676135°	37	6/23/2021	-