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Southern Resident Killer Whale (*Orcinus orca*) summer distribution and habitat use in the southern Salish Sea and the Swiftsure Bank area (2009 to 2020)

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

The Southern Resident Killer Whale (SRKW; *Orcinus orca*) population in Canadian Pacific waters is listed as Endangered under the Species at Risk Act. Efforts in support of recovery are underway from numerous government sectors, stakeholders, industry and others. Critical habitat has been identified for this population and includes the waters on the continental shelf off southwestern Vancouver Island and eastward to portions of the inner waters of the Salish Sea. As the spatial extent of critical habitat is large, there is a need to focus mitigation efforts on areas that have the greatest potential to provide benefits to the population. To support requests for advice on spatial and temporal boundaries identifying areas of high relative SRKW occurrence, a novel approach was undertaken to facilitate collation of disparate datasets and to address preferential sampling bias in sightings data. The results presented here indicate that from May to October, the highest SRKW frequency of occurrence is found in the waters in the vicinity of Swiftsure Bank, the eastern portion of Haro Strait, sections of Swanson Channel and Boundary Pass, and near the Fraser River. Analysis of behavioural data provides further information on habitat use and identifies key foraging areas at Swiftsure Bank and Haro Strait. Evaluation of acoustic detections and encounter durations from recorders deployed in SRKW critical habitat lend further support to strengthen the interpretation of sightings data and provide further information on fine scale habitat use within the population’s critical habitat.

1. INTRODUCTION

Four sympatric populations of Killer Whales (*Orcinus orca*) have been described in Canadian Pacific waters. The Southern Resident Killer Whale (SRKW) population is the smallest of the four and in 2020, consisted of only 74 individuals (2020, Centre for Whale Research). The SRKW population is listed as Endangered under Canada's *Species at Risk Act* (SARA). A declining population and increasing threats with the potential to further reduce numbers were cited as reasons for designation (COSEWIC 2001). Areas of coastal and inland waters around Vancouver Island have been identified as SRKW critical habitat (CH) under the SARA (Figure 1; Fisheries and Oceans Canada 2018).

The SRKW live in stable groups referred to as matrilines and may consist of multiple generations of individuals that are related by matrilineal descent. Closely associated matrilines are grouped into pods, which share repertoires of stereotyped calls that can be used to acoustically differentiate pods and some matrilines (Ford 1991). The SRKW population consists of three pods, J, K, and L, and 17 matrilines.

The SRKW population range extends over 2000 km of coastline from Monterey Bay, California to Chatham Strait, Alaska (Figure 1). Sightings data indicate that from late spring through to early autumn, SRKWs maintain a sustained presence within the Salish Sea (Figure 2; Ford et al. 2017; Ford 2006). Whales of the 'resident' ecotype are known to feed primarily on salmon, and SRKW summer movement patterns reflect the migratory spawning routes of Chinook (*Oncorhynchus tshawytscha*) stocks of the Fraser River, with a shift to Chum (*O. keta*) and Coho (*O. kisutch*) in Puget Sound for the late summer/fall (Ford and Ellis 2006; Ford et al. 1998; Hanson et al. 2010). As winter approaches, a reduction in the concentration of salmon is coincident with dispersion of SRKW from the area, and the variety of species within the SRKW diet is observed to increase in the winter months (Ford et al. 2010; Ford et al. 2017; Hanson et al. 2021).

The Salish Sea includes the waters of Juan de Fuca Strait (JDF), the Strait of Georgia, Haro Strait and Puget Sound, with a western boundary defined by a line from Cape Flattery to Carmanah Point (Figure 1 and Figure 3). The area of SRKW CH to the west of the Salish Sea boundary encompasses La Perouse Bank, Swiftsure Bank, and various canyons and submarine features. For ease of reference, this portion of SRKW CH will be referred to as 'the Swiftsure area' throughout this document. The phrase 'the study area' refers hereafter to both the Salish Sea and the Swiftsure area.

The current state of knowledge on SRKW distribution in the Salish Sea has been based primarily on presence-only data from platforms of opportunity (P_{opp}) sightings reported by voluntary observers (Hauser et al. 2007; Olson et al. 2018). Two SRKW sightings datasets exist: the British Columbia Cetacean Sightings Network dataset (BCCSN; a collaboration between Ocean Wise's Coastal Ocean Research Institute and Fisheries and Oceans Canada; DFO), and the Orca Master dataset (OM; The Whale Museum, Friday Harbour, Washington). These opportunistic datasets benefit from widespread participation of the general public and whale watch operators, which provide spatial and temporal coverage that extends beyond what is possible through scientific survey effort alone. A method of effort correction for these platform of opportunity datasets was developed using a kernel density model to construct a plausible distribution of marine mammal observer effort (Rechsteiner et al. 2013). When these effort estimates were applied to the OM dataset sightings from 1974 to 2014, areas of high SRKW density were observed along the east side of Haro Strait, the west of Pender Island, and south of Saturna Island (Olson et al. 2018; Figure 3).

The DFO Cetacean Research Program has maintained a SRKW encounter database since 1973 (Ford et al. 2017). A variety of methods were used to populate this database, with the majority of encounters obtained during dedicated studies of killer whales, along with some contributions from other researchers who collected photographs opportunistically while undertaking other marine activities. These data demonstrate a strong presence of SRKW for the waters around Swiftsure Bank, located to the west of JDF (Ford et al. 2017; Ford 2006). The DFO SRKW encounter data has little geographic overlap with the P_{opp} sightings data, where a generalized boundary between these datasets occurs in the vicinity of Jordan River at the midpoint of JDF (Figure 3). The majority of these data are from dedicated survey effort that provide both presence and absence data for analysis, as well as robust daily effort data by which to express sightings per unit effort. The ability to combine the DFO dataset with P_{opp} sightings datasets to evaluate relative occurrence in SRKW CH has been hindered by challenges in unifying presence-only data with presence-absence survey data and issues with effort correction.

Species distribution models are useful tools to identify preferred habitats, which can be used to inform management decisions. Models that incorporate temporal variables are particularly informative, as they provide better resolution and an improved understanding of seasonal changes in habitat use. These models also provide a greater ability to test assumptions and quantify uncertainties. Recent advances in statistical modelling provide a novel approach, i.e., Integrated Nested Laplace Approximation, to address problems with opportunistic data, such as the P_{opp} data, that lack quantified effort (Watson 2020; Watson et al. 2021). In spatio-temporal point-pattern data such as whale sightings, the issue of preferential sampling and variability related to sampling effort can introduce bias or inaccuracies to the outputs. This novel approach allows for the estimation of SRKW frequency of occurrence while adjusting for variability in both observer effort and whale detectability.

While sightings and occurrence data provide information on habitat preference, the evaluation of behavior informs our understanding of habitat use. For SRKWs, reduced prey availability has been identified as a primary threat to recovery, and identification of areas that support foraging is needed. The SRKW population is characterized as nutritionally stressed, as evidenced by a reduction in survival and reproduction (Ford et al. 2010; Ward et al. 2009; Wasser et al. 2017), and an overall decline in body condition (Fearnbach et al. 2011; Fearnbach et al. 2018). A comparison of photogrammetry data from 2008 to images obtained in 2013 indicates that 25% of the population exhibited a decline in body condition over the five-year period, with the majority of those individuals being reproductive-aged females (Fearnbach et al. 2018). In addition, adult whales that are under 40 years of age exhibit significantly shorter body lengths than those 40 years of age or older (Groskreutz et al. 2019), suggesting that nutritional stress has been chronic for this population. Mortality in the population exhibits a close relationship with the coast-wide abundance of Chinook Salmon, indicating that this prey species may be an important limiting factor in their population dynamics (Ford et al. 2010; Vélez-Espino et al. 2015; Ward et al. 2009). The immediacy of addressing the nutritional needs of SRKW elevates the importance of obtaining detailed information on habitat use for foraging.

Efforts to characterize habitat use have occurred primarily within the inland waters of the Salish Sea during late spring to early autumn, and indicate that SRKWs spend the majority of their time foraging and travelling (Ashe et al. 2010; Heimlich-Boran 1988; Hoelzel 1993; Noren and Hauser 2016; Osborne 1986). Localized areas associated with foraging include the south and west coasts of San Juan Island, Boundary Pass, Swanson Channel, Active Pass, waters off the mouth of the Fraser River, and the Vancouver Island shoreline of the JDF (Ford 2006; Hanson et al. 2010). Compared to the inner Salish Sea (southern Strait of Georgia and Puget Sound), much less is known regarding the fine-scale habitat use patterns within the JDF (particularly west of Jordan River) and the waters surrounding Swiftsure Bank, which now form part of SRKW CH (Ford et al. 2017).

In addition to opportunistic sightings and dedicated survey data, information on SRKW may be collected using passive acoustic monitoring (PAM) systems. Although limited in their spatial coverage, the use of PAMs provides some benefits over visual surveys as they are not as hindered by time of day, sighting conditions, or sea state. In a number of studies, they have been shown to detect whales more frequently than visual surveys (Barlow and Taylor 2005; McDonald and Moore 2002; Mellinger et al. 2007; Rankin et al. 2007; Širović et al. 2004). The duration of an acoustic encounter also has the potential to provide information that may not be easily obtained via visual surveys. When combined with concurrent visual data or behavioural observations, a greater understanding of the significance of detection data may be achieved.

The substantial volume of information and ongoing research on this population has provided a challenge in the form of collating and expressing the knowledge in a cohesive way to support mitigation. The following analyses detail the application of Watson's (2020) approach to the available P_{opp} and DFO data to unify sightings obtained using disparate methods, and to express the relative importance of SRKW frequency of occurrence over a wider geographic area. Further details on habitat use are provided through the collection and analysis of behavioural data from areas of high occurrence, and through the evaluation of acoustic detections and encounter durations from PAMs in SRKW CH to strengthen interpretation of sightings.

2. METHODOLOGY

Analyses used a combination of SRKW sightings and survey effort data from two separate sources. Two separate modelling approaches were applied to the P_{opp} and DFO datasets. Kernel density modeling using the P_{opp} data was conducted to provide a comparison with previous effort-correction models that used this approach (Olsen 2018). Occurrence modelling was conducted to incorporate information from both P_{opp} and DFO datasets.

2.1. SIGHTINGS DATA

2.1.1. Platforms of Opportunity data

Sightings across ten years (2009 to 2018) were obtained from two voluntary observer sightings networks – the Canadian-based BCCSN and the American-based OM database. Data from May 1st to October 31st were analysed and this period is hereafter referred to as 'summer'. The OM and BCCSN datasets were combined and are referred to as 'Platforms of Opportunity dataset (P_{opp})' throughout this document.

2.1.2. Whale Watch data

A subset of the P_{opp} data was used to develop a more precise observer effort estimate with high sightings certainty. For the analysis presented here, only sightings reported by whale watch operators were used, as there is a high level of confidence in their SRKW ecotype and pod identification skills. Furthermore, the whale watch operators are frequently on the water, and will often share SRKW sightings with each other, reducing the likelihood of missing SRKW observations. These data provide the best opportunity to generate estimates of observer effort with a high degree of accuracy and precision by knowing the time spent on the water and the search/travel route. This information was collected through interviews with the whale watch operators (Watson 2020; Watson et al. 2021). This subset of the P_{opp} data is hereafter referred to as the 'WW dataset' (Figure 4).

2.1.3. DFO Research data

Twelve years (2009 to 2020) of SRKW encounter data and accompanying GPS vessel tracks from DFO surveys were analysed (Figure 5). Data collected between 2009 and 2020 were from on-water surveys primarily conducted throughout the Swiftsure region and surrounding areas, and ranged from dedicated SRKW surveys to ancillary sightings obtained during other research activities. The majority of data were from dedicated effort-corrected surveys conducted from two vessel platforms, a 8 m long rigid hull inflatable, similar to the type of vessels used by most whale watch operators, and a similar sized aluminum vessel. Data included location (lat/long), pod identification, and group size information for each sighting. Effort is defined as logged GPS tracks of the research vessel for each day prior to encountering SRKW by the vessel operator, an experienced individual with extensive knowledge of the SRKW population. The encounter data associated with DFO research activities consists of both presence and absence data and are hereafter referred to as the ‘DFO dataset’.

2.1.4. Combined sightings data

The “combined datasets” refers to the sightings from the WW data and the DFO dataset. The WW operator observations are ‘presence only’, as the reported information does not include locations or duration of search effort where whales were absent. As vessel tracks for WW effort were not recorded, the DFO data were converted to presence-only to allow the datasets to be combined. This dataset is hereafter referred to as the ‘combined sightings dataset’.

Both the WW and DFO sightings data have significant spatial and temporal autocorrelation, with sightings often made of the same pod in quick succession within the same day. The resolution of DFO research data is in the order of 15-30 second intervals, while WW sightings data are recorded at variable intervals throughout a given day. To remove these autocorrelations, the first sighting of the day of each pod was selected, removing all effort for each day which occurred after the initial sighting. As whales move quickly relative to the study area (~5 to 7 km/hr; Hanson et al. 2017), an overnight window was sufficient to remove any between-sightings autocorrelation (minimum time period between effort days is eight hours: Watson et al. 2021).

2.2. EFFORT CORRECTED MODELLING

2.2.1. Kernel Density Model

The 2009-2018 P_{opp} SRKW sightings data were fit to a Kernel Density Model as described in Olson et al. (2018). To reduce sampling bias and effort-correct the sightings data to create a relative density estimate in the Salish Sea, a five-step process was followed:

1. Eliminate duplicates
2. Estimate geolocation information for data points without GPS coordinates
3. Estimate SRKW group size
4. Apply effort correction for the number of whales sighted using a 25 km^2 grid
5. Generate effort-corrected kernel density estimates

First, reported sightings of SRKW that were separated by less than one hour and less than two nautical miles (nm) apart were considered repeat sightings of the same individuals, and all sightings within this time and distances criteria were removed from the datasets. Second, the approach to location information was standardized to express each sighting by latitude/longitude for both sets of data. For BCCSN dataset, the latitude/longitude of each sighting is reported. For the OM dataset, location is described by latitude/longitude or to the nearest quadrant (one of 445 quadrants of approximately 4.6 x 4.6 km developed by The Whale Museum; (Heimlich-Boran 1988). Sightings located within a quadrant were shifted to a unique location within the quadrant in relation to the sightings that had GPS data (defined as 'jittering') so that all data were assigned latitude/longitude. Third, as not all sightings data included the number of whales present, the median number of animals per pod was estimated from data that included counts of individuals per encounter. Fourth, the number of whales per grid cell was expressed using effort grid shapefiles developed for the BCCSN data (Rechsteiner et al. 2013) and OM data (Olson et al. 2018). The effort for each grid cell was then expressed as a proportion of the maximum total effort (Figure 6). To estimate the relative summer density of SRKW across geographic areas, the total number of individuals for each reported sighting was divided by the effort value assigned to the area where the sighting occurred. In the fifth step, the effort-corrected density estimates were then smoothed using the Kernel Density tool in ArcGIS™ (Version 10.8.1) using the default settings (1 km grid cell output and 4 km search radius), and expressed as the annual frequency of SRKW summer occurrence.

2.2.2. SRKW Occurrence Model

A Log-Gaussian Cox process (LGCP) framework was applied to the combined dataset to build effort-corrected models of SRKW frequency of occurrence, following the methodology outlined in Watson (2020). The fundamental components of this framework include: 1) point location sightings data for SRKW identified to pod; 2) a defined computational mesh surface for model integration across the study area (Figure 7); and 3) a dual mesh surface that matches the extent of the computational mesh and incorporates the observer effort as a covariate (Figure 7; Watson 2020; Watson et al. 2021). The dual mesh consists of Voronoi polygons, which encompass all points around a mesh node that are closer to that node than any other. These polygons form the integration points used to map observer effort and SRKW observations.

The daily GPS track lines of DFO vessels were used to approximate DFO observer effort. Effort was calculated from time 'on effort' until the first sighting of a whale pod was made. Research vessel locations were determined from the GPS locational data at regular 30-second intervals using a continuous-time correlated random walk model. This model was used to fit a track line to each trip using the R package 'crawl' (Johnson and London 2018; Johnson et al. 2008). Each point represents an effort level of 30 seconds, which can be summed up within the cells of the dual mesh, providing an estimate of total effort for each mesh node. The cumulative monthly observer effort was estimated from all DFO survey effort and then summed across the 12 years of DFO surveys.

WW effort was defined using a stochastic emulator, developed to estimate the cumulative boat-hours spent in each of the cell of the dual mesh for each day, month, and year from 2009 to 2018 (Watson 2020). As whale watch sightings are not linked to a specific vessel, observer efficiencies across all whale watch vessels operating within the study area were assumed to be constant. Data on the number of active whale watch ports per year, maximum number of trips departing each day from each port, change in number of daily trips across the months, and number of hours of trips from each port for the period May to September was obtained from Soundwatch (Seely et al. 2017). Effort was assumed to decrease as a function of distance from port based on maximum distance and route information provided by the whale watch operators. Effort was summed separately for each pod, and subsequent effort was discarded once a pod was sighted, while effort to sight the other pods continued until either the pod(s) were sighted or the day ended. For each day, the number of hours into the operational day at which the initial sightings were made was recorded with an assumed daily operational period of 9 am to 6 pm (Seely et al. 2017). As SRKW seldom remain in a location for extended periods of time, the overnight window of 15 hours between effort days was deemed sufficient to remove the spatial autocorrelation (Watson et al. 2021). To account for the changing effort throughout the day, we used the numbers of vessels reported by Soundwatch to be in close proximity with whales by hour of day as our proxy for whale-watch effort intensity. Days with no effort due to weather were identified and removed using historical data to calculate the number of days where wind speed exceeded industry-based thresholds for cancellations (Watson 2020).

Daily sightings effort for each pod was calculated as the time from the beginning of the daily operational period (9 am) until either the end of the operational period (6 pm) or the time of the first sighting for a pod. Effort was then defined as a fraction of the nine hour operational period (e.g., if the first sighting of J pod occurred at 1 pm, the effort required to obtain that sighting would be expressed as four hours out of a total of nine possible effort hours). The fraction of WW observer effort in a given month per year was defined as the sum of the daily fraction of observer effort for each of the three pods by month for each year. Spatial distribution of effort was modelled, based on reported individual whale watch operator boat-hours per port, and the distribution of effort was then integrated by month and year for each port as per Watson (2020). To estimate the cumulative monthly observer effort, effort from all whale watch observers was summed across all 10 years.

To address sources of uncertainties in the estimates described above (e.g., monthly search effort, number of days cancelled due to weather), probability distributions were calculated, with the coefficient of variation exceeding 0.25 for the estimates from some of the smaller ports. The distributions were calculated from 1,000 Monte Carlo samples of the effort field, and for each sampled observer effort field. To produce the estimates of whale intensity, the final LGCP model was fit and sampled once from the posterior distributions of all the parameters and random effects. The 1,000 new posterior distributions helped account for the uncertainty in whale watch observer effort.

As both WW and DFO observer types involved similar-sized vessels, they were assumed to have identical efficiencies. The two observer effort meshes were therefore summed to obtain the total observer effort (Figure 8).

Several candidate models were fit for the analysis using the R-INLA package with the stochastic partial differential equation approach (Lindgren and Rue 2015; Lindgren et al. 2011; R Core Team 2020; Rue et al. 2009). The combined sightings data (from WW and DFO) were fit to the model. All models used the estimated observer effort field without detectability or observer effort covariates. Model construction started with the simplest form of complete spatial randomness, which assumed that, dependent on observer effort, sightings location for each pod and month are driven by a homogeneous Poisson process. Therefore, the model assumed that all whales and whale pods were equally likely to be observed throughout the study area for all months. Additional models included temporal splines and Gaussian (Markov) random fields with separable spatio-temporal covariance structures. Model selection using deviance information criteria (DIC) was performed on a single realization of the observer effort field for each model. This approach balances the goodness-of-fit of the model with a penalty for the model's complexity and is used in Bayesian model selection (Spiegelhalter et al. 2002). The final 'best' model identified using DIC and posterior predictive check assessments, included a spatial random field shared across the three pods, pod-specific spatio-temporal effects, and a spatial field unique to pod L.

As the WW effort data have inherent uncertainty and the DFO effort data are accompanied by vessel track data, the best model was then re-run 1,000 times using the uncertainties associated with the WW observer effort using the MCMC approach as described in the previous section, sampling once from each model run to generate an approximation of posterior of the fitted model. The posterior frequency distribution was then projected onto a 300 x 300 pixel field (pixel size: ~ 0.8 km^2) using the R package 'inlabru' (Bachl et al. 2019). Posterior frequency statistics were then computed for each pixel. Posterior predictive checks on the candidate models were also conducted (Gelman et al. 1996). In particular, the ability of the models to accurately estimate the total number of first sightings of each pod per month was assessed, as well as the models' ability to suitably capture the spatial trend by comparing the observed number of sightings falling within the study area with their model-estimated credible intervals.

The number of SRKW sightings per unit search effort was expressed as the intensity of SRKW occurrence. Variations in intensity of occurrence were visualized by identifying values that exceeded certain thresholds, with a >0.9 confidence level. Data from all six months were pooled to identify the exceedance threshold values indicating the 70%, 80%, and 90% intensity of SRKW occurrence for the whole study period. These global thresholds were then applied to data for each month to represent how the distribution of SRKW occurrence varied over the six month study period using a common baseline. The monthly expression of intensity of occurrence allowed for evaluation of the distribution of habitat preference over the study period. For each month, the areas of highest intensity of occurrence were visually represented by a 90% polygon, with diminishing intensity described by 80% and 70% polygons for each month to express variation in spatial and temporal intensity of occurrence.

A second set of maps were created to illustrate the spatial distribution of occurrence intensity *within* a given month. For this approach, threshold values were computed for each month using only the data from that month. These "within month" exceedance thresholds highlighted important areas of habitat preference across a single month and were not influenced by the distribution observed in the other months.

2.3. SRKW BEHAVIOURAL ANALYSIS

2.3.1. Data Collection

Behavioural data was collected in JDF and the Swiftsure area by DFO during surveys from June to August in 2018 to 2020. Additional data from observational studies from Haro Strait and surrounding waters were provided by the National Oceanic and Atmospheric Administration (NOAA) and included focal follows conducted in 2006 (Noren et al. 2009; Noren and Hauser 2016), and in 2007 to 2009 (Holt et al. 2013).

2.3.2. Focal Follow Surveys

DFO behavioural sampling was conducted using a focal follow approach, where an individual (focal) animal was closely tracked to observe its activity state (Martin et al. 1993). Individual SRKW were first photographed and identified prior to behavioural sampling. As the behavioural study was focused on identification of key foraging areas, adult females with young offspring were prioritized to ensure a sufficient sample size of this segment of the population. If there were no females with offspring present or focal follow data had already been collected on the females, then individuals from other age/sex classes were sampled. Observers travelled in parallel with the animal, no closer than 100 m, and assessed the animal's behavioural state at five-minute intervals. Behaviour was categorized as: probable prey-searching, prey-capture, travel, or resting (Table 1; based on previous descriptions by Ford 1989, Noren et al. 2009, and Holt et al. 2013). The duration of a focal follow was variable, with cessation determined by: a) inclement conditions hindering observation of the focal animal (typically in Beaufort sea state 4 or above, or visibility less than 400 m); b) if the focal animal was lost to observers; c) after one hour (12 scans), if the animal was not actively foraging; or d) when the animal had been followed for more than one hour and ceased to actively forage – whichever of the above came first. While SRKW have been shown to change their foraging behaviour in the presence of vessels within 400 m (Holt et al. 2021), these changes appeared to occur at fine spatial and temporal scales and were unlikely to have biased detected regional patterns of foraging within this study.

Focal follow protocols used by NOAA in 2006 (Noren et al. 2009; Noren and Hauser 2016) were similar to those employed by DFO; however, focal individuals were selected at random, with the goal of sampling both adult males and females. Behavioural information was recorded every 10 minutes from the focal animal. Both NOAA and DFO protocols collected similar behaviour category data (forage, travel, rest, and social; Table 1). NOAA focal follows were terminated if a surfacing event was missed by the observer, if other vessels obstructed observations, or after approximately 40 minutes of continuous sampling.

2.3.3. Group Behavioural Surveys

For DFO surveys, a group behavioural survey protocol was used when sea state conditions reduced the ability to consistently locate a focal animal (generally in swell > 1 m and/or Beaufort sea state > 3 (Karniski et al. 2015)). This survey method involved transiting among a group of animals, assessing the dominant behaviour of the group as a snap-shot for that time, and then moving to the next group. Upon reaching a target group, each individual was photo-identified to confirm group membership and group size. The research vessel travelled in parallel to the target group at a distance no closer than 100 m for five minutes to assess behavioural state. Behavioural state was defined using the same ethogram as the focal follows (Table 1). The dominant behavioural state for the group was defined as the behavioural state which more than half the group was exhibiting for more than half the five-minute observation time. In the event that data took longer than five minutes to collect, for example in the case where not all individuals in the group were photographed, behaviour was assessed every five minutes until departing the group.

Groups were defined using the ‘10 meter chain rule’ (Smolker et al. 1992), where an individual is considered to be a member of a group if it is within 10 m of any other member. The exception to this definition of group membership was when individual(s) external to but within close proximity with the target group (< 100 m) exhibited coordinated behaviours with the group and were therefore included in the group’s membership. Therefore, spatially and behaviourally solitary individuals were considered their own group. To avoid bias in sampling, systematic group selection was conducted by methodically moving through the animals based on a pre-selected direction, where observers worked from the leading group to the following group, or inshore-to-offshore. In situations where two or more groups were equally eligible to be selected, selection alternated between choosing the larger or smaller of the groups.

Behavioural sampling conducted by NOAA from 2007 to 2009 (Holt et al. 2013) was with groups of whales defined by the 10 m chain rule described above. Visual behavioural data were collected concurrent to acoustic recordings from a stationary (engines off) research vessel positioned ~1 km ahead of the sampling group. Group size included all individuals within 1 km of each other, and behavioural data were recorded every 10 minutes. Behaviour of the group was assigned to one of four states (prey-pursuit, prey-searching, travelling, or resting; see table 1 for definitions), each described as probable and not definitive.

2.3.4. Behaviour Analysis

Data from all four behavioural studies (DFO focal and group behavioural studies, and NOAA focal and group behavioural studies) were analyzed independently using the same statistical approach and model structures. Initial data exploration within all four datasets used variogram analyses to assess spatial autocorrelation and bi-nominal broken-stick regression analyses to assess the extent of temporal autocorrelation. The datasets were limited to observations of two behavioural states, Travel and Forage, that comprised the binary response variable for our models (Travel=0, Forage=1). A summary of model parameters is presented in Table 2.

For each study, a space-time model with a binomial error distribution was fit to the data using the R-INLA package with the stochastic partial differential equation approach (Lindgren and Rue 2015; Lindgren et al. 2011; R Core Team 2020; Rue et al. 2009). These models contained a temporal random effect and spatial random effect to account for repeated measures and autocorrelation within the data. Continuous spatial and temporal random effects were included using Gaussian Markov Random Fields. Temporal random fields were based on a 1D mesh with knots located at a constant interval within a follow or effort-day (Table 2). Spatial random fields were built from Delauney triangulation meshes informed by the location of the study's observations as well as the bordering coastline. The two NOAA studies' geographic coverage was within an archipelago; therefore, the NOAA models were built using non-stationary (barrier) spatial fields, which recognize land features and restrict model calculations to occur around and not over these features (Bakka et al. 2016). The DFO study areas lacked such land barrier features and so the associated models were built using stationary spatial fields.

The Gaussian Markov Random Fields were then defined by using Penalized Complexity priors to account for spatial and temporal range and limit the expected magnitude of the standard deviations (Fuglstad et al. 2019).For example, the prior probability of ρ that the range of the given field was less than x minutes or kilometers, for the time and space Gaussian Markov Random Field, respectively (Table 2). A prior probability of 0.01 that the standard deviations of the fields exceeded 3 was assigned; therefore, the prior beliefs were that the fields were smooth and did not have large variation in amplitude. This ensured the model was set to have no expectation that a particular behavior would be more likely to occur anywhere in the study area.

For each space-time model, 1000 samples were generated from the approximated posterior of the fitted model over the spatial mesh, projected onto a 300 x 300 pixel field (pixel size: 0.14–0.30 km^2, depending on the dataset) using the R package inlabru (Bachl et al. 2019). Posterior frequency statistics were then computed for each pixel. To facilitate comparison among the four studies' models, polygons of areas where there was a >0.7, >0.8, and >0.9 probability that foraging or travelling were the dominant behaviours were identified using individual focal follow and group behavioural survey data.

2.4. ACOUSTIC DETECTIONS

2.4.1. Data Collection

Acoustic recordings were obtained from passive acoustic monitoring systems at three locations within SRKW CH: Swiftsure Bank, Port Renfrew and Jordan River (Table 3; Figure 1). Recorder deployment locations were selected to represent areas of SRKW habitat use, as well as those that were likely to be affected by vessel traffic transiting the shipping lanes. The distance between successive recorder locations was approximately 30 km.

The recordings were made using an Autonomous Multichannel Acoustic Recorder (AMAR, Jasco Applied Sciences G4) equipped with a GeoSpectrum Technologies M36-100 hydrophone mounted on a mooring system manufactured by Oceanetic Measurement Ltd, which positioned the hydrophone approximately 2 m from the sea floor. The system was calibrated by the manufacturer, and then again at 250 Hz prior to each redeployment. Recordings were made continuously at a sample rate of 256 kHz with 24-bit resolution and stored on internal SD memory cards as wav files; recorders were serviced regularly to ensure continuous recording (Table 4). On recovery, wav files were post-processed with custom Python scripts, modified from those used by Merchant (2015).

2.4.2. Killer Whale Detection and Identification

For each deployment, the acoustic data were stored as four- or five-minute long wav files. All wav files were first processed using the open-source software PAMGuard (Gillespie et al. 2008), equipped with a user-configured automated detector (Whistle and Moan detector; Gillespie et al. 2013). The detection algorithm searched the spectrogram for sounds with signal to noise (SNR) ratios exceeding a predetermined amplitude threshold of 5 dB within the 800 to 30000 Hz frequency band. Applying this threshold produced a two-dimensional (time~frequency) binary map of spectrogram points, which were above and below the 5 dB threshold. Points in close proximity which exceeded the threshold were then joined to form contours (i.e., what the detector recognized as a Killer Whale tonal or pulsed call). Additional “alarm” settings were used to reduce the number of false positives by configuring the detector to trigger only if a certain number of calls were heard in a given time frame (see Table 5); prior detection assessments demonstrated success in this approach to improve the detection algorithm’s precision and accuracy in detecting killer whale calls (Table 5).

Detector output consisted of the timestamps of all detections, which were then binned into their respective four- or five-minute acoustic file. Acoustic encounters appeared as clusters of wav files containing detections, interspersed with acoustic files containing no detections. A manual and aural review was conducted to first confirm killer whale call presence in a given file within the cluster, then to identify the approximate start and end times of each encounter. Given the objective of the study, not every file containing detections had to be reviewed, only what was necessary to confirm killer whale population and to determine encounter duration. Files containing detections were reviewed in either Raven Pro (Center for Conservation Bioacoustics 2014) or PAMlab-Lite (JASCO Applied Sciences 2017) sound analysis software. Killer whales were noted as present or absent in a given acoustic file, where presence was confirmed if one or more stereotyped pulsed calls were found. As identification of population is based on the presence of stereotypic calls, whistles or echolocation clicks alone were not used to confirm presence. Given the taxonomic resolution of the detector (species-level only), and the presence of multiple killer whale populations on the west coast of Canada, every encounter was manually reviewed by a second acoustician with in-depth knowledge of the stereotypic pulsed call repertoire produced by each killer whale population.

The duration of SRKW acoustic encounters was also assessed. Encounters were considered independent if calls were absent for two hours or more (Burham et al. 2016; Riera et al. 2013). This two-hour separation between encounters was based on the average killer whale travel speed of 7 km/hr, which would place the whale within audible range of the recorder for approximately 1.7 h, assuming a mean detection distance of 5.9 km for June/July at the Swiftsure recorder location (Riera et al, 2019). As the two-hour separation threshold is dependent on assumptions of both whale travel speed and detector performance, encounter durations were also assessed using a three-hour threshold to define separate encounters to evaluate the potential impact of the assumptions.

2.4.3. Estimation of Automated Detector Performance

Several metrics were used to assess automated detector performance on a file-by-file basis, including recall (R; Eq. 1), precision (P; Eq. 2), and accuracy (A; Eq. 3),

$$R = \frac{TP}{TP + FN} \tag{1}$$

$$P = \frac{TP}{TP+FP} \tag{2}$$

$$A = \frac{TP+TN}{TP+TN+FP+FN} \tag{3}$$

where recall (R) describes the proportion of acoustic files with true detections that were captured by the detector, precision (P), describes the proportion of files with automated detections that were correct, and accuracy (A) describes the overall ability of the detector to correctly identify killer whales when they are present, and when they are not. True positives (TP) refer to the number of files in which the detector correctly identified killer whales; false positives (FP) refer to the number of files in which the detector falsely identified killer whales; true negatives (TN) were files in which the detector correctly identified killer whale as being absent (no vocalization), and false negatives (FN) were files in which the detector missed killer whale vocalizations. During the process of manually reviewing files to assess acoustic encounter duration, a proportion of files were reviewed which did not contain detections. This proportion varied with each recorder location and the number of encounters found, and was thus a non-random, unevenly distributed subset which contributed to the overall calculation of TNs and FNs. An additional small subset (1%) of data without automated detections was manually reviewed to calculate TNs and FNs. This subset consisted of a random sample of ~1% of the daily recordings (distributed relatively evenly across each day), from all three recorder locations for the entire study period. Both subsets were combined to calculate detector performance metrics.

3. RESULTS

3.1. KERNEL DENSITY MODEL

The 2009 to 2018 SRKW sightings data from OM and BCCSN were corrected for bias, resulting in a database of 36,623 sightings from the original 75,354. The Kernel Density Estimates were visualized to display the relative frequency of SRKW occurrence within the study area (Figure 9). From the P_{opp} data, the most consistent area of high occurrence for SKRW is in the waters of Haro Strait off the western side of San Juan Island.

Other areas of relatively high SRKW occurrence are the waters of Swanson Channel along the western side of North Pender Island, and in Boundary Pass along the southeastern end of Saturna Island (Figure 9). Contiguous with the area of high relative occurrence in Haro Strait, the divergence of observations suggests a relatively equal distribution of movement of animals through Active Pass to the north and Boundary Pass to the south.

3.2. SRKW OCCURRENCE MODEL

The 2009 to 2018 whale watch sightings data (n=1,906) combined with the 2009 to 2020 DFO sightings data (n=369) were incorporated into a modeling framework that provides monthly estimates of SRKW intensity of occurrence within CH. The final best model, as selected by deviance information criterion (DIC) and assessed with posterior predictive checks, included a spatial-temporal field shared across the three pods and a spatial field that was unique to L pod (Table 6). The unique spatial field accounted for specific spatial autocorrelation attributed to L pod and improved the model performance. The model was able to accurately estimate the total number of first sightings of each pod, per month (Figure 10).

A map summarizing the SRKW occurrence for 2009 to 2020 from May to October was produced by taking the exponent of the log intensity values from all model parameters across all months for each of the 1000 MCMC simulations and calculating the sightings per unit effort (time), expressed as intensity of occurrence (Figure 11). The relative intensity of occurrence of SRKW in the Salish Sea from May to October, as predicted by the model using combined WW and DFO data, was spatially dominated by the waters at the entrance to JDF and Swiftsure Bank, with a smaller area of consistently high occurrence in Haro Strait along the west side of San Juan Island. Additional areas that exhibited a high probability of occurrence of SRKW include a contiguous path from Haro Strait northward into Boundary Pass to a location at the southern end of Swanson Channel, adjacent to the bluffs along the west side of North Pender Island, as well as areas along the eastern side of the Strait of Georgia in the region of the Fraser River. A general pattern of elevated occurrence is seen along the eastern end of JDF in the waters between Jordan River and Sooke. Spatial distribution of occurrence in these areas exhibited a closer association to land masses than to central waters of the channels.

Areas of highest SRKW occurrence intensity varied monthly from May to October, but were similar regardless of whether search effort was considered across all months (Figure 12) or on a monthly basis (Figure 13). These preferred habitats included waters in the area of Swiftsure Bank, the eastern portion of Haro Strait, the mouth of the Fraser River, Active Pass, Swanson Channel near the western side of North and South Pender Island, the northern aspect of Boundary Pass along South Pender and Saturna Island (Figure 11). The SRKW Occurrence Model outputs demonstrate that the Swiftsure area has the largest spatial extent of high intensity SRKW occurrence, with a smaller region of high intensity occurrence in Haro Strait along the west side of San Juan Island. For the Swiftsure area, the probability of occurrence increased steadily from May to July, peaked in August, and then diminished into the fall. For Haro Strait, the peak in the probability of SRKW occurrence was in September, before a reduction was noted for the month of October.

3.3. BEHAVIOURAL MODEL

From 2018-2020, the DFO focal follow study collected 889 behavioural observations from 34 unique individuals over 93 follows (Table 7). The majority of DFO focal follow observations (n = 743/889) indicated Travel or Forage behaviour (Table 8; Figure 14a). During the same time period, the DFO group behavioural surveys collected 1131 behavioural observations, 821 of which were of Travel or Forage behaviour (Table 8; Figure 14b).

The vast majority of 2006 NOAA behavioural observations indicated Travel or Forage behaviour (n = 522/571;Figure 14c), with observations of Travel behaviour greatly outnumbering Forage observations (Table 8). NOAA group behavioural data from 2007-2009 typically noted Travel or Forage behaviour (n=358/373; Table 8; Figure 14d). All four datasets exhibited strong temporal and spatial autocorrelation. While the two DFO datasets exhibited similar temporal autocorrelation, with time in the range of roughly one hour, spatial autocorrelation was present in the DFO datasets at different spatial scales (Table 9). The temporal autocorrelation seen in the NOAA data was significantly longer in duration than in the DFO data (1.5 hrs and 3 hrs for 2006 and 2007-2009, respectively; Table 9). The spatial autocorrelation in the 2007-2009 NOAA data was on a similar scale to that of DFO’s group behavioural survey data. However, the spatial effect of the 2006 NOAA focal follow model was exceptionally large, at roughly 180 km.

Comparison of the DFO focal follow and group behavioural survey models suggest similar broad spatial patterns in SRKW travel and forage behaviours in the Swiftsure area and JDF. Both models predict high probability of Travel behaviour in JDF and on Swiftsure Bank, and both predict high probability of Forage behaviour off Nitinat and off the east edge of Swiftsure Bank (Figure 15a,b; Figure 16a).

Complementary spatial patterns in SRKW Travel and Forage behaviours within the Haro Strait region of the inner waters were identified using NOAA's data. While NOAA's 2006 data was unable to identify areas preferred for foraging behaviour, it indicated a high probability of Travel at and beyond the northern area of San Juan Island, which was similar to what the 2007-2009 NOAA data showed (Figure 15c,d; Figure 16b). Areas with a high probability of Forage were identified off the west and south coast of San Juan Island using NOAA's 2007-2009 data.

3.4. ACOUSTIC DETECTIONS AND ENCOUNTER DURATION

From May to October, 2018, a total of 474 cumulative days of passive acoustic monitoring data was collected from three locations within the western part of SRKW CH (Swiftsure Bank: 167 d, Port Renfrew: 125 d, Jordan River: 182 d; Table 10). Battery life elapsed earlier than anticipated (prior to periodic recorder servicing) at Swiftsure and Port Renfrew in 2018, resulting in a 17-d gap from July 30 to August 15 at Swiftsure and a 60 d gap from June 21 to August 18 at Port Renfrew. Minor technical difficulties resulted in a brief 2 d gap without recordings at Jordan River from June 7 to 8th, 2018. From May to October, 2019, a total of 552 cumulative days of passive acoustic monitoring data were collected from Swiftsure Bank (184 d), Port Renfrew (184 d) and Jordan River (184 d), with no gaps in recordings (Table 10).

In 2018, 27% of the acoustic files contained automated detections at Swiftsure, 2.1% at Port Renfrew, and 2.4% at Jordan River. Of the files with detections at Swiftsure, 17.4% (n=2507) were manually reviewed to validate SRKW presence, 34.6% (n=295) at Port Renfrew, and 57% (n=798) at Jordan River. In 2019, 6.3% of the acoustic files contained detections at Swiftsure Bank, 2.0% at Port Renfrew, and 2.1% at Jordan River. Of these files with detections, 35.4% (n=1484) were manually reviewed at Swiftsure, 31.1% (n=421) at Port Renfrew, and 51.3% (n=697) at Jordan River.

In 2018, SRKW were acoustically detected at Swiftsure on 47.3% of recording days (79/167), at Port Renfrew on 48.8% (61/125), and at Jordan River on 30.2% of recording days (55/182). In 2019, SRKW were acoustically detected at Swiftsure on 33.2% of recording days (61/184), at Port Renfrew on 30.4% (56/184) of recording days, and at Jordan River for 14.7% of the recording days (27/184). The percentage of days with SRKW detections was low at all locations in May 2018 and 2019 (< 7%), and progressively increased to a peak in August both at Swiftsure (93.8% in 2018 and 80.7% in 2019) and Port Renfrew (77.0% in 2018 and 71.0% in 2019). Peak SRKW presence occurred in October at Jordan River in 2018 (58.1% of recordings days), whereas it was considerably lower in October 2019 (32.3%). Presence at Port Renfrew and Jordan River was lower in all months in 2019 compared to 2018; however, this comparison is affected by the absence of recorder effort in July 2018 at Port Renfrew (Table 11; Figure 17).

Over the two-year period for all sites combined, there were a total of 507 encounters with killer whales of which 481 were positively identified to killer whale population, and 414 (86.1%) included SRKW. Swiftsure had the highest number of SRKW encounters (93 in 2018; 86 in 2019) followed by Port Renfrew (74 and 75) and Jordan River (59 and 27). The number of encounters per month and year at each location is shown in Table 11 and Figure 17.

Overall mean (median) ± standard deviation (SD) duration (h) of SRKW encounters in 2018 was 6.35 (5.0) ± 4.8 h at Swiftsure, 2.8 (2.2) ± 2.2 h at Port Renfrew, and 2.5 (2.1) ± 1.7 h at Jordan River. In 2019, SRKW encounter durations decreased to 3.1 (2.1) ± 3.1 h at Swiftsure, increased slightly to 3.4 (2.3) ± 3.0 h at Port Renfrew and remained relatively stable at Jordan River, 2.8 (2.2) ± 1.9 h. Mean (median) ± SD time periods between consecutive SRKW encounters were 39.5 (14.2) ± 105.3 h at Swiftsure, 34.1 (17.2) ± 50.3 h at Port Renfrew, and 92.7 (46.4) ± 182.7 h at Jordan River. Monthly variations in encounter duration for each site and year are shown in Table 11 and Figure 18. The effect of using a 3 h threshold (without killer whale call heard) to define separate encounters instead of the 2 h threshold had no significant effect on the total number of SRKW encounters or the mean encounter duration for each year-site-month combination (Pearson's Chi-squared tests, all *p*-values > 0.05).

Detector performance were as follows for the three recording sites of Swiftsure, Port Renfrew, and Jordan River: recall rate (the proportion of true detections (files) that were captured by the automated detector) was 0.58, 0.61 and 0.30, respectively; precision (the proportion of automated detections (files) that were correct) was 0.23, 0.49, and 0.23; accuracy (the proportion of true positives and true negatives, combined) was 0.56, 0.66 and 0.53. A high percentage of files contained false positives (Swiftsure: 77%, Port Renfrew 51%, Jordan River 77%), triggered mainly from vessel noise and humpback whale vocalizations. Given the lower-than-expected recall, a sensitivity test was performed by randomly excluding 50% of the daily acoustic files and re-calculating monthly killer whale presence for each site. This sensitivity test resulted in differences of less than 4% for monthly killer whale presence across all years and sites, suggesting that findings at the resolution presented here (daily scale) were robust against suboptimal detector performance, as well as variable performance across sites and months. Lower recall rates at Jordan River implied that a higher proportion of files containing killer whale calls were missed by the detector compared to the other two sites. However, lower acoustic presence of killer whales at Jordan River was supported by the visual survey data. Acoustic detections represent minimum estimates of monthly SRKW presence and encounter durations at each location (Figures 17-19).

4. DISCUSSION

Understanding SRKW patterns of occurrence and habitat use in CH is an essential component in the path to survival and recovery of this endangered population. As the spatial extent of CH is large, the ability to focus mitigation in areas of high occurrence will result in greater efficacy of actions and have a higher likelihood of success. Models of habitat preference were used here to describe the animal-habitat relationship and to provide a means of predicting SRKW differential space use.

Using a novel statistical approach to address preferential sampling bias and collate disparate datasets, the expression of relative SRKW occurrence over a much broader geographic scope was possible. The SRKW Occurrence Model outputs demonstrated that the Swiftsure area has the largest spatial extent of high intensity SRKW occurrence, with a smaller region of high intensity occurrence in Haro Strait along the west side of San Juan Island. While the waters to the west of JDF were known to be important habitat for the population (Ford et al. 2017), the majority of published works on SRKW presence, distribution patterns, and habitat use have been undertaken in or in close proximity to Haro Strait (Hauser et al. 2007; Seely et al. 2017; Olson et al. 2018; Larson et al. 2018). An additional location that exhibited a high probability of occurrence is the region of the Fraser River delta. For most locations, with the notable exception of the Swiftsure area, the pattern of high intensity occurrence favoured waters closer to landmasses than to central passages in waterways.

It is important to note that these model outputs provide a measure of the *relative probability* of occurrence within the study area. The concept of habitat preference, or the disproportional use of an area when compared to the overall available habitat (Hall et al. 1997; Beyer et al. 2010) provides information on important areas that are assumed to influence fitness. For the SRKW data presented here, the intensity of occurrence polygons may be interpreted as the areas of preferred habitat within CH and over various time frames. The average annual SRKW frequency of occurrence map (Figure 11) provides a spatial overview of the probability of SRKW presence in CH and represents the population's general habitat preference and distribution during summer (May to October) over the entire study period (2009–2020).

The variation in SRKW intensity of occurrence across the summer months (Figure 12) demonstrates both temporal and spatial habitat preference, with peak intensity of occurrence in August and spatial distribution favouring Swiftsure and Haro Strait. The monthly variation in occurrence aligns with the general hypothesis that SRKW summer occupancy coincides with Fraser River salmon spawning runs to their natal rivers and streams (Groot et al. 1984, Healey and Groot. 1987). For the months of September and October, the data indicate a decreased intensity of occurrence in the Swiftsure area with a less profound decrease in Haro Strait when compared to the August peak. This pattern of occurrence aligns with the fall Chum Salmon runs (*Oncorhynchus keta*) in Puget Sound, which increase in prevalence in the SRKW diet in October (Hanson et al. 2010; 2021) and coincides with decreased SRKW occurrence around the Fraser River and Swiftsure Bank.

The "within month" analysis provides an estimate of the distribution of intensity of occurrence that occurred each month (Figure 13), and represents the SRKW habitat preference for each of the six months of the study. These individual monthly intensity polygons are not influenced by the intensity of occurrence in other months, and provide greater spatial resolution over a shorter time frame. As a result, the intensity of occurrence polygons tend to be larger, specifically for the shoulder months (e.g. May, October). These intra-month occurrence predictions provide an added level of detail when considering management actions that are temporally limited (e.g., decisions on the location of a fishing opening within a month or locations of short term measures on vessel activity).

It is of interest to note that the majority of high intensity occurrence polygons are located in close proximity to areas of high vessel traffic (both commercial vessel traffic along the shipping lanes and recreational vessel transits from adjacent ports and marinas). While SRKW are known to be affected by physical and acoustic disturbance (Bain et al. 2006; Holt et al. 2009, 2011, 2015, 2021; Houghton et al. 2015; Lusseau et al. 2009; Tyack 2008; Williams et al. 2009), our data do not indicate displacement from these locations. The enduring presence of SRKW in areas of elevated vessel traffic should not necessarily be taken as evidence of tolerance of, or acclimation to disturbance, but instead as a measure of the vital importance of these locations to the needs of the population.

A previous fine-scale analysis of SRKW summer occurrence in the Salish Sea was conducted using the P_{opp} data and documented SRKW presence from 1976 to 2014 (Olson et al. 2018). The data were fit to a Kernel Density model and effort-corrected using an estimated observer effort grid (Rechsteiner et al. 2013). While the SRKW Occurrence Model has significant advantages over the Kernel Density approach used by Olsen et al. (2018), the effort correction mesh used in the SRKW Occurrence Model is dependent on the consistent and continuous efforts of ecotourism operators. With the implementation of increased approach distance regulations for SRKW, directed effort to locate and sight SRKW has changed, and reported sightings have diminished. Future effort-correction models may have to focus on observer groups that are not affected by approach distance regulations, such as shore-based sightings, crew of large marine vessels, or coastal workers. A comparison of outputs from the two models was undertaken to assess the robustness of effort estimates used for various observer groups in the Kernel Density model.

When the outputs from the 2009-2018 P_{opp} Kernel Density analysis (Figure 9) and the WW and DFO combined data SRKW Occurrence Model analysis (Figure 11) are compared, the SRKW relative occurrence is higher in the areas adjacent to North Pender Island (Swanson Channel) and Saturna Island (Boundary Pass) in the P_{opp} analysis. While the effort grid applied to both the BCCSN and OM data was developed from the estimated observer effort by category and then weighted by the relative contribution of each category (after Rechsteiner et al. 2013), the high observer effort in the areas noted above was not fully captured in the estimates of effort. For example, The Whale Trail, a non-profit organization based in Seattle, WA, that promotes and facilitates citizen sightings, has five shore-based viewing locations on North and South Pender Island overlooking Swanson Channel, and also has a shore-based viewing location on Saturna Island. In addition, the Saturna Island Research and Education Society (SIMRES), a community-based non-profit organization that supports SRKW research, has recently launched its own Saturna Sighting Network. If observer effort in these areas is underrepresented in the effort grid, the density of whales in those areas would be elevated in the resulting occurrence map.

The effort estimates used in the analysis of the WW and DFO combined data was derived using a stochastic emulator of the cumulative boat hours and provided high temporal resolution of sightings effort. The difference between the relative densities of Swanson Channel and Boundary Pass were therefore likely due to the higher precision and incorporation of uncertainty in the evaluation of effort for the WW and DFO combined data analysis. This is an important observation, as a number of management actions to protect SRKW were implemented in these areas, and a higher degree of precision in the identification of SRKW occurrence will aid in refining the location for future mitigation efforts.

Uncertainties also exist in the P_{opp} effort grid's ability to assess where effort may be lower than expected. Categories of P_{opp} observer effort include residents of population centers (Rechsteiner et al. 2013). The area in the vicinity of the Fraser River lies within the cost-distance analysis category of the city of Vancouver, and was assigned a moderate level of effort in the estimated effort analysis. The expansive delta and sand bars near the arms of the Fraser River, and the tidal bore that occurs at the river mouth create less than ideal recreational boating conditions, and result in uneven distribution of effort around the population center. However, fishing effort near the mouth of the Fraser River is high, with variability in presence related to the timing of various fishing openings and salmon runs. While vessel presence in the vicinity of the Fraser River may be high, the recreational fishing sector is underrepresented in the sightings databases. The combination of assumed high effort with low reporting of sightings in the P_{opp} data analysis was reflected in the occurrence data (Figure 9), which showed a lower relative occurrence than what was depicted from the combined WW and DFO data analysis (Figure 11). Exploration of improved effort-correction methodologies for non-directed opportunistic sightings data may be necessary to support the use of platform of opportunity data for future years.

Behavioural state analysis

While SRKW relative occurrence data provides information on habitat preference, an understanding of how the population uses the habitat is required to identify the function which it serves. This study combined SRKW behaviour data from previous publications with the results of new surveys to assess habitat use in CH, with a focus on identifying areas that support foraging behaviour.

Behavioural data from the western part of SRKW CH showed multiple areas of high foraging probability along the bathymetric contours that descend from the shallows of Swiftsure Bank. The combination of deep water adjacent to steep walls aligns with previous observations of habitat associated with SRKW foraging behaviour (Heimlich-Boran 1988; Jacobsen 1990; Nichol and Shackleton 1996; Ford et al. 1998). Predation events in the area as reported by Ford et al. (2017) occurred in waters with depths averaging 89 m, with over 80% of the Chinook being of Fraser River origin. Chinook are found at greater depths than other salmon species in the area, and occupy a position in the water column that is farther from the surface and closer to the bottom (Smith et al. 2015; Riddell et al. 2018). The shelf is cut by several deep canyons, which create upwelling of cold nutrient-rich water. The presence of the shallow bank in the path of the constant ebb and flow of tides at the entrance to JDF condenses the stratified ocean environment that normally distributes in a depth column of 2-300 m, and forces the biomass up and onto Swiftsure Bank, creating a large pool of colder surface water and an area of high productivity (Burger, 2003). These features likely provide a foraging advantage to SRKW, and support access to the incoming salmon bound for their natal rivers and streams (Ford et al. 2010; Hanson et al. 2010).

In JDF, the predominant behaviour is travel. The movements of individuals in JDF were directional and parallel to the shore, suggesting that the waters of JDF are primarily used for transit between key foraging areas. The JDF is identified as CH in both Canadian and US waters, and is bisected by the shipping lanes. As impacts from vessel traffic is a threat to recovery of the SRKW population, these waters are of interest and warrant further investigation. Future analyses of SRKW movements and behaviour in relation to tide, currents and other oceanographic parameters will further inform the understanding of habitat use in the area.

Findings from the analysis of the NOAA behavioural datasets collected in the eastern part of SRKW CH corroborate previous work demonstrating that foraging is the dominant behavior in the waters to the south and west of San Juan Island. In addition to associating with deeper waters, Chinook also tend to move in main current areas and orient along axes of tidal currents, which would also favour water adjacent to the east side of Haro Strait. The pattern of a relatively flat ocean floor rising rapidly to form a wall along San Juan Island is observed in a number of foraging areas, and likely provides some advantage during pursuit (Wright et al. 2017; Jacobsen 1990; Nichol and Shackleton 1996). The reduced benthic rugosity and the high relief along the island with deep nearshore areas may also improve foraging success, as echolocation and prey pursuit may be impeded in areas of complex bathymetry. Investigations into SRKW occurrence and behavior with bathymetry and other covariates is currently underway.

The predominant behavior exhibited in areas to the north of Haro Strait was travel. While foraging has been frequently observed in the areas of Boundary Pass and Swanson Channel, particularly along the west side of Pender Island, a larger dataset would improve our understanding of habitat use in these areas. Further investigation into behavior at other locations of high SRKW occurrence is required to provide insight into habitat use in other areas within SRKW CH. Overall, these behavioural analyses indicate the presence of primary foraging locations (Swiftsure Bank and Haro Strait) with movement of animals travelling through JDF as they move between foraging locations or in and out of the Salish Sea.

Acoustic detections

Acoustic detection and encounter data support the conclusions from visual surveys for both occurrence and behavioral analyses. Acoustic data show SRKW were frequently present in the vicinity of Swiftsure Bank and Port Renfrew, and less so at Jordan River, which aligns with the sightings data and frequency of occurrence model outputs. Seasonal patterns in the acoustic dataset suggest lower presence in May at all recorder sites, a peak in presence in August both at Swiftsure and Port Renfrew, and a later peak at Jordan River in October. Lower SRKW detections in May align with seasonal trends in occurrence at Swiftsure Bank presented in Ford et al. (2017) and Riera et al. (2019), as well as SRKW occurrence in coastal waters from Washington to California during the winter and spring (Hanson et al. 2013, Rice et al. 2017). A later peak in SRKW acoustic presence at Jordan River could reflect more frequent forays into the inner Salish Sea following autumn Chinook salmon migrations and coinciding with the relatively high prevalence of Puget Sound chum salmon in their diet (Hanson et al. 2021). Both acoustic and visual seasonal trends in SRKW occurrence, particularly the lower occurrence in May and peak occurrence in August at Swiftsure and Port Renfrew, showed similar patterns.

Comparison of SRKW monthly presence during the summer at Swiftsure across two inter-decadal time periods (2009-2011 vs 2018-2019) confirms the frequent summertime use of the Swiftsure Bank area (Ford 2006, Ford et al. 2017, Riera et al. 2019). When comparing monthly occurrence patterns between decades, a shift in peak occurrence at Swiftsure was noted, from June/July during 2009-2011, to August in 2018-2019. Similar shifts in seasonal occurrence have been observed in recent years within the eastern part of SRKW CH, suggesting a trend towards later arrival in all parts of SRKW CH over the past decade (Olson et al. 2018, Shields et al. 2018). Further analysis of contemporary PAM data throughout SRKW CH is underway to substantiate this trend.

Acoustic encounter duration (the period of time that vocalizing SRKWs spent within audible range of the recorders) provided an additional layer of information on habitat use patterns. Acoustic encounter duration can serve as a proxy for occupancy and an indicator of habitat preference (Palmer et al. 2019). Movement patterns associated with different behaviours suggest that animals which spend extended periods of time within a given area are more likely to be foraging, resting or socializing (also referred to area-restricted movements), compared to travelling, which tends to be directional movement with shorter time spent in a given area (Kareiva and Odell 1987). Mean encounter durations were significantly higher at Swiftsure in 2018 when compared to the other two sites, and no significant difference in encounter durations between sites was found in 2019. Encounter duration also showed higher variability at Swiftsure compared to Jordan River, which suggests that waters around Jordan River (i.e. mid-JDF) are associated with a more directional movement pattern with less variation in behaviours. Higher variability in encounter duration at Swiftsure compared to Port Renfrew or Jordan River may in part be due to the variety of behaviours that occur on Swiftsure, where there is evidence of travelling, foraging and socializing (more likely for animals to remain in one location for a period of time). Longer and more variable acoustic encounters at the Swiftsure Bank recorder compared to recorders within JDF also align with the behavioural data characterizing the extent of the foraging grounds, where whales routinely move between the migratory paths of salmon returning to the Nitinat River, Fraser River, and Puget Sound. Longer acoustic encounters at Swiftsure, particularly in 2018, may also be related to prey selection and behaviour. For instance, in 2018, SRKW were observed on numerous occasions foraging in a relatively localized area near Swiftsure Bank on sablefish (*Anoplopoma fimbria;* S.J. Thornton, pers. comm). Shorter and less variable acoustic encounters at Port Renfrew and Jordan River may indicate whales were travelling through these areas as they accessed key foraging areas in Haro Strait and at Swiftsure. These acoustic findings corroborate behavioural observations and model predictions, where SRKW were frequently found in the Swiftsure area during the summer months, often exhibiting spread-out search-phase foraging movements, followed by bouts of foraging, before switching back to travelling and/or prey searching. Behavioural surveys of SRKW within the JDF, particularly east of Port Renfrew, identified travelling as the dominant behaviour, where direction of travel was either eastbound or westbound. During the summer behavioural surveys (June to August), SRKW would often transit between waters off Port Renfrew to the Swiftsure Bank area following depth contours, which presumably increased their opportunity to intercept prey.

Acoustic data provided an additional means to investigate SRKW patterns of occurrence in the western part of CH and allowed for SRKW monitoring when visual boat surveys were unfeasible (e.g. during early and late summer months, poor weather days, as well as throughout the night). The use of multiple recorders enabled broader spatial coverage of the region, and decreased the likelihood of a missed detection due to non-vocalizing whales. Although passive acoustic monitoring has some advantages over visual surveys, there are a number of limitations. Missed detections are possible, as acoustic monitoring relies on vocalizations occurring when the animal is within the range of the recorder. Vocalization rates may vary with behaviour, time of day, and number of individuals in a group, and this variability is not easily quantified. Acoustic detection rates also varies with the range of the detector, which in turn is affected by environmental conditions and ambient noise levels. While similar limits are encountered for visual surveys during conditions of poor visibility or increasing sea state, the ability to acoustically detect whales during periods of darkness and inclement weather provides a clear advantage over visual surveys for consistent long term monitoring programs.

There are also sources of uncertainty related to the processing of acoustic data for detections. In this study, only the dominant class of vocalization (pulsed calls) were used to confirm SRKW presence. If whales were only producing clicks and/or whistles, or if calls were too faint or of poor quality to confidently identify the killer whale population, they would be missed in this analysis. While the use of automated whale call detectors offered a more efficient approach over manual analysis, it added some uncertainty due to a high false positive rate, often triggered by vessel noise and humpback whale vocalizations. In addition, analyzing a small subset of data containing no automated detections revealed that the detector missed SRKW calls from a number of files, resulting in an elevated false negative rate. The effect of these false positives and false negatives on both recall and precision resulted in most sites exhibiting poor to average detector performance; however, much of the uncertainty associated with the detector performance was ameliorated by summarizing detections at the daily scale. Importantly, the daily SRKW presence at each recorder site, as well as the number of encounters and encounter durations, were all derived from manually validated acoustic files, and therefore represent minimum estimates. In this study, the recall rates were quite variable between sites, due in part to variations in ambient acoustic noise, resulting in missed calls. While considerable effort is underway in improving detector parameters, the need for manual verification of recordings remains one of the greatest limiting factors in passive acoustic monitoring.

There are additional uncertainties associated with the interpretation of encounter duration, such as periods where SRKW were not vocalizing within the range of detectability, as well as limits in the detection range of the recorder. Short encounters may signify that whales transited through an area, or that whales were present for longer periods but engaged in quiet behaviours such as resting (Ford 1989). Furthermore, longer acoustic encounters could occur if whales were spread out and travelling, where each individual whale may spend a shorter duration in the vicinity of the recorder, but as a group, the overall detection period would be extended. Encounter durations are affected by the detection range of the recorder and the rate of vocalization; however, the temporal threshold used to define separate acoustic encounters (2 h vs 3 h) did not alter the total number of encounters per month or the duration of encounters. The scale chosen to summarize SRKW detections (daily) was deemed suitable, despite inter-site differences in detector performance, as well as potential variability in SRKW detection range due to bathymetry, depth of recorder, or ambient noise conditions.

This is the first study to use passive acoustic monitoring to investigate SRKW summertime presence at multiple locations simultaneously within the western sector of their CH. Additional years of data from these deployment sites, winter data, and other deployments that have not yet been analysed will provide further insight into SRKW occurrence throughout the year. When analysed in conjunction with behavioural data, these acoustic recorders may be used to inform predictive movement models and contribute to mitigation efforts for recovery.

5. CONCLUSION

Sightings data indicate that SRKWs spend a large proportion of their time in waters of the inner Salish Sea and the Swiftsure area, which are a relatively small part of their overall range (Ford et al. 2017). The data presented here provide the best available information on relative SRKW summer frequency of occurrence in the southern Salish Sea and the Swiftsure area, and indicate occurrence is dominated by the waters in the vicinity of Swiftsure Bank, with an area of continuous high intensity occurring in Haro Strait along the west side of San Juan Island. Coastal waters near the Fraser River also feature prominently in the intensity maps, and demonstrate a steady increase in SRKW presence beginning in May and rising to a peak occurrence in September.

These analyses provide greater resolution for SRKW summer occurrence, and a shift in the current paradigm of habitat use in CH as being dominated by the waters of Haro Strait. The opportunity to combine data from disparate sources has allowed for a wider geographic scope over which to express SRKW relative occurrence, and has emphasized the importance of the Swiftsure area to the population. Comparisons of new findings to the previous modeled data of SRKW presence in the inner Salish Sea have demonstrated differences in model outcomes for SRKW presence in Boundary Pass, Swanson Channel and areas near the Fraser River. The outcomes of the behavioural surveys identified the Swiftsure area and Haro Strait as key foraging areas, and highlighted these areas as candidates for mitigation actions to protect sensitive foraging environments. Acoustic detections and encounter duration data lent further support to the relative occurrence findings and behaviour observations. The ability to evaluate spatiotemporally-aligned acoustic and visual detection datasets offered opportunities for evaluation of behaviour observed at the surface with associated vocal behaviour at depth.

The data used to support these analyses span less than a generation of SRKW existence, and represent the summer (May to October) frequency of occurrence and habitat use. The extrapolation of these findings to other time periods or for other behaviours should be undertaken with caution. Over the last decade, a change in SRKW habitat preference has been observed and is currently under investigation for understanding the factors associated with this change in habitat use. These insights into SRKW areas of importance will provide guidance for management actions and inform the direction of future research.

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8. TABLES

Table 1. Killer whale behavioural state descriptions used for the DFO behavioural studies, adapted from Ford (1989), Noren et al. (2009), and Holt et al. (2013). Note that not all cues for a given behaviour will always be observed for that behaviour state (see Noren and Hauser 2016).

Behavioural state		**Description**
Travel	Regular	Directional movement at a steady pace (2-5 knots, usually ~4 knots), shorter-duration dives (< 30 sec), often with coordination of the entire group
	Fast	Directional movement at a fast pace (6+ knots), shorter-duration dives (< 30 sec), often with coordination of the entire group; can include porpoising
Forage	Search phase	Directional movement, individuals in group spread out, longer-duration dives (> 1 minute), an overall zigzag movement pattern of the individual's path may be discernible
	Active	Active pursuit (fish chase), capture (kill) and consumption of prey; pursuit-like behaviour includes burst-swimming (sudden changes in speed and/or direction), high-arched dives, non-directional swimming, lunging at the surface, and longer-duration dives (> 1 minute).
Rest		Stationary or swimming at speeds of approximately 2 knots or less, often with respiratory synchrony and close proximity of individuals within group (tight); groups typically rest in a tight line side-by-side (‘resting line’)
Social		Interacting with other individuals or with inanimate objects (e.g. playing in kelp); can include sexual (i.e. exposed penis) and surface active behaviours (e.g. breaching, spy-hopping); often non-directional movement

Table 2. INLA model parameters for DFO focal follow (FF) and group behavioural survey (GBS) and NOAA behavioural studies analyzed using Gaussian Markov Random Fields (GMRF).

Study	**Temporal mesh**		**Spatial GMRF**	**Penalized Complexity priors**			
				Time		*Space*	
	Resolution	Replicate		Range (mins)	Probability	Range (km)	Probability
DFO FF (2018-2020)	5 min	Follow	Stationary	28	0.975	4.7	0.975
DFO GBS (2018-2020)	10 min	Date	Stationary	82	0.975	4.7	0.975
NOAA (2006)	30 min	Date	Non-stationary	169	0.975	27.5	0.975
NOAA (2007-2009)	30 min	Date	Non-stationary	158	0.975	26.5	0.975

Table 3. Periods of acoustic recording at each location and for each month of analysis. Months with data recorded without interruption are referred to as "Full"; otherwise the days of the month with recordings are indicated.

Year	Month	Swiftsure Bank	Port Renfrew	Jordan River	Sooke	Haro Strait	Boundary Pass
2018	May	Full	Full	Full	Full	Full	Full
	June	Full	1-20	1-6*, 9-30*	Full	Full	Full
	July	1-29*	None	Full	Full	Full	Full
	August	16-31*	19-31*	Full	Full	Full	Full
	September	Full	Full	Full	Full	Full	Full
	October	Full	Full	Full	Full	Full	Full
2019	May	Full	Full	Full	1-18, 31	Full	Full
	June	Full	Full	Full	Full	Full	Full
	July	Full	Full	Full	Full	Full	1-2, 18-31
	August	Full	Full	Full	1-9, 17-31	Full	Full
	September	Full	Full	Full	1-7, 10,13-15, 17-30	Full	Full
	October	Full	Full	Full	1, 18-19, 22-31	Full	Full
2020	May	None	None	14-31	None	None	12-31
	June	21-30	21-30	Full	None	None	Full
	July	Full	Full	Full	None	15-31	Full
	August	Full	Full	Full	Full	Full	Full
	September	Full	Full	Full	Full	Full	Full
	October	1-26	1-25	1-22	1-23	1-28	1-29

Table 4. Summary of acoustic data collection and analytical methods used to assess SRKW acoustic occurrence at Swiftsure Bank from 2009-2011 (Ford et al. 2017; Riera et al. 2019) and from 2018-2019 (this study) between May 1 and October 31.

Study variable	**Ford et al. 2017, Riera et al. 2019**	**This study**
Recording dates	Aug 2009 to July 2011	May to Oct 2018-2019
Data gaps	May - July 2009 Aug – Oct 2011[a]	29 July – 16 August 2018 (18 d)[b]
Mooring location	48° 31' N, 124° 56' W	48° 31' N, 124° 56' W
Acoustic recorder system	• AURAL-M2 (Autonomous Underwater Recorder for Acoustic Listening-Model 2; *Multi Électronique*) • HTI-96-MIN (High Tech) hydrophone	• AMAR G4 (Autonomous Multichannel Acoustic Recorder; *Jasco Applied Sciences*) • GeoSpectrum Technologies M36-100 hydrophone
Nominal receiver sensitivity/response	-165 dBV / μPa	-165 dBV / μPa
Mooring depth	72 m	74 m
Distance above seafloor	10 m	2 m
Sampling frequency/rate	16 kHz	256 kHz
Recording schedule[c]	One-third duty cycle • 2009-07 to 2010-03: 30-min cycle duration (9 or 10min on/20 or 21 min off) • 2010-03 to 2011-07: 15-min cycle duration (4.5min on/10.5 min off)	Continuous
Auditing methods	• First year: manual inspection of all recordings • Second year: automated detector (SONS application; *Laboratori d'Aplicacions Bioacústiques*) and manual inspection of recordings identified as containing KW vocalizations	Automated detector (PAMGuard Whistle & Moan) and manual inspection of recordings identified as containing KW vocalizations
Detector settings	SONS detector searched the 8.2 kHz frequency band	PAMGuard detector searched the 0.8-30 kHz frequency band

[a] *Recordings available but have not been analyzed*

[b] *Battery life depleted sooner than expected, resulting in a data gap*

[c] *During data exploration, acoustic data from 2018-2019 were subsampled to mimic the duty cycle recording schedule employed in the earlier dataset (2009-2011); no difference in SRKW monthly detection days was identified.*

Table 5. Parameter settings used for PAMGuard's Whistle and Moan detector for automated detection of killer whale pulsed calls.

Parameter category	Parameter	Setting
Filter	Filter type	IIR Chebyshev
	Filter response – Band pass	High pass: 600 Hz Low pass: 48000 Hz
	Filter order	4
	Pass band ripple	2.0
Fast Fourier Transform (FFT - Spectrogram)	Sample rate	250000 Hz
	FFT length	1024
	FFT hop	512 (Default – 50%)
	Window	Hann
	Frequency resolution	244.14 Hz
	Time resolution	4.10 ms
	Time step size	2.05 ms
Click removal	OFF	-
Spectral Noise Removal	OFF	-
Whistle & Moan Detector – Detection	Minimum frequency	800 Hz
	Maximum frequency	30000 Hz
	Connection type	Connect 8 (sides & diagonals)
	Minimum length	25 time slices
	Minimum total size	25 pixels
	Crossing and joining	Re-link across joins
	Maximum cross length	25 time slices
Whistle & Moan Detector – Noise & Thresholding	Median filter length	61
	Average subtraction	0.02
	Gaussian Kernel Smoothing	ON
	Thresholding	5.0 dB

Parameter category	Parameter	Setting
Alarm	Count type	Single
	Count time	6.0 s
	Amber count	2.0
	Red count	3.0
	Minimum gap	0.5 s

Table 6. The deviance information criterion (DIC) and delta DIC values of all the SRKW occurrence models tested with the model components summarized in the columns.

Model	***DIC***	***∆DIC***	***Shared Field***	***Field for L***
0	1380	6419	x	x
3	-4887	152	Spatial	Spatial
1	-4818	222	Spatial	x
2	-4967	72	Spatio-temporal	x
4	-5039	0	Spatio-temporal	Spatial

Table 7. Focal follows conducted on SRKW individuals by DFO in 2018-2020. ID represents the alphanumeric designation for the individual killer whale followed.

ID	2018	2019	2020	Total
J16	3	1	2	6
J17	2	0	0	2
J19	2	0	1	3
J22	2	1	0	3
J31	2	2	3	7
J35	1	0	0	1
J37	1	1	1	3
J39	1	0	0	1
J41	2	0	0	2
J46	0	1	0	1
J51	1	0	0	1
K12	1	1	1	3
K14	0	1	2	3
K16	0	1	2	3
K20	0	0	1	1
K22	1	1	1	3
K27	0	1	4	5
K43	0	0	1	1
L103	2	0	3	5
L22	0	1	2	3
L25	0	0	1	1
L47	0	0	1	1
L54	0	0	1	1
L55	0	0	2	2
L72	2	0	1	3
L77	1	0	2	3
L82	0	0	3	3

ID	2018	2019	2020	Total
L83	1	0	0	1
L85	0	0	1	1
L86	0	0	3	3
L88	0	0	1	1
L90	1	1	0	2
L91	2	1	3	6
L94	2	1	5	8
TOTAL	**30**	**15**	**48**	**93**

Table 8. Summary of observations for DFO focal follow (FF) and group behavioural survey (GBS) and NOAA behavioural studies.

Study	**N observations**			**Effort-days**	**Focal follows**	**Unique individuals followed**	**Summary of follows/surveys**					
							Duration (min)		N observations		Time between observations (min)	
	Total	*Travel*	*Forage*				*Mean*	*Range*	*Mean*	*Range*	*Mean*	*Range*
DFO FF (2018-20)	889	418	325	41	93	34	53	5-120	9.6	1-22	5.6	2-25
DFO GBS (2018-20)	1131	397	424	55	n/a	n/a	112	5-538	7.0	1-104	8.7	1-108
NOAA (2006)	571	402	120	38	123	33*	46.8	5-241	4.2	1-12	17.5	3-193
NOAA (2007-09)	373	122	236	37	n/a	n/a	199	5-447	9.7	1-20	22.8	1-167

* This represents a minimum count, as six unidentified individuals were observed in the 2006 NOAA study.

Table 9. Summary of spatial (km) and temporal (min) autocorrelation within the DFO focal follow (FF) and group behavioural survey (GBS) and NOAA behavioural studies, as indicated by the Gaussian Markov Random Fields (GMRF) behavioural model hyperparameters from prior distribution.

Study	GMRF	Mean	SD	0.025 quantile	Median	0.975 quantile	Mode
DFO FF	Time	60.7	14.7	37.8	58.7	95.1	54.7
	Space	14.0	6.8	5.4	12.5	31.5	10.1
DFO GBS	Time	57.8	13.2	36.9	56.0	88.5	52.5
	Space	7.0	3.2	2.5	6.5	14.8	5.4
NOAA (2006)	Time	88.0	47.7	24.3	78.9	206.0	59.4
	Space	179.5	1.7	65.1	176.7	532.7	166.8
NOAA (2007-09)	Time	179.2	41.1	111.8	174.7	272.5	166.1
	Space	19.6	2.7	3.1	19.2	143.4	17.6

Table 10. Summary of the number of days per month with SRKW acoustic detections, the number of effort (or monitoring) days per month, and the percentage of detection days per month at Swiftsure Bank from 2009 to 2011 and 2018 to 2019. Data from 2009-2011 are courtesy of DFO's Cetacean Research Program (Ford et al. 2017; Riera et al. 2019).

Year	Month	# effort days	# detection days	% detection days
2009	Aug	31	11	35.5
2009	Sep	30	9	30.0
2009	Oct	31	5	16.1
2010	May	31	9	29.0
2010	Jun	30	19	63.3
2010	Jul	31	14	45.2
2010	Aug	31	10	32.3
2010	Sep	30	6	20.0
2010	Oct	31	7	22.6
2011	May	16	5	31.3
2011	Jun	30	17	56.7
2011	Jul	31	21	67.7
2018	May	31	1	3.2
2018	Jun	30	9	30.0
2018	Jul	29	19	65.5
2018	Aug	16	15	93.8
2018	Sep	30	13	43.3
2018	Oct	31	21	67.7
2019	May	31	1	3.2
2019	Jun	30	1	3.3
2019	Jul	31	12	38.7
2019	Aug	31	25	80.7
2019	Sep	30	15	50.0
2019	Oct	31	7	22.6

Table 11. Monthly Southern Resident Killer Whale acoustic detection (det.) days, number of encounters (enc.) and encounter duration (dur.) in hours (mean and SD) for three locations (Swiftsure, Jordan River, Port Renfrew) from May to October in 2018 and 2019.

Site	Year	Month	# effort days	# det. days	% det. days	# enc.	Mean dur. (h)	SD dur. (h)
SWIFTSURE	2018	May	31	1	3.2	1	3.5	-
SWIFTSURE	2018	Jun	30	9	30.0	10	5.8	3.8
SWIFTSURE	2018	Jul	29	19	65.5	20	6.6	5.0
SWIFTSURE	2018	Aug	16	15	93.8	27	8.2	5.6
SWIFTSURE	2018	Sep	30	13	43.3	16	3.6	2.1
SWIFTSURE	2018	Oct	31	21	67.7	17	5.9	4.7
PORT RENFREW	2018	May	31	2	6.5	2	3.1	3.5
PORT RENFREW	2018	Jun	20	7	35.0	7	3.1	3.4
PORT RENFREW	2018	Jul	0	-	-	-	-	-
PORT RENFREW	2018	Aug	13	10	76.9	13	3.7	2.7
PORT RENFREW	2018	Sep	30	20	66.7	28	2.2	1.9
PORT RENFREW	2018	Oct	31	21	67.7	23	2.8	1.7
JORDAN RIVER	2018	May	31	1	3.2	1	1.6	-
JORDAN RIVER	2018	Jun	28	7	25.0	8	2.9	0.9
JORDAN RIVER	2018	Jul	31	9	29.0	9	1.9	1.8
JORDAN RIVER	2018	Aug	31	12	38.7	10	2.8	2.1
JORDAN RIVER	2018	Sep	30	8	26.7	7	2.9	1.7
JORDAN RIVER	2018	Oct	31	18	58.1	24	2.4	1.7
SWIFTSURE	2019	May	31	1	3.2	1	0.1	-
SWIFTSURE	2019	Jun	30	1	3.3	1	2.3	-
SWIFTSURE	2019	Jul	31	12	38.7	13	3.1	2.3
SWIFTSURE	2019	Aug	31	25	80.7	37	4.2	3.9
SWIFTSURE	2019	Sep	30	15	50.0	24	2.1	1.8

Site	Year	Month	# effort days	# det. days	% det. days	# enc.	Mean dur. (h)	SD dur. (h)
SWIFTSURE	2019	Oct	31	7	22.6	10	2.0	1.3
PORT RENFREW	2019	May	31	0	0.0	0	-	-
PORT RENFREW	2019	Jun	30	0	0.0	0	-	-
PORT RENFREW	2019	Jul	31	9	29.0	8	3.1	3.1
PORT RENFREW	2019	Aug	31	22	71.0	35	3.3	2.7
PORT RENFREW	2019	Sep	30	17	56.7	21	4.2	3.8
PORT RENFREW	2019	Oct	31	8	25.8	11	2.1	1.8
JORDAN RIVER	2019	May	31	1	3.2	1	2.1	-
JORDAN RIVER	2019	Jun	30	0	0.0	0	-	-
JORDAN RIVER	2019	Jul	31	2	6.5	2	1.9	0.7
JORDAN RIVER	2019	Aug	31	6	19.4	6	2.8	1.9
JORDAN RIVER	2019	Sep	30	8	26.7	10	2.4	1.7

9. FIGURES

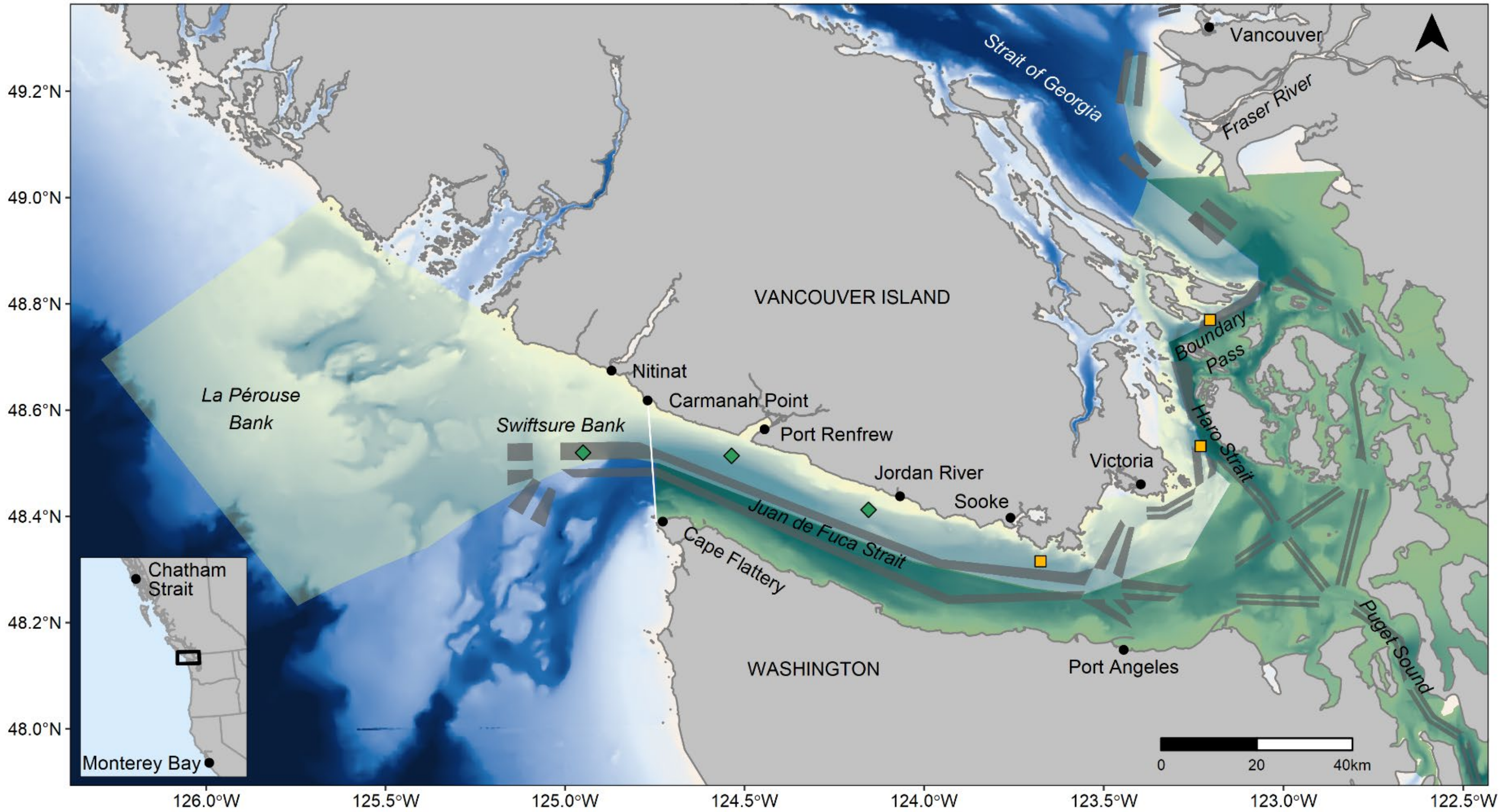

Figure 1. The waters around southern Vancouver Island, British Columbia. The shaded areas delineate SRKW CH in Canadian (yellow) and US (green) waters. Shipping lanes are indicated in grey. Green diamonds indicate locations of acoustic recorder deployments used in this study; yellow squares indicate locations of recorders where analyses are pending. The white line indicates the western boundary of the Salish Sea; waters to the east of Sooke are referred to as the 'inner Salish Sea' throughout this document. The waters west of the white line are referred to as the 'Swiftsure area'.

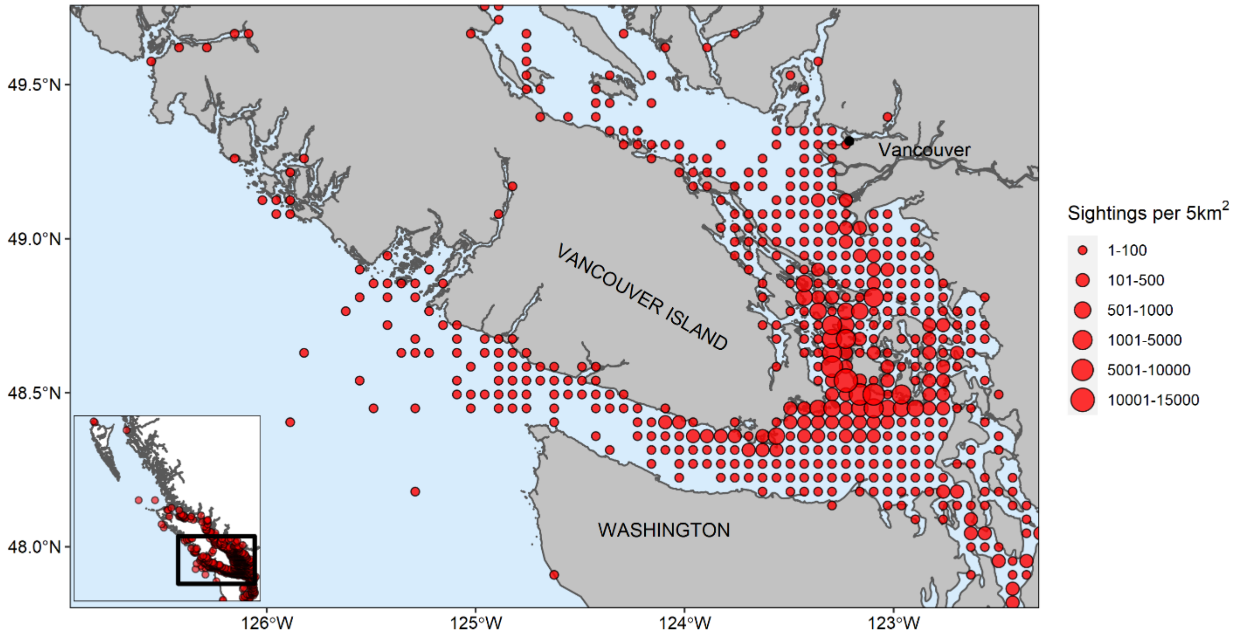

Figure 2. Distribution of sightings and encounters with SRKW (n = 79,231), from Ford et al. (2017). Data sources include DFO Cetacean Research Program encounters (1973-2014), BC Cetacean Sightings Network sightings (2000-2015), and OrcaMaster sightings (1990-2015). Inset map does not include encounters in southeastern Alaska, or encounters south of Washington State.

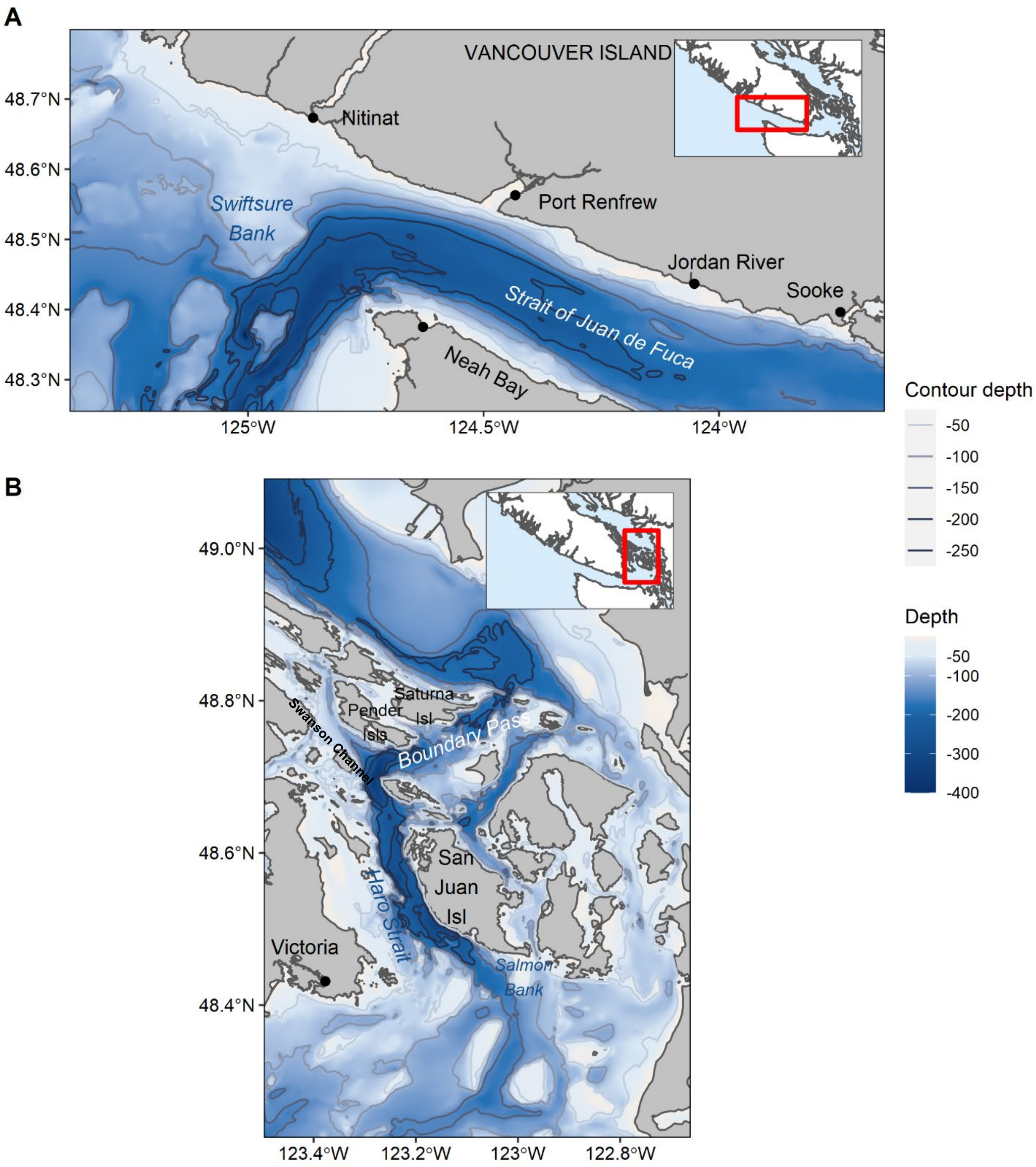

Figure 3. Bathymetric details for the Swiftsure area and portions of the inner Salish Sea.

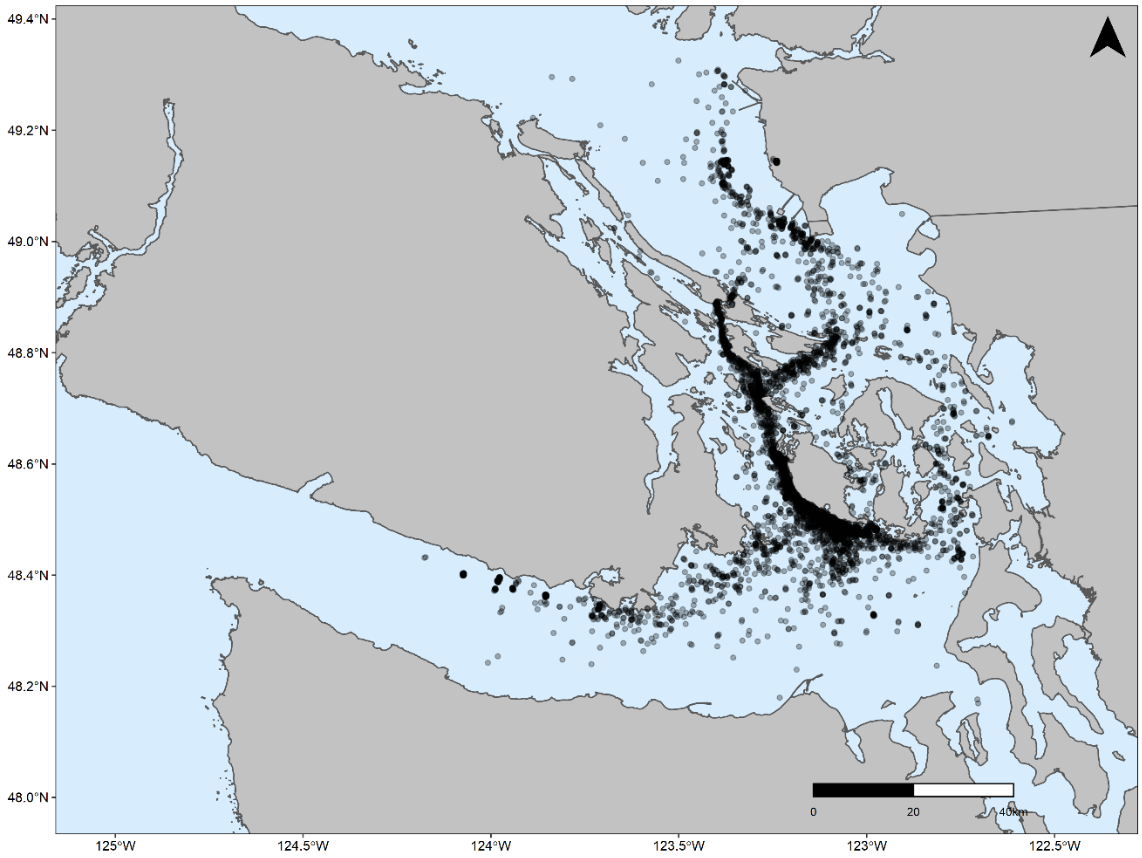

Figure 4. Location of sightings reports from the Whale Watch observer category extracted from the BC Cetacean Sightings Network and OrcaMaster databases from May to October, 2009 to 2018 (duplicates removed). Grey circles indicate sightings; locations with overlapping sightings appear black in the figure.

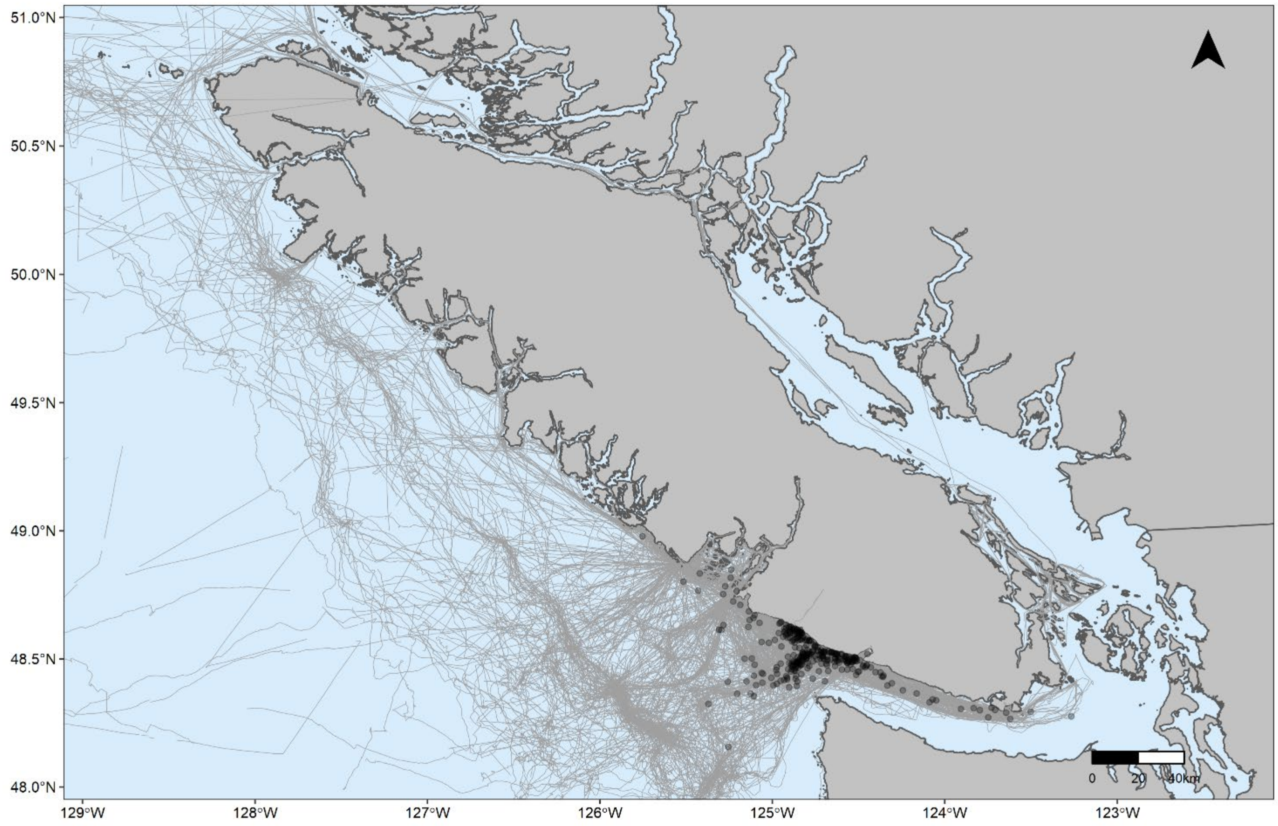

Figure 5. DFO sightings data uncorrected for effort (grey lines) in May to October, 2009–2020. SRKW encounters (grey filled circles) are defined as the positive identification of member(s) of the SRKW population at a single location on a given day. Locations with overlapping encounters appear black in the figure.

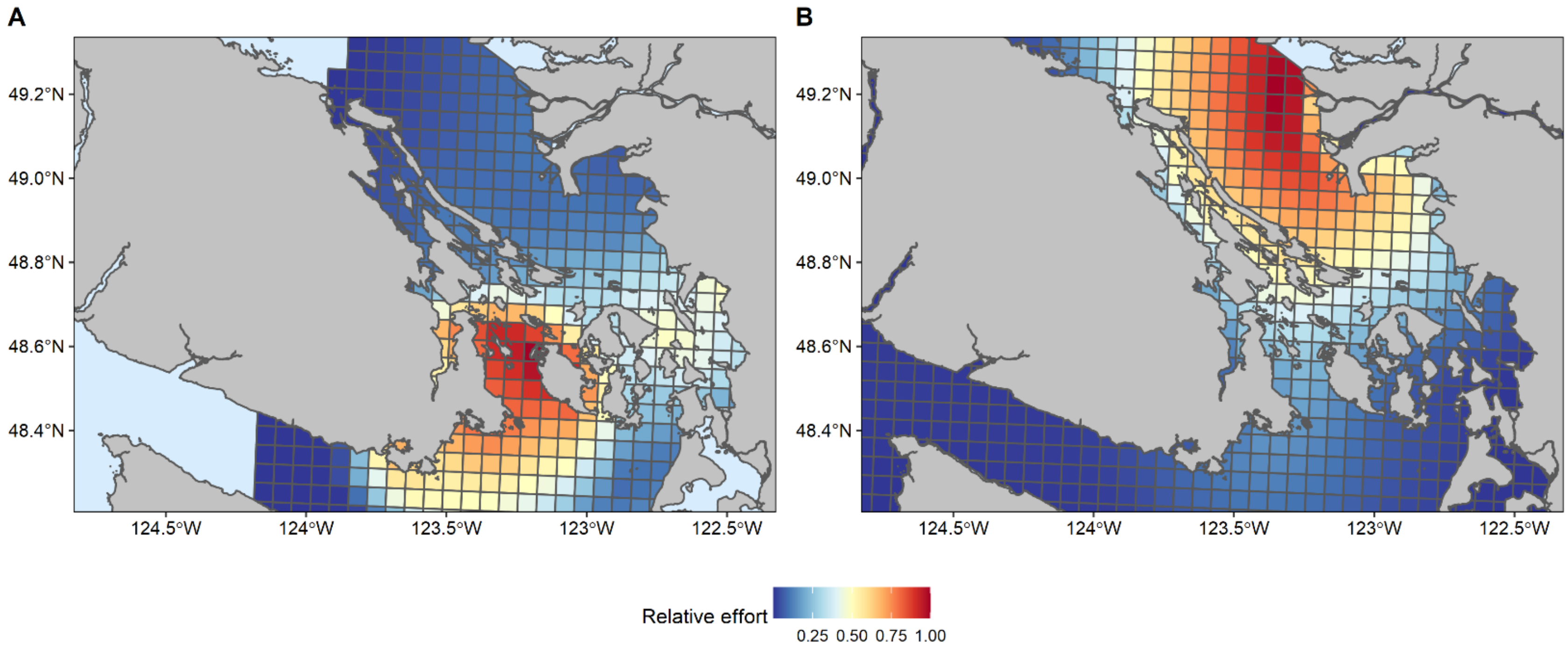

Figure 6. Effort grid (25 km^2) for OrcaMaster (left) and BC Cetacean Sightings Network (right) used in the platform of opportunity data analysis. Grids were developed by reconstructing and combining the distribution of effort for seven observer groups to generate a total value of effort for each grid cell as described in Rechsteiner et al. (2013).

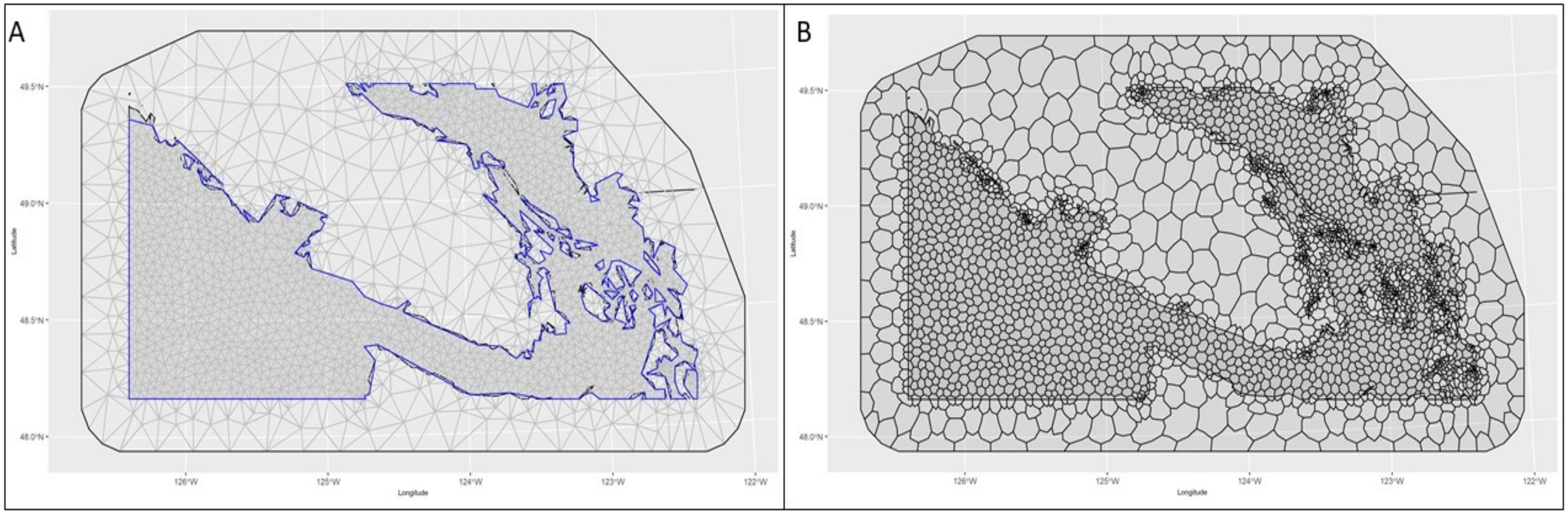

Figure 7. A) Computational mesh and B) and the corresponding dual mesh, formed by constructing Voronoi polygons around the mesh vertices. The Voronoi polygons form the integration points used to map observer effort and SRKW observations.

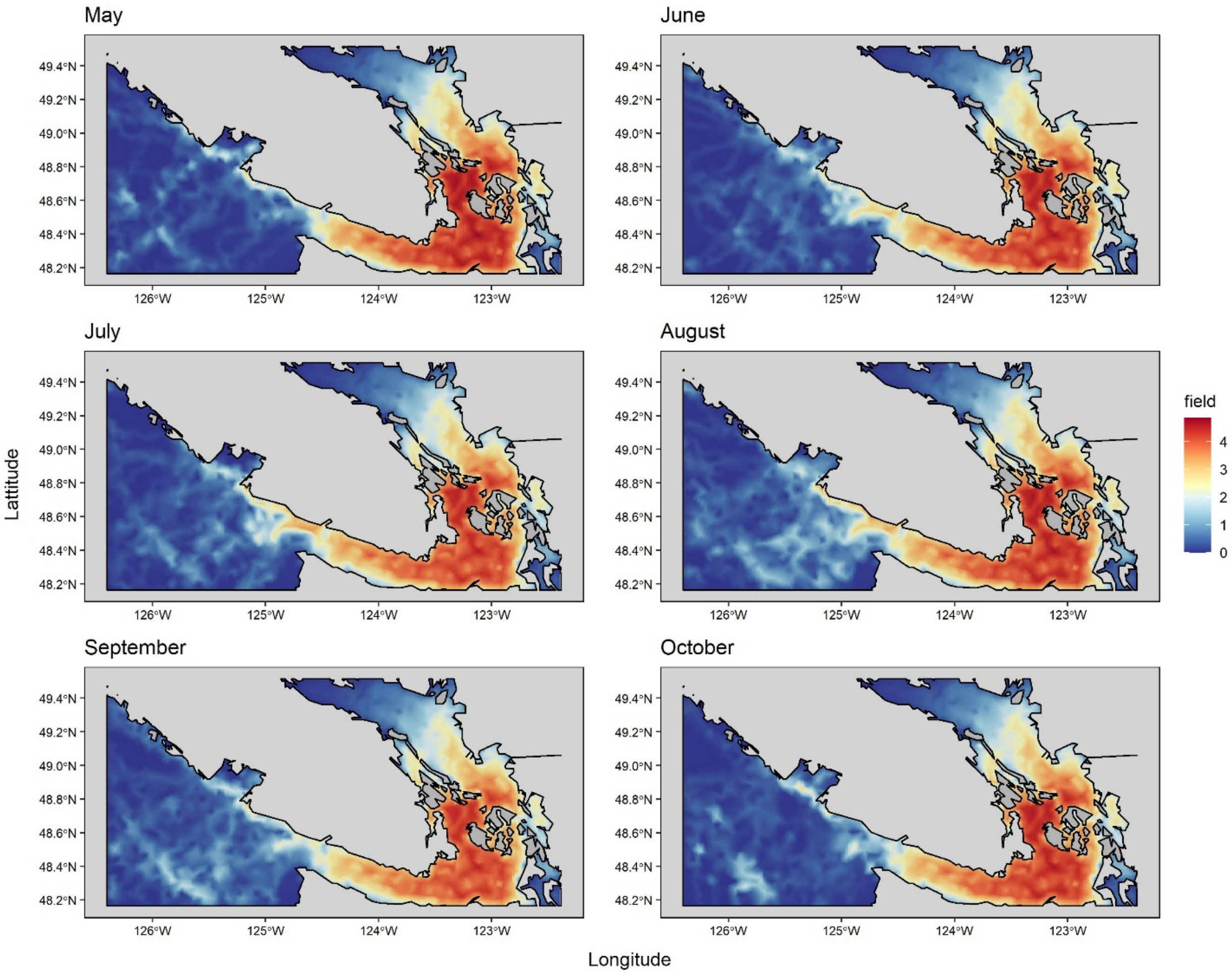

Figure 8. The log of total search effort (hrs), DFO and WW effort combined, estimated for each month and summed across all years for J pod.

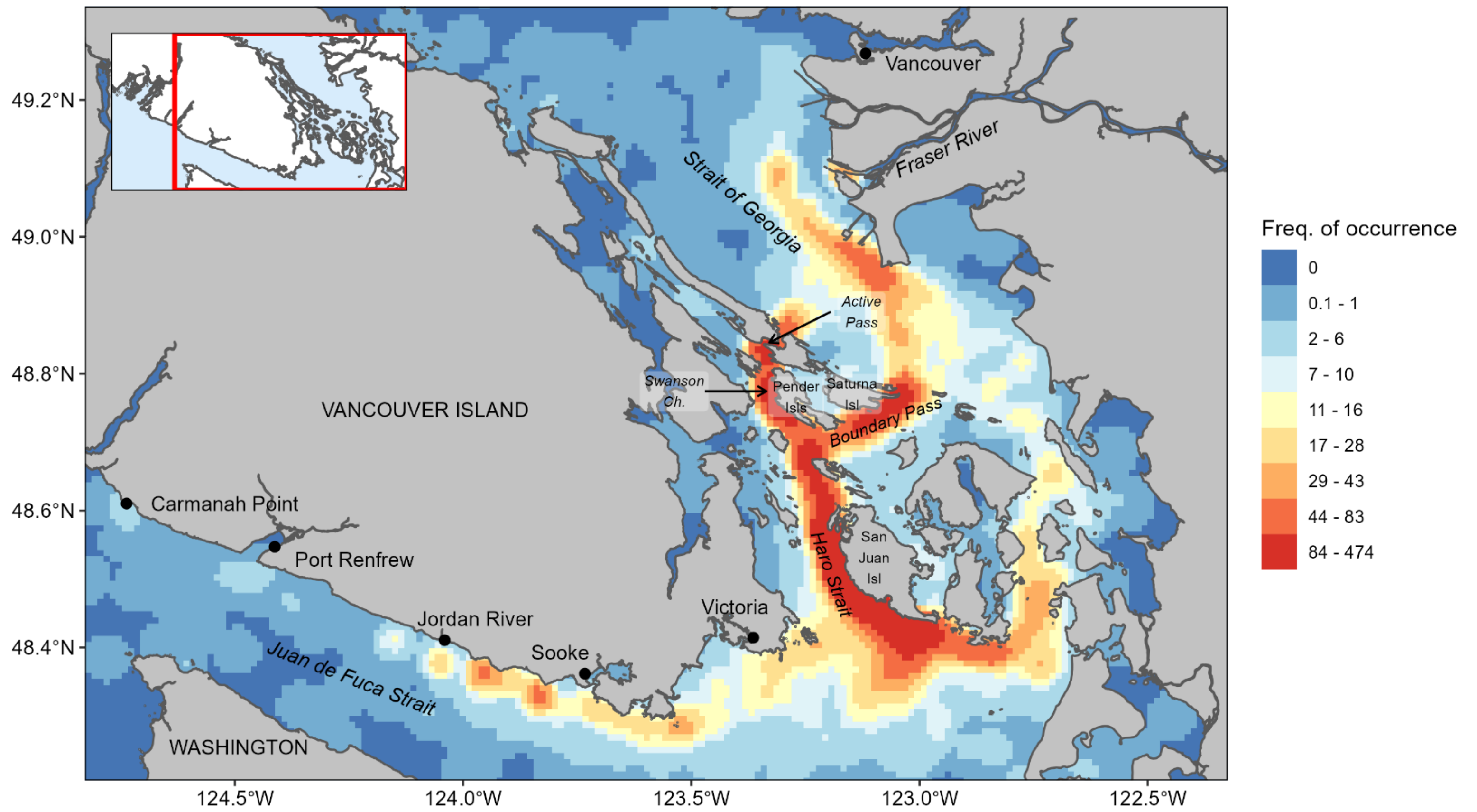

Figure 9. Annual frequency of SRKW occurrence from May to October as predicted by the 2009-2018 platform of opportunity (BC Cetacean Sightings Network/OrcaMaster) sightings fit to a Kernel Density model.

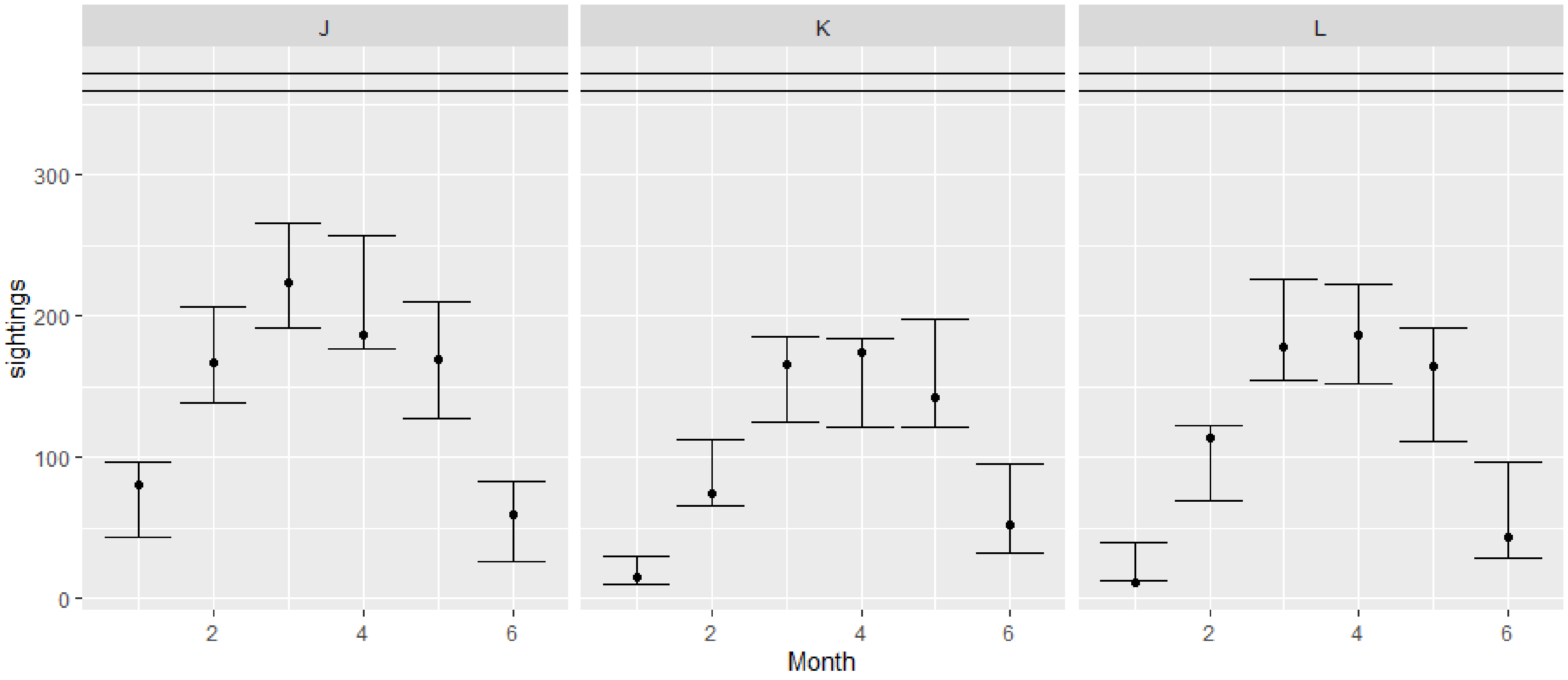

Figure 10. Model estimates of the total observed number of sightings made per month for each pod (J, K and L) with the posterior 95% credible intervals shown. The horizontal lines show the maximum possible number of sightings that could be made in months with 30 and 31 days, respectively.

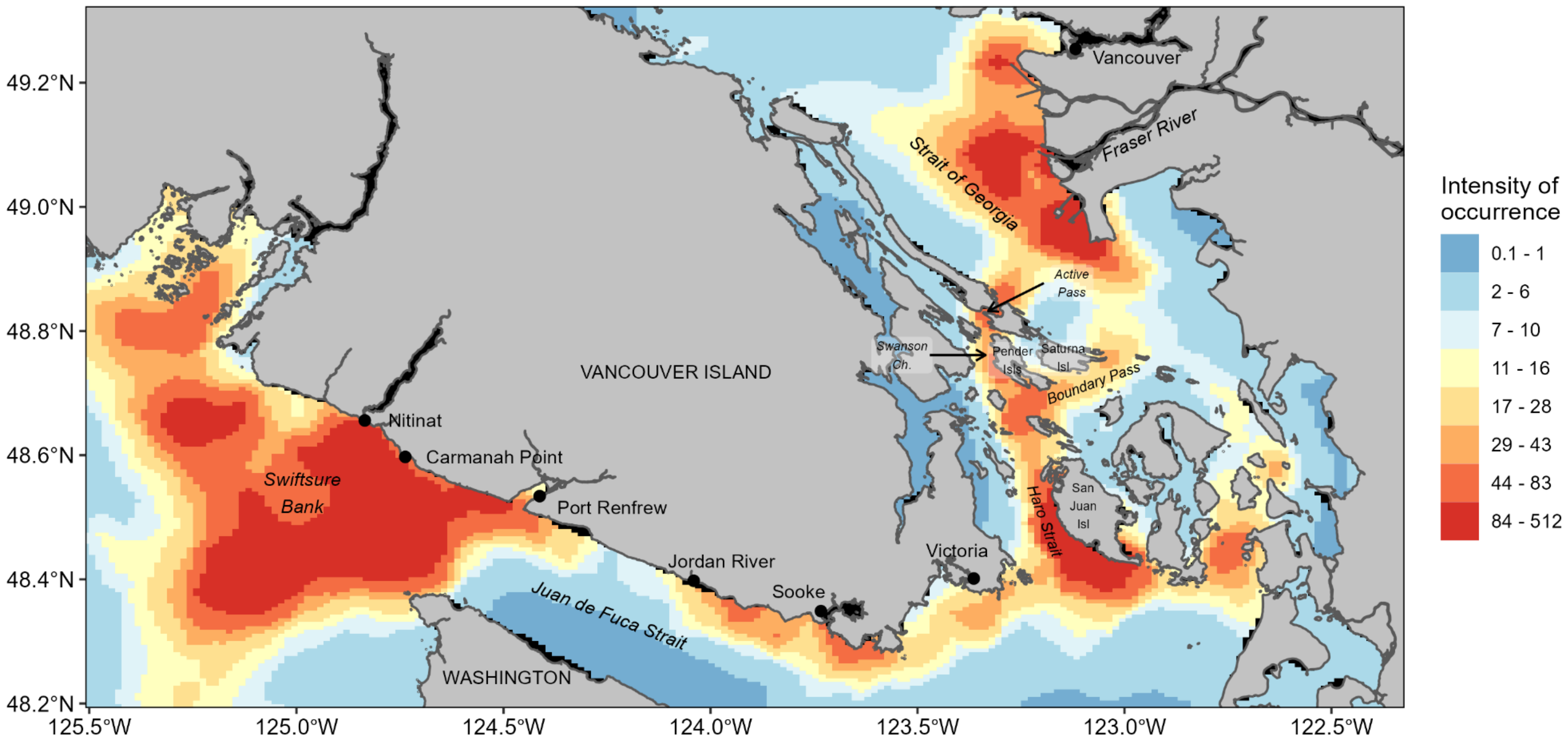

Figure 11. Annual SRKW intensity of occurrence as estimated by the SRKW occurrence model using combined WW and DFO data for May to October, 2009—2020.

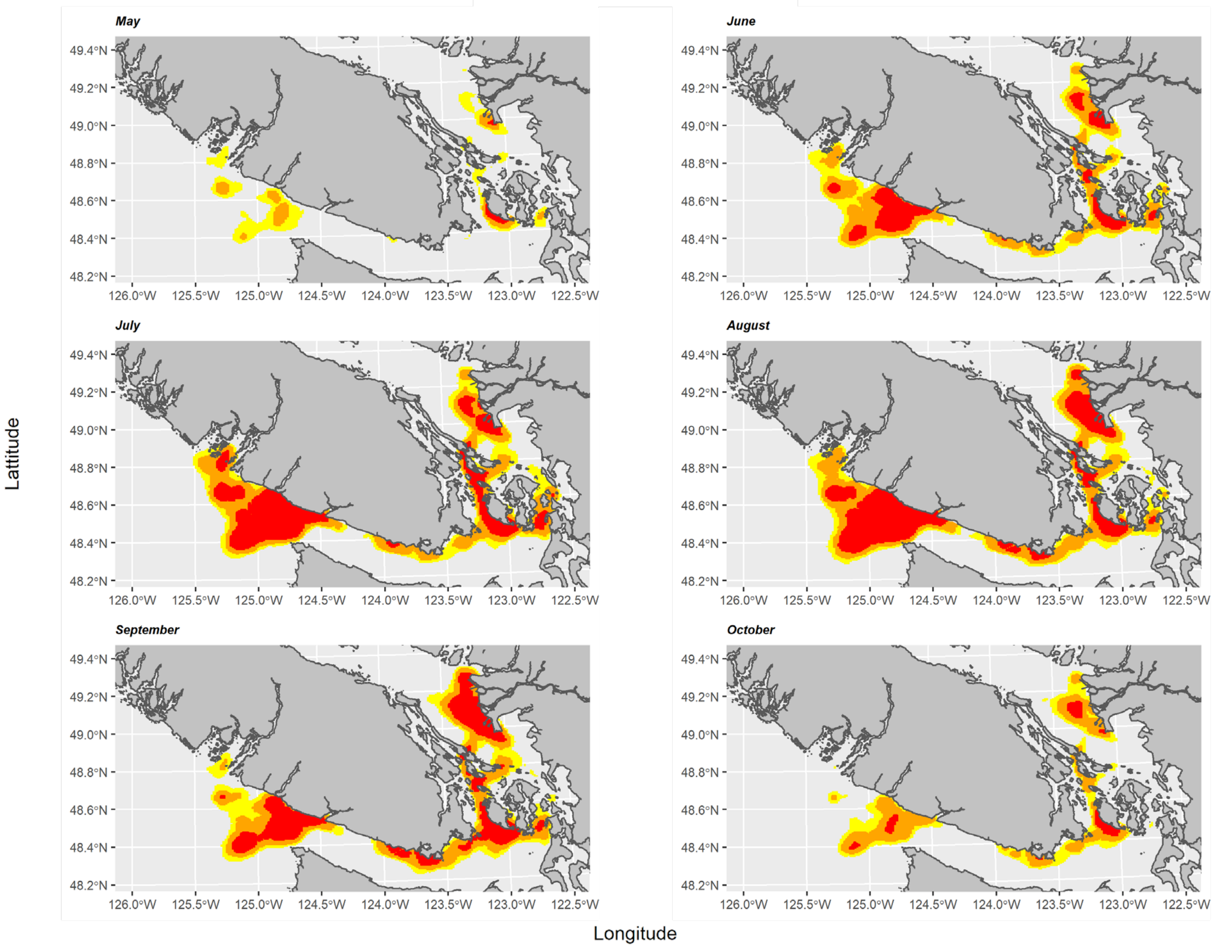

Figure 12. Predicted monthly habitat preference of SRKW when in their critical habitat, using data from all summer months (May to October) for estimating preference thresholds. The expected number of SRKW sightings per unit search effort at a given location is referred to as the SRKW intensity of occurrence. The 90% polygon (red) represents the areas of highest SRKW intensity of occurrence values over the six month period, with diminishing intensity described by the 80% (orange) and 70% (yellow) polygons.

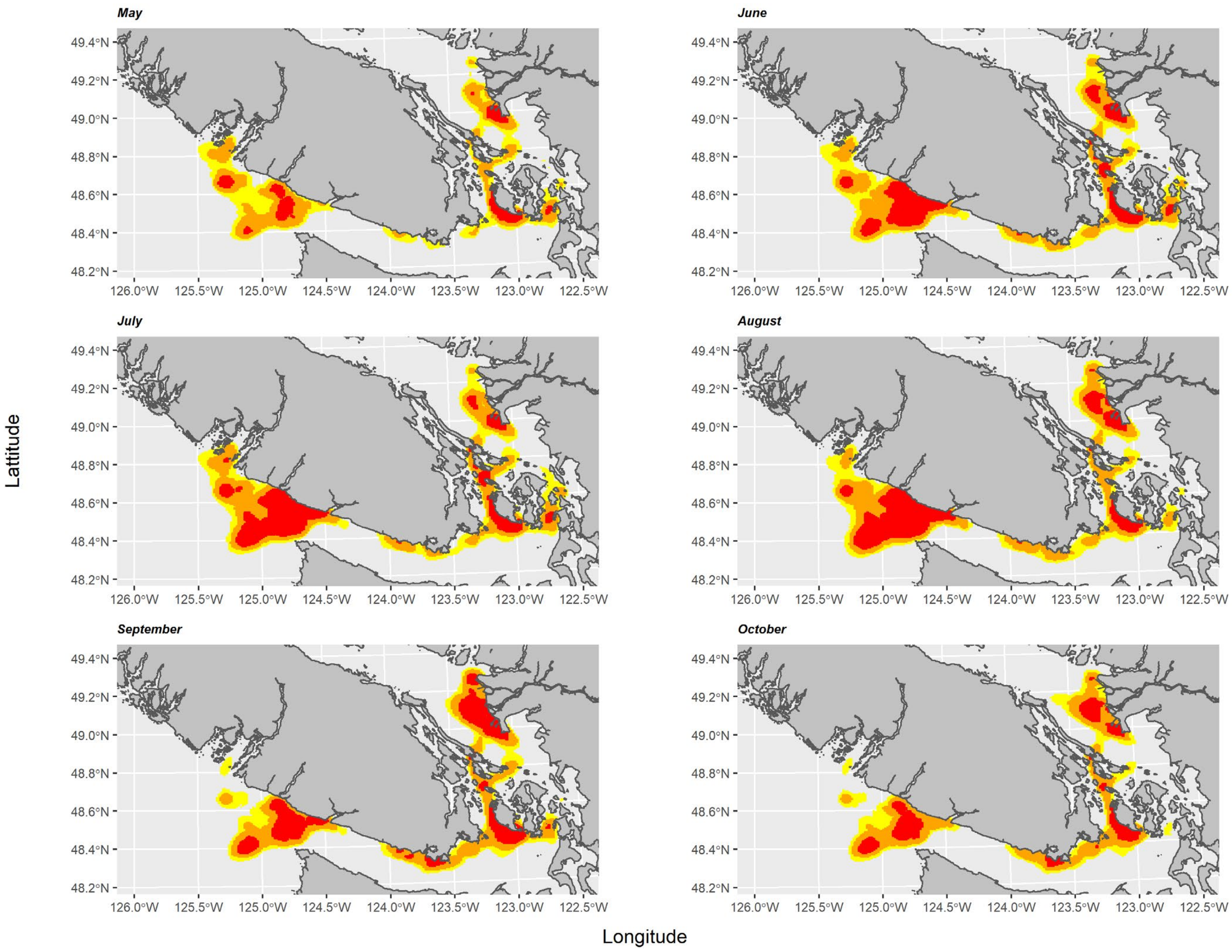

Figure 13. Predicted monthly habitat preference of SRKW when in their critical habitat, using data from each month for estimating preference thresholdsThe expected number of SRKW sightings per unit search effort within each month at a given location is referred to as the SRKW intensity of occurrence. The 90% polygon (red) represents the areas of highest SRKW intensity of occurrence values within each individual month, with diminishing intensity described by the 80% (orange) and 70% (yellow) polygons.

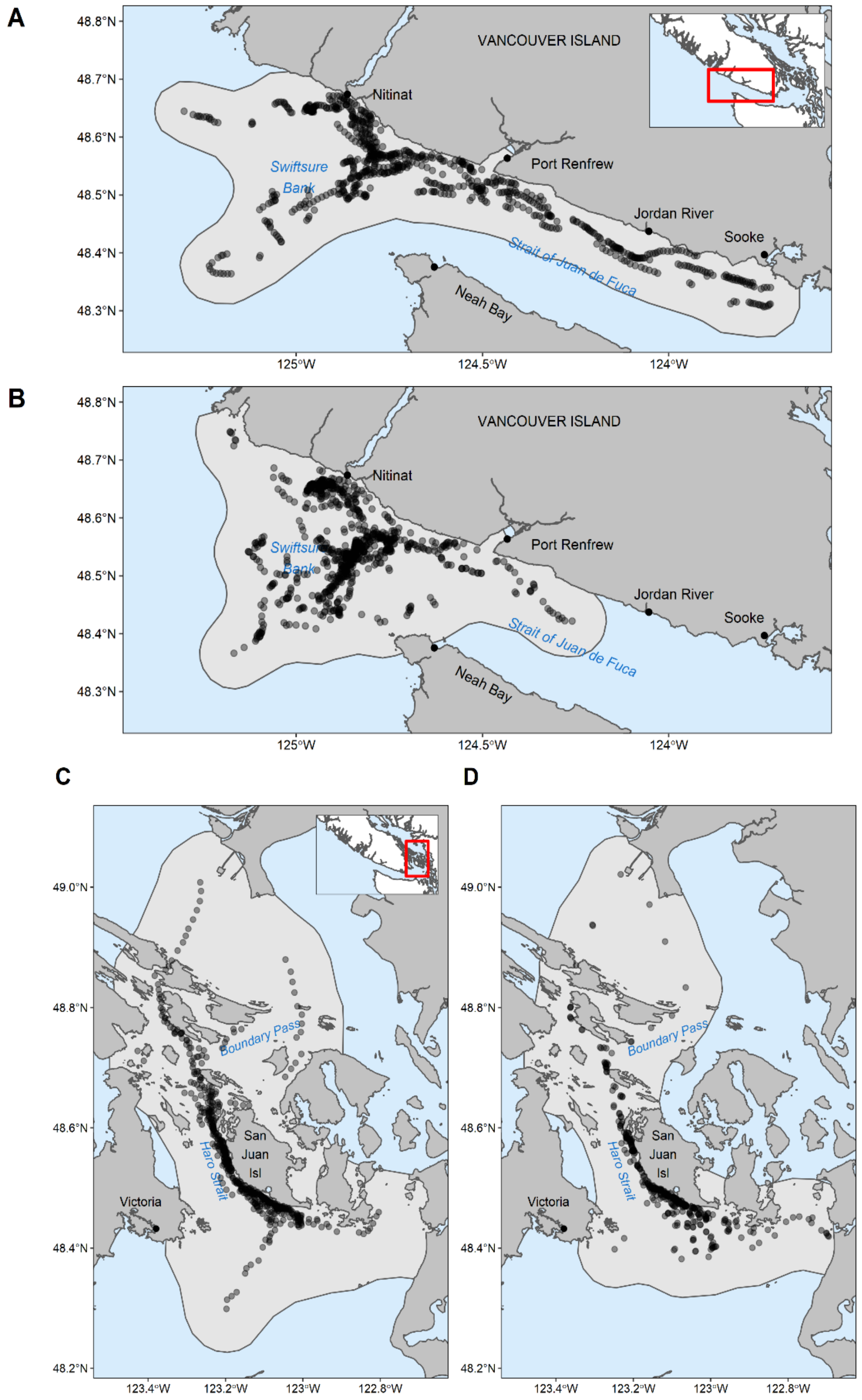

Figure 14. Travel and forage behaviour observation locations for a) DFO focal follows (2018-2020; b) DFO group behavioural surveys (2018-2020); c) NOAA focal follows (2006); and d) NOAA behavioural sampling (2007-2009). Polygons indicate bounds of model extents; each grey circle represents a single behavioural scan. Locations with overlapping scans appear black in the figure.

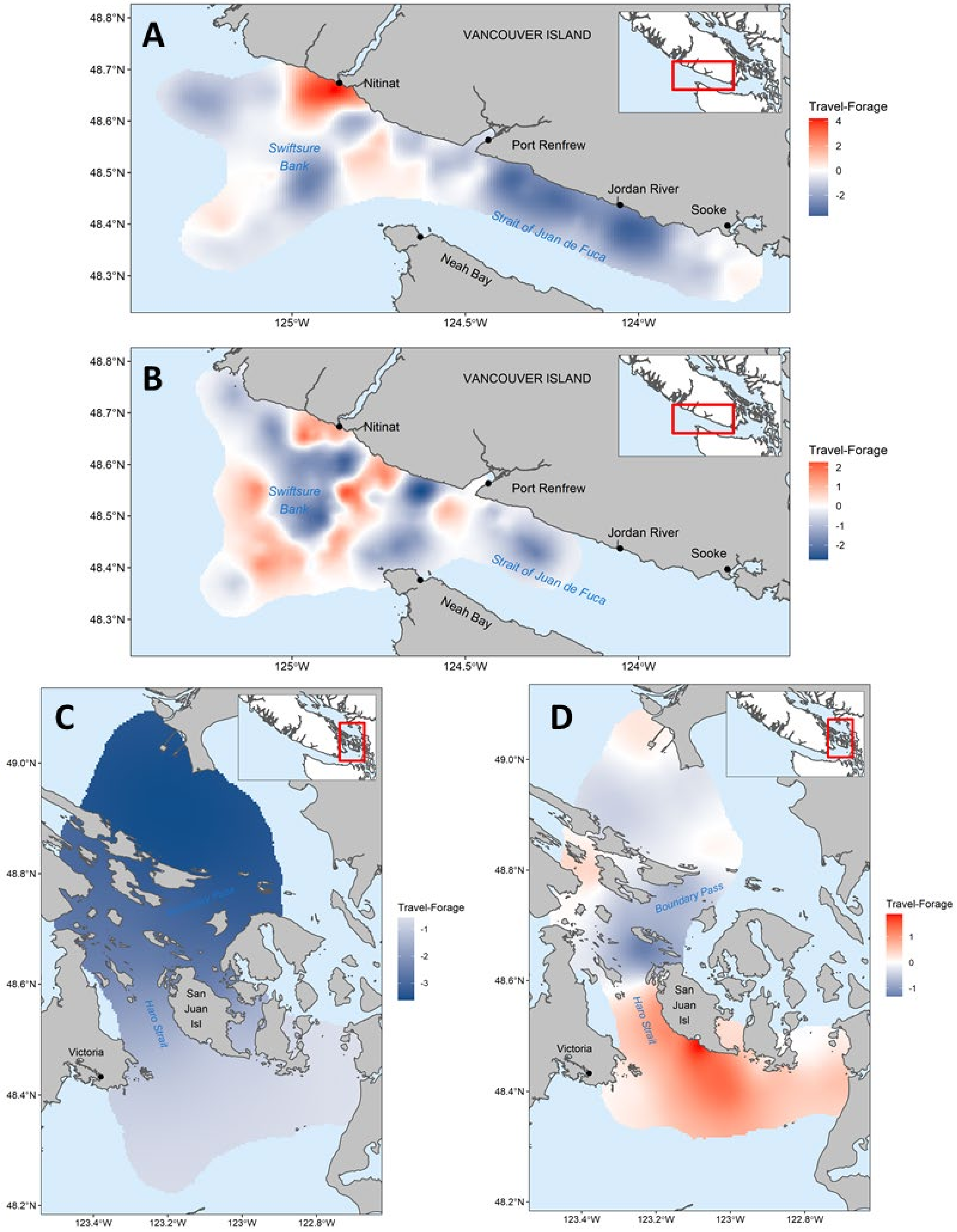

Figure 15. Space-time behavioural models predicting Travel (blue) and Forage (red) behavioural states. Posterior means of spatial Gaussian Markov Random Fields are presented for a) DFO focal follow; b) DFO group behavioural surveys; c) NOAA 2006 focal follow; and d) NOAA 2007-2009 behavioural sampling.

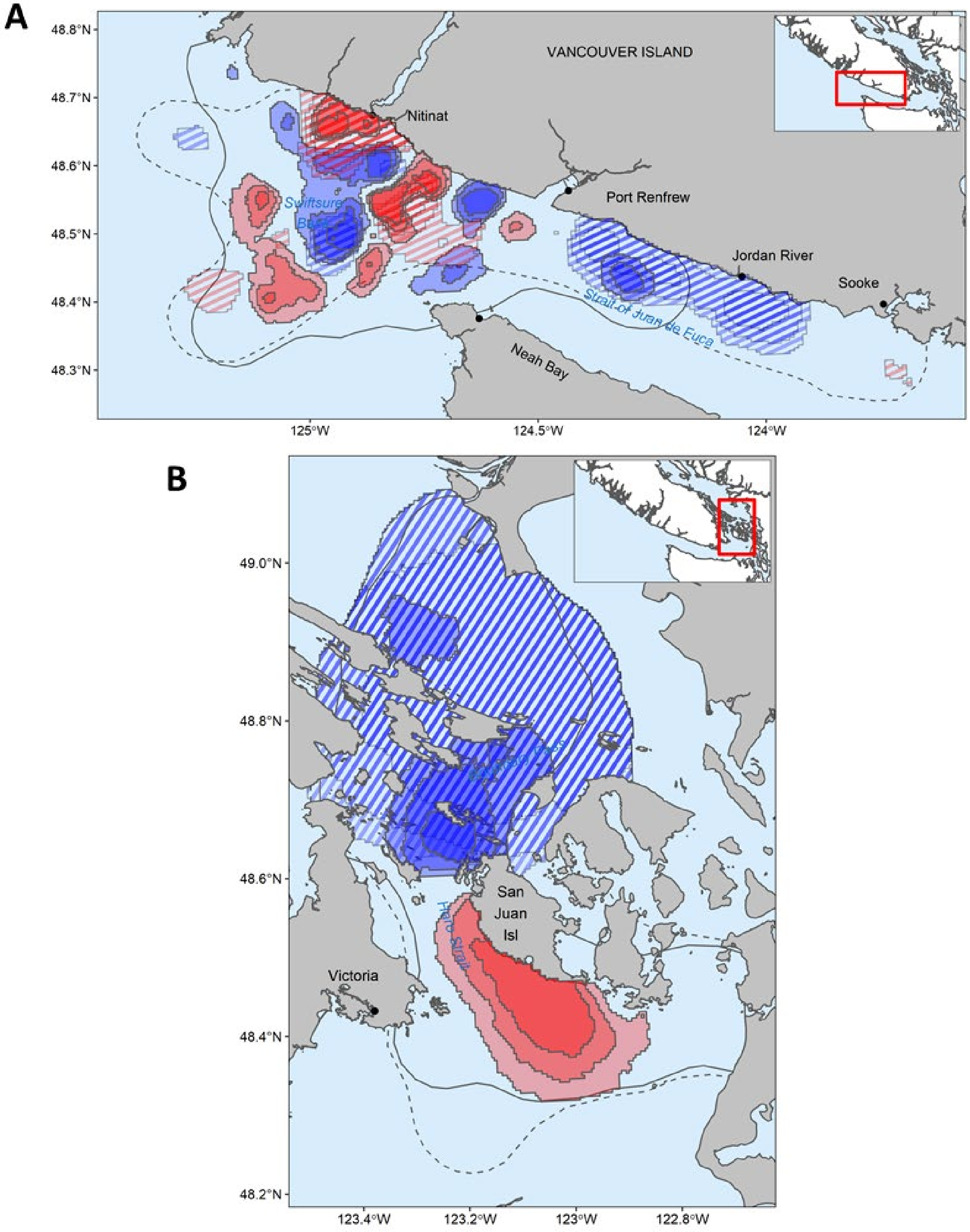

Figure 16. Areas of likely travel (blue) and Forage (red) behaviour as predicted by model outputs; increased transparency of the polygon denotes decreasing confidence (> 0.7, > 0.8, and > 0.9 probability) that foraging or travelling were the dominant behaviours. a) DFO focal follow (hatched) and group behavioural survey (solid) models; and b) NOAA 2006 focal follow (hatched) and NOAA 2007-2009 behavioural sampling (solid) models.

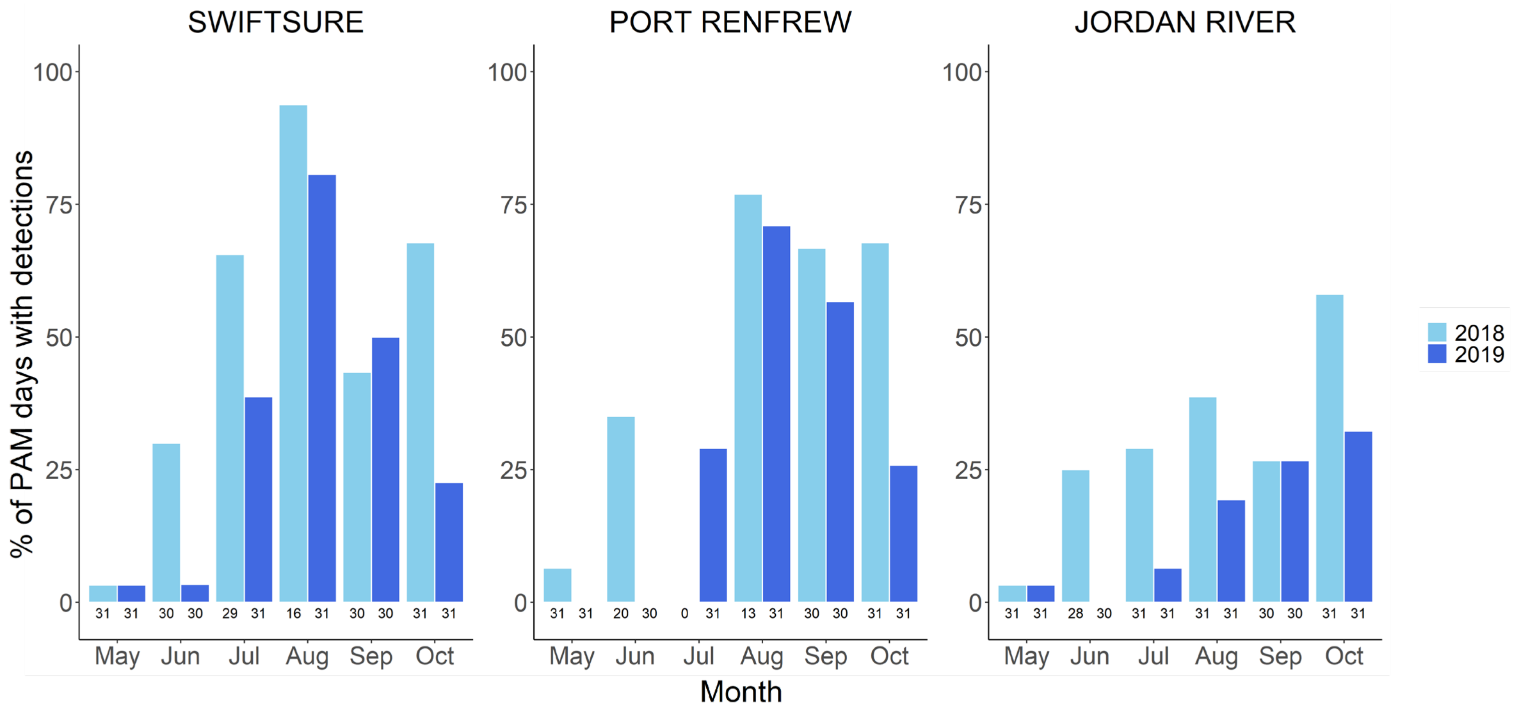

Figure 17. Number of days per month with Southern Resident Killer Whale acoustic detections (validated stereotypic pulsed calls) at Swiftsure Bank, Port Renfrew, and Jordan River from May to October in 2018 (light blue) and 2019 (dark blue), expressed as a percentage (%) of passive acoustic monitoring (PAM) or effort days. Number of effort days per month are shown below each bar.

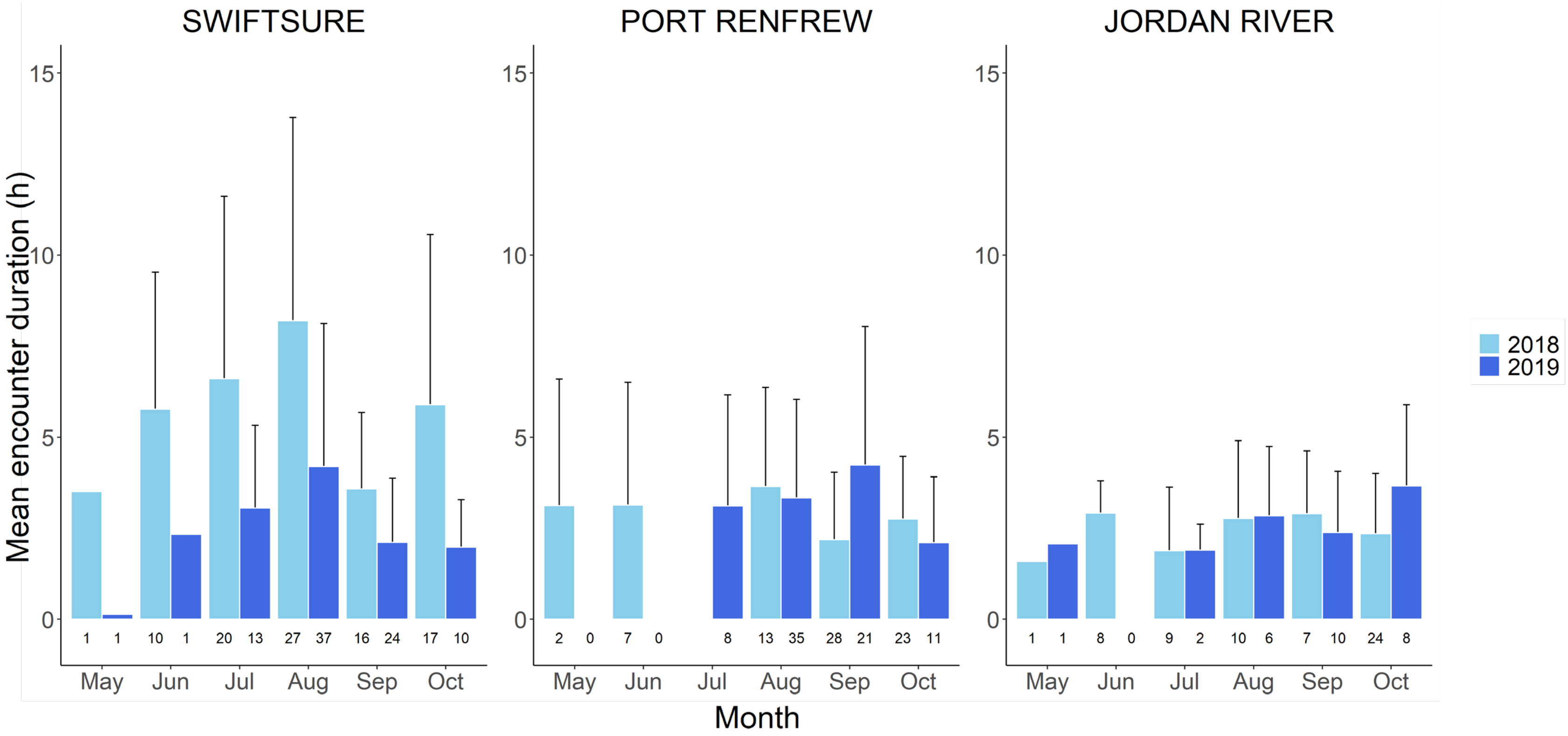

Figure 18. Acoustic encounter duration (h) of Southern Resident Killer Whales at Swiftsure Bank, Port Renfrew, and Jordan River from May to October in 2018 and 2019 (mean and standard deviation), as determined from validated stereotypic pulsed calls. Total number of encounters per month are shown in black below each bar. Note there were no effort days in July 2018 at Port Renfrew.

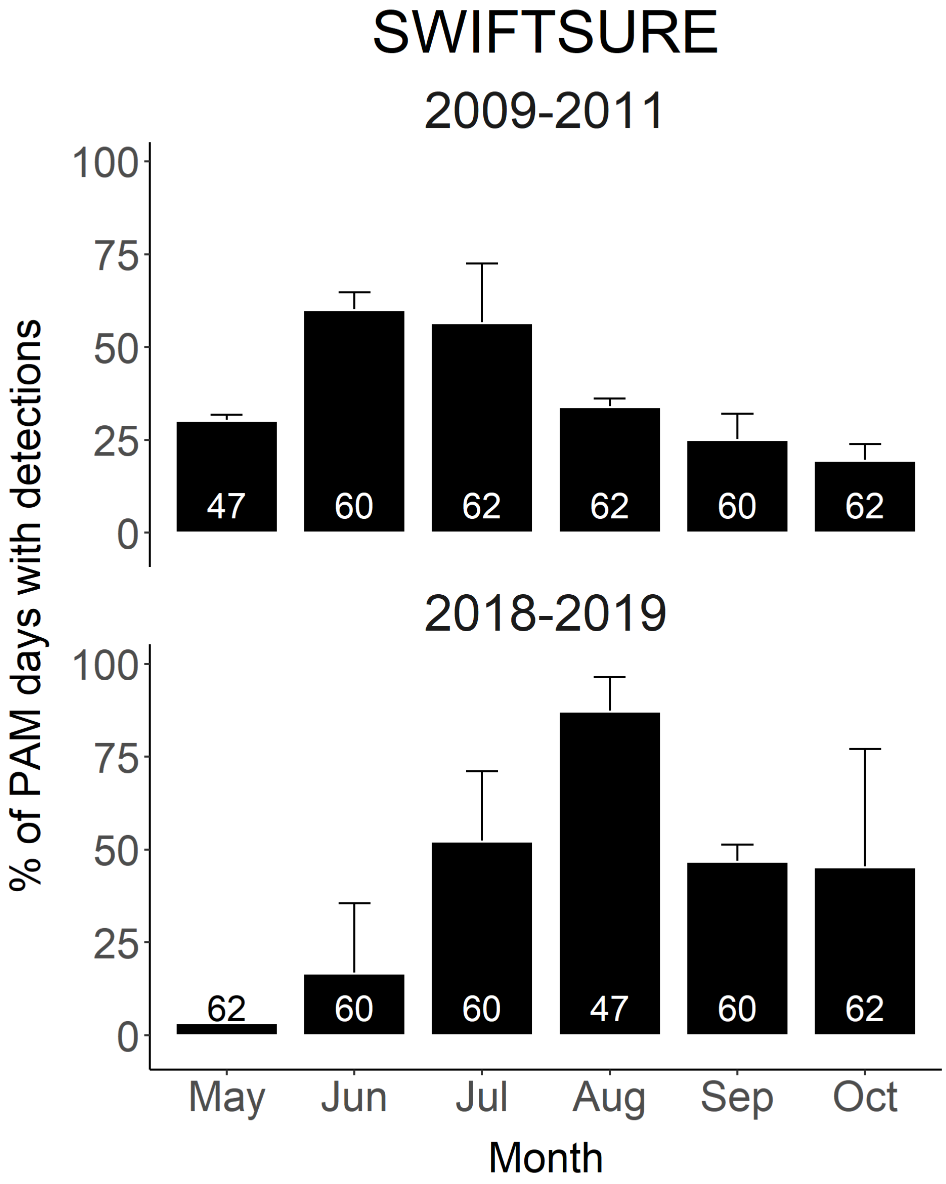

Figure 19. Number of days with Southern Resident Killer Whale acoustic detections (validated stereotypic pulsed calls) at Swiftsure Bank from May to October for 2009 to 2011 combined (top) and 2018 to 2019 combined (bottom), expressed as a percentage (%) of passive acoustic monitoring (PAM) or effort days. Bars show mean and standard deviation. Number of effort days per month are shown in white at the base of each bar.