



# Noise exposure from commercial shipping for the southern resident killer whale population



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## ABSTRACT

This study assesses vessel-noise exposure levels for Southern Resident Killer Whales (SRKW) in the Salish Sea. Kernel Density Estimation (KDE) was used to delineate SRKW summer core areas. Those areas were combined with the output of a regional cumulative noise model describing sound level variations generated by commercial vessels (1/3-octave-bands from 10 Hz to 63.1 kHz). Cumulative distribution functions were used to evaluate SRKW's noise exposure from 15 vessel categories over three zones located within the KDE. Median cumulative noise values were used to group categories based on the associated exposure levels. Ferries, Tugboats, Vehicle Carriers, Recreational Vessels, Containers, and Bulkers showed high levels of exposure ( $L_{eq-50th} > 90$  dB re 1  $\mu$ Pa) within SRKW core areas. Management actions aiming at reducing SRKW noise exposure during the summer should target the abovementioned categories and take into consideration the spatial distribution of their levels of exposure, their mechanical and their operational characteristics.

## 1. Introduction

It is thought that millions of species inhabit our oceans and seas (Appeltans et al., 2012; Mora et al., 2011), an environment where sound is often the most effective means to transmit and receive information (Simmonds et al., 2014). Sound can be used, depending on the species, for the perception of features in the environment, such as underwater topography and prey or predator detection (Simpson et al., 2015, 2016), or to help support complex social interactions, such as mating, competition and cooperation (Bruitjes and Radford, 2013; Eskelinen et al., 2016). Similarly to many terrestrial species (Brumm and Todt, 2002; Penna et al., 2005; Schaub and Schnitzler, 2007), signaling and audition of marine species have evolved in environments with sometimes high levels of natural background noise (Baumann-Pickering et al., 2015; Foote and Nystuen, 2008; Holt et al., 2011). For example, many fish species show preferences for specific soundscapes and respond to changes in the natural background noise levels by increasing the loudness of their signals, a phenomenon called the Lombard effect (Filiciotto et al., 2013; Holt and Johnston, 2014; Lugli, 2014). Furthermore, evidence of the role of sound and background noise for crustacean species are also starting to be documented. Marine

tidal turbine noise was shown to affect the length of estuarine crabs' time to metamorphosis (Pine et al., 2016) and anthropogenic noise has been linked to behavioral, physical and physiological effects in several invertebrate species (Carroll et al., 2017). The effects of anthropogenic noise can also extend to the lower levels of the trophic chain. A study conducted off the southern coast of Tasmania, Australia recently showed how air-gun noise may cause high mortality in plankton species as far away as 1.2 km from the source (McCauley et al., 2017).

During the past 50 years, the increase in human activities in our oceans has caused a progressive increase in background noise levels in various marine ecosystems (Chapman and Price, 2011; McDonald et al., 2008). Sounds produced by seismic explorations, navy sonar exercises, pile driving for offshore construction, ice-breaking, and commercial or recreational vessels have all been recognized as sources of anthropogenic noise that occur in addition to natural ambient sounds (Hildebrand, 2009; Merchant et al., 2012; Cosens and Dueck, 1993).

The past two decades of research on the impacts of anthropogenic noise have shown that noise caused by human activities can affect several aspects of a species' life cycle. Responses from exposure to anthropogenic noise range from the alteration of an animal's physiology (Habib et al., 2007; Nichols et al., 2015), to modifications and

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disruption of its anti-predatory, reproductive and feeding behaviors (Meillère et al., 2015; Schmidt et al., 2014; Voellmy et al., 2014). Amid the known anthropogenic sources of noise in the oceans, commercial shipping is the most ubiquitous. According to the United Nations Conference on Trade and Development (UNCTAD, 2017), commercial shipping represents approximately 90% of the global trade occurring worldwide, a number that is expected to grow in the future. In < 50 years, the world's cargo fleet showed a six-fold increase in capacity, from the 262,070 thousands of deadweight tonnage reported in 1968 (UNCTAD, 1969), to the 1.8 billion thousand reported on January 1st, 2016 (UNCTAD, 2017). Currently, the world's commercial fleet accounts for 90,917 vessels (UNCTAD, 2017).

Among all marine species, marine mammals and more specifically, cetaceans, are considered to be highly susceptible to sound and impacted by noise. While the complexity and intensity of acoustic activity may vary among individuals, groups, populations, and species (Au et al., 2000; Perrin et al., 2009), the production and perception of sound permeates every aspect of their life-cycles. *Odontocetes* (i.e. toothed whales) use echolocation to perceive the surrounding environment and to identify and pursue prey (Geisler et al., 2014; Gutstein et al., 2014), while several species of *Mysticetes* (i.e. baleen whales) are known to produce elaborate mating calls and songs (Payne and McVay, 1971; Delarue et al., 2009; Garland et al., 2013; Paniagua-Mendoza et al., 2017). Evidence of the use of sound in complex social interactions exist for both groups, such as feeding calls during foraging bouts, called bubble-net feeding, produced by humpback whales (*Megaptera novaeangliae*) (Friedlaender et al., 2011) and group hunting in killer whales (*Orcinus orca*) (Van Opzeeland et al., 2005). Furthermore, acoustic communication plays a role in mother-calf interactions (Vergara and Barrett-Lennard, 2008; Videsen et al., 2017) and in the transmission of social behavior from one generation to the next through vocal learning (Janik, 2014; Reiss and McCowan, 1993). As a consequence, changes to the soundscape experienced by these animals could have an impact on their survival (Harwood et al., 2016; Videsen et al., 2017).

Anthropogenic noise has the potential to cause adverse impacts when its frequencies overlap with the frequencies of a species' audiogram, the spectrum of acoustic frequencies that can be perceived by the animals' auditory system (i.e. hearing range). Large commercial vessels generate noise with most energy being emitted at frequencies below 1 kHz. Mysticetes, hear and produce sounds in a similar range of frequencies, and are considered vulnerable to noise from shipping (Southall et al., 2007). Odontocetes, signaling using higher frequencies and having lower sensitivity to low-frequency sounds, are generally considered less impacted than mysticetes by low-frequency noise (Southall et al., 2007). Nonetheless, recent findings suggest that odontocetes' sensitivity to noise from shipping might have been underestimated (Dyndo et al., 2015; Aguilar Soto et al., 2006). In particular, a study undertaken in Haro Strait (Fig. 1C), which straddles the Canada-US border, documented how ship noise within the critical habitat (Fig. 1B) of the endangered Southern Resident Killer Whale (SRKW) population raised background noise levels ( $91 \pm 4$  dB re  $1 \mu\text{Pa}$ ) not only in the low-frequency domain, but also for high frequencies, with an increase of 5–13 dB re  $1 \mu\text{Pa}$  in the 10 kHz to 40 kHz band (Veirs et al., 2016). As argued by Veirs et al. (2016), sound from shipping may not only mask killer whale communications, but can also interfere with their echolocation signals within a range of several kilometers around the noise source. Such interference has the potential to lower survival rates and reproductive success of individuals, and, in the long term, may affect the survival and dynamics of the entire population (Harwood et al., 2016). High extinction risk was the reason SRKW were listed as endangered and protected under Canada's Species at Risk Act (SARA) and the United States' Endangered Species Act (ESA). Furthermore, the majority of the Salish Sea has been recognized by both Canada and the US as critical habitat for SRKW (National Oceanic and Atmospheric Administration, 2006; Fisheries and Oceans

Canada (DFO), 2011). Yet, the designated areas only delineate the limits of SRKW's critical habitat at the time of the designation and extensions to the protected habitat are currently under consideration (Fisheries and Oceans Canada (DFO), 2017a). Like all *resident* killer whales, the members of SRKW are socially organized into clans, pods, and *matrilines*. Matrilines, consisting of a mother and all her offspring, travel and forage in close proximity to each other throughout their lives, while pods are temporally stable social groups that consist of related matrilines and share most of their vocal repertoires. Clans comprise pods that share calls and are therefore considered to be acoustically related (Ford, 1991). SRKW consist of one clan (J-clan) and three pods (J, K, and L) (Bigg et al., 1990; Parsons et al., 2009). The complex social organization of this population is thought to influence SRKW spatial distribution within their critical habitat (Hauser et al., 2007). Hauser et al. (2007) investigated the spatial distribution of SRKW, identifying shared areas among all SRKW, as well as pod-specific core areas for this population.

Only 76 SRKW individuals survive in the wild ([www.whaleresearch.com/orca-population](http://www.whaleresearch.com/orca-population)) (Center for Whale Research, 2017) and several anthropogenic activities undertaken within the Salish Sea are threatening the persistence of this population. Both the survival and the reproductive success of SRKW's individuals have been linked to prey availability (Baird, 2001; Krahn et al., 2002; Ward et al., 2009; Ford et al. 2009). SRKW's diet is largely composed of salmonid species, primarily Chinook, but also Steelhead, and occasionally Sockeye, Chum, and Coho salmon (Hanson et al., 2010; Ford and Ellis, 2006). As concluded by Williams et al. (2011), the current decline of both SRKW and their preferred prey, as well as the transboundary nature of these two species, present a challenge for their successful conservation. Being framed around the concept of production optimization for the benefit of both the US and Canada Salmon fisheries, the objectives of the Pacific Salmon Treaty do not consider the prey requirements of a recovering SRKW population in the allocation of the bilateral fisheries quotas (Williams et al., 2011). SRKW was estimated to consume 12–23% of Fraser River Chinook in the summer and a fully recovered population could consume up to 20–40% of the available Chinook (Williams et al., 2011). Other examples of current threats to SRKW are the high levels of contaminants observed in individuals (Krahn et al., 2007, 2009; Ross et al., 2000) and the physical and acoustic disturbance caused by vessel traffic (Holt et al., 2009; Houghton et al., 2015; Lusseau et al., 2009; Veirs et al., 2016).

With Canada's Policy for Conservation of Wild Pacific Salmon far from being fully implemented (Price et al., 2017) and the limited actions that can be undertaken to lower SRKW's level of contaminants, disturbance from vessel traffic arguably represents the only major environmental stressor for SRKW that could be addressed in the short-term. Both the US Recovery Plan for Southern Resident Killer Whales (National Marine Fisheries Service, 2008) and the Canadian Recovery Strategy for the Northern and Southern Resident Killer Whales (Fisheries and Oceans Canada (DFO), 2011) recognize the potential impact that noise could have on the recovery of SRKW. In particular, the new Action Plan to achieve recovery of the threatened and endangered Northern and Southern resident killer whales (Fisheries and Oceans Canada (DFO), 2016) explicitly introduces noise as a threat to the recovery of British Columbia's killer whale populations and specifies a list of action measures that should be put in place to reduce disturbance from anthropogenic noise to the acoustic habitat of killer whales and the marine environment.

As part of the MEOPAR (Marine Environmental Observation Prediction and Response Network) funded Noise Exposure to the Marine Environment from Ships (NEMES) project, this study investigated the predicted levels of noise exposure modelled from commercial vessel traffic within SRKW's summer core areas and aims to inform managers and decision-makers on the spatial distribution of noise and whales in specific locations of the Salish Sea. Our goal was to identify areas in the Salish Sea where high levels of noise from shipping

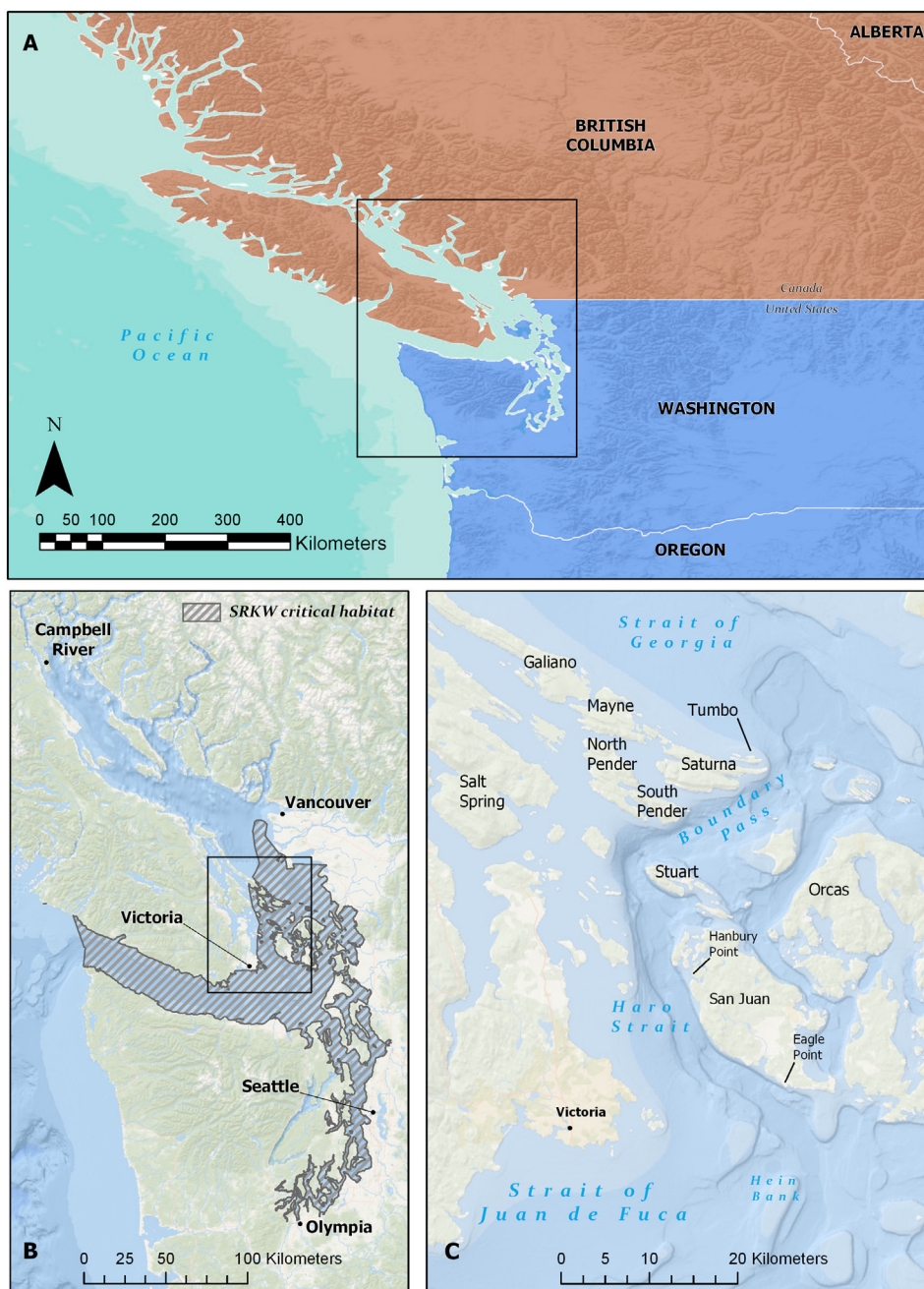


Fig. 1. Canada's west coast (A), the Salish Sea and SRKW critical habitat (B) and the study area considered for the analysis of SRKW's levels of noise exposure (C).

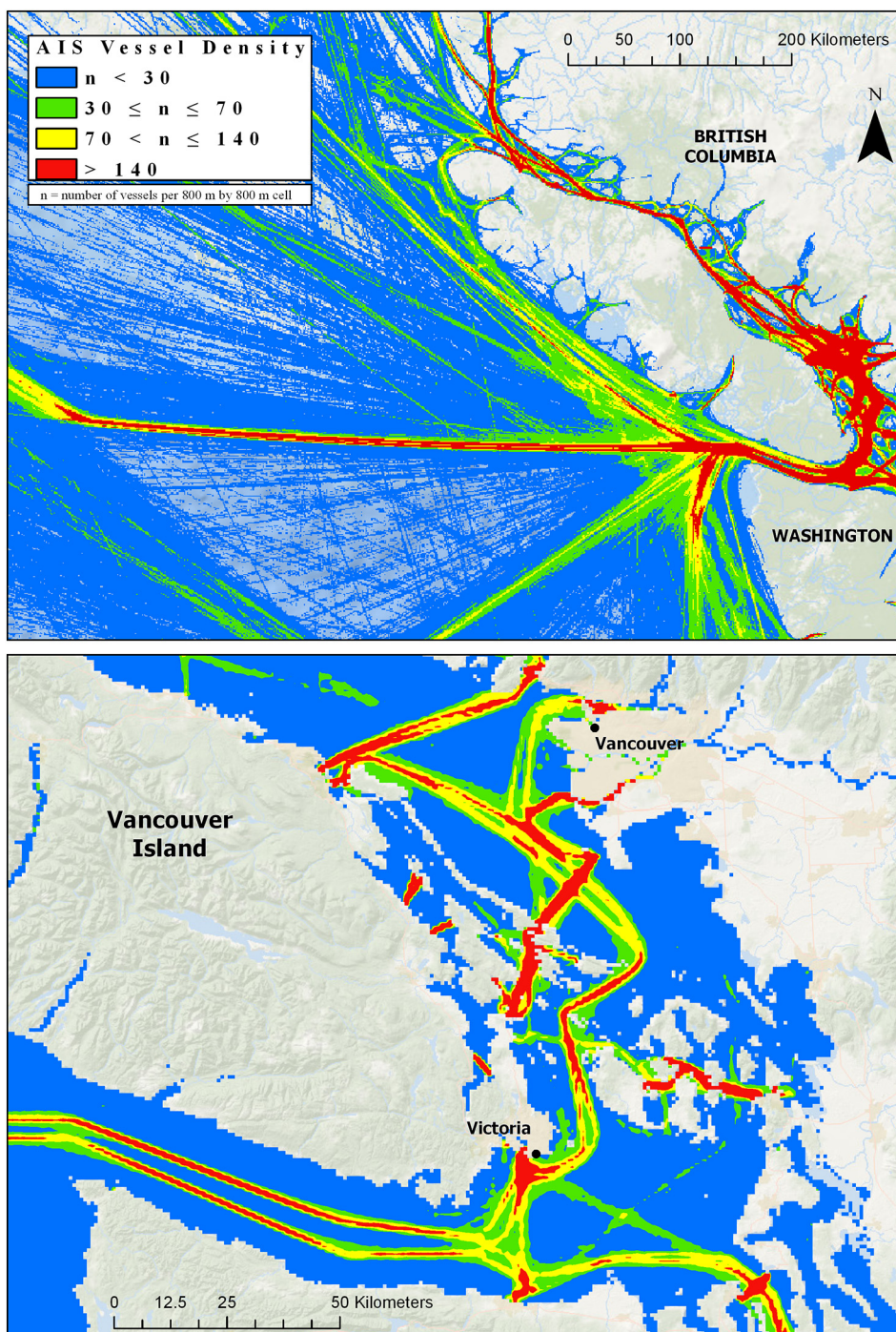
and high probability of SRKW presence co-occur. This was done by combining fine scale Kernel Density Estimation (KDE) of the SRKW population's core habitat with the output of a cumulative vessel noise model (O'Neill et al., 2017). The cumulative noise model was informed about vessel density and distribution by Satellite Automatic Identification System (S-AIS) records.

## 2. Methods

### 2.1. Study area

In 2013, British Columbia (BC) waters accounted for > 50% of the ship traffic density occurring nationally in Canada (Simard et al., 2014). With major ports like Vancouver and Prince Rupert, BC, and Seattle, Washington State (WA), serving major Canadian and US economic centers, the distribution of shipping along the southern BC coast is

mostly concentrated within the Salish Sea, an inland sea encompassing Canadian and US national waters (Figs. 1 and 2). The Salish Sea extends from Olympia (WA, US) in the South to Campbell River (BC, Canada) in the North (Barrie et al., 2014). It covers an area of 16,925 km<sup>2</sup> and includes 7470 km of coastline (Gaydos et al., 2008). The complexity of the Salish Sea ecosystem is reflected in the geomorphology of the region. The Salish Sea's landscape was formed during a succession of geological events that shaped the Southern coast of BC into an intricate network of waterways. The Salish Sea region hosts the largest coastal population in Canada, with consequent high levels of coastal development. The Salish Sea is not only an area characterized by intense human activity but also a hotspot of marine biodiversity. Previous studies identified 172 species of birds and 37 species of mammals in this region (Gaydos and Pearson, 2011), as well as 253 species of marine fishes (Pietsch and Orr, 2015) that are highly dependent on this ecosystem for the full expression of their biological functions. The increasing human



**Fig. 2.** Map of aggregated AIS vessel density for the year 2015 (A). Map of aggregated AIS vessel density for the month of July 2015 (B). Both maps were derived from the same AIS dataset used by JASCO Applied Sciences to estimate levels of cumulative noise from shipping in the Salish Sea. The legend refers to both maps.

pressure on the Salish Sea ecosystem is threatening its biodiversity. The consequences of anthropogenic activities are reflected by the growing number of species, sub-species and ecologically-significant units of populations that are mentioned in provincial and federal lists of threatened species, both in Canada and the USA (Zier and Gaydos, 2016).

## 2.2. Cetacean sightings

We used SRKW sighting data collected by the Soundwatch Boaters Education Program (SBEP) between May 2011 and September 2014. These observations are part of a larger compilation of sightings, the

Southern Resident Sighting Compilation (Olson et al., 2015), produced by the Whale Museum (Friday Harbor – Washington, US). Sightings are collected from opportunistic platforms, such as commercial whale-watching boats and private vessels, as well as dedicated research vessels. This dataset contains a total of 83,474 records (1948 to 2014) describing the date, time and location of the sightings, the observed pod or pod combination and includes notes about the observed behavior of killer whales. Since the compilation collects data from observers with different levels of experience, the accuracy of pod designation may vary from one observer to another. Since 2009, each pod designation is accompanied by a “likely pod” designation determined by staff members of the Whale Museum, increasing the accuracy of the dataset. However,

pod misidentifications cannot be completely removed and some of the reported SRKW sightings might be of individuals belonging to one of the other orca ecotypes (i.e. offshore, transient) present in the area. Sightings are summarized using an irregular grid (Fig. 7E) of approximately 5 km by 5 km cells (i.e. quadrants) and the observations are not corrected for search effort. SBEP provides detailed geo-referenced sightings which are not aggregated in quadrants.

Another benefit of this dataset is the possibility to estimate the effort per unit area invested by the SBEP's volunteers from their yearly reports (Eisenhardt, 2012; Eisenhardt & Koski 2011, 2013 and 2014). For each season of operation, SBEP reports the number of vessels contacted in each one of the 444 quadrants in which the Salish Sea is subdivided. Where a “contact” consists of SBEP's volunteers approaching boaters to inform them on the best practices for the operation of vessels in the proximity of marine mammals. The relationship between the number of sightings and the number of contacts recorded per hour was tested using Spearman's correlations test. The area of each quadrant, as well as the number of vessels contacted within it, were computed using Esri ArcMap® 10.3.1 software. The number of contacts divided by the total area of a quadrant provided an estimation of the effort per unit area invested by the volunteers in each quadrant (Fig. 7A to D). Cetacean sightings were recorded at 30-minute intervals throughout the summer, applying the same protocol followed for SRKW's sightings compilation. Hence, the number of vessel contacts per unit area can be considered as a proxy for the search effort invested by SBEP in collecting cetacean presence data.

The SBEP dataset consists of 13,179 sightings collected during 16 years of activity in the Salish Sea. The purpose of this study was to estimate the probability of SRKW being exposed to certain levels of noise by area, under the current intensity of ship traffic. Since the noise model outputs hereby considered are representative of the summer season, only relatively recent sightings, collected for the period May–September 2011 to 2014 were used for the identification of SRKW's summer core areas, totaling 3,150 sightings. The derived effort ( $E_{z-y}$ ) was computed for each year as follows:

$$E_{z-y} = N_{z-y}/A_{z-y}, \quad (1)$$

where  $N_{z-y}$  is the average number of contacts occurring in quadrant  $z$  for the  $y$  season and  $A_{z-y}$  is the total area of quadrant  $z$  for the  $y$  season. As a consequence, before proceeding with the creation of the summer core area maps, each sighting occurring in a quadrant was divided by the corresponding  $E_{z-y}$  value computed for the zone. Sightings recorded within a quadrant with  $E_{z-y} = 0$  were considered as being “off effort” observations and were excluded from the analysis. Assuming that quadrants with no contacts are “off effort” introduces a limitation: some quadrants might have no contacts, but still, be highly frequented by SRKW.

To test whether or not the resulting KDE relative to the entire population was descriptive of SRKW summer distribution, the final results were compared to the British Columbia Cetacean Sightings Network (BCCSN) (<http://wildwhales.org>) dataset. Established in 2000 and hosted by the Vancouver Aquarium, the BCCSN is a network of > 6,000 volunteer observers distributed across British Columbia. Contributors include whale watching naturalists, lighthouse keepers, commercial mariners and recreational boat operators, as well as researchers. The information collected through the network is shared with government agencies, universities and ENGOs for conservation research. For example, Williams and O'Hara (2010) used the information collected by the BCCSN to compile a list of known ship strikes involving BC cetacean species from 1999 to 2007. The sightings collected by BCCSN's volunteers were instrumental to the delineation of SRKW critical habitat within Canadian waters (Fisheries and Oceans Canada (DFO), 2011) and were used by the Vancouver Fraser Port Authority to inform the environmental assessment for the Robert's Bank Terminal 2 project (Wood and Chemelnitsky, 2014). In the BCCSN dataset, effort-weighted summer sightings of resident and transient orcas (Rechsteiner et al.,

2013) collected since the early 1980s are reported for the same 444 quadrants used by SBEP. The correlation between the KDE produced in this study and the number of sightings per-unit effort reported by BCCSN was tested using the ArcMap software ordinary least squares (OLS) geoprocessing tool.

Each SRKW sighting reported by SBEP is accompanied by a pod designation. A member of the SRKW population can belong to one of three socially distinct units (i.e. J, K or L pods). Furthermore, individuals often form mixed groups, where one or more members of a pod are typically observed within a larger group of individuals belonging to another pod. As a consequence, there is a total of seven pod combinations recorded in the SBEP dataset: J, K, L, JK, KL, JL, JKL. Considering each combination as a separate social entity within SRKW would have greatly reduced the number of sightings available for the estimation of SRKW summer areas. In order to produce an area estimation representative of the entire population, and of its three main social groups, each sighting was assigned to one of three clusters: J-group, K-group, and L-group. Where the J-group included the J pod, as well as the JK and JL pod combinations, the K-group included the K pod and the KL pod combination, and where the L-group included the L pod and the JKL combination. Such group compositions were first described and used by Hauser et al. (2007).

### 2.3. SRKW summer core area assessment (kernel density estimation)

Kernel Density Estimation (KDE) is a well-established approach for assessing habitat use (Worton, 1989). KDEs have been used to derive home ranges for several terrestrial and aquatic species from a variety of data sources: radio-tracked animals (Tumenta et al., 2013), indirect signs of presence (Sawyer, 2012), photo-identification records (Rayment et al., 2009) and visual surveys (Hauser et al., 2007). KDEs were computed, using ArcMap Kernel Interpolation with Barriers geoprocessing tool, for each group and for the entire population, applying a 5th-degree polynomial function:

$$1 - \left(\frac{r}{h}\right)^3 \left(10 - \left(\frac{r}{h}\right) \left(15 - 6\left(\frac{r}{h}\right)\right)\right), \text{ for } \frac{r}{h} < 1. \quad (2)$$

where  $r$  is the radius, centered on a point within the study area, and  $h$  is the bandwidth or smoothing parameter. In order to allow a comparison of animals' home ranges and sound from shipping, the KDEs were computed at the same spatial resolution as the cumulative noise model (i.e. 800 m). The boundaries of SRKW summer core areas were then identified using the 95% and 50% Percentage Volume Contours (PVCs) of each KDE. PVCs are a common measure of the extent of animals home ranges (Garitano-Zavala et al., 2013; Sprogis et al., 2016; Tumenta et al., 2013) and represent the limits of an area in which an individual has a definite probability to be found (Kern et al., 2003). Since the outcomes of a KDE are highly dependent on the selection of the appropriate bandwidth (Worton, 1989), appropriate  $h$  values were selected following the method described in Kie (2013). Starting from a reference bandwidth,  $h_{ref}$ , a set of bandwidth values ranging from  $1.4 \times h_{ref}$  to  $0.1 \times h_{ref}$  was used to derive 95% percentage volume contours (PVC) for the entire population and each pod-group. The optimal bandwidth was then selected as the minimum value of  $h$  generating the least fragmented 95% PVC. Fragmentation of the 95% PVC was evaluated considering the number of polygons and the perimeter-area ratio (Fig. 3). Once an  $h$  value was selected for a pod-group, the corresponding KDE was designated as representative of the pod-group summer habitat-use, while the other alternatives were discarded. In order to allow comparisons between the various KDEs, raster values were re-scaled between 0 and 1.

Representing a non-parametric approach to the evaluation of animals home-ranges, KDEs do not require a priori identification of the sample's distribution (Anderson, 1982; Worton, 1989). However, the quantification of uncertainty for non-parametric methods is often



Fig. 3. Bandwidth selection procedure. Bars represent the number of polygons constituting each iteration of a KDE. Bandwidth (h) values are represented by the blue line and the average perimeter-area ratio of the polygons constituting the 95% PVC of the KDEs are shown in green. The red box highlights the h value that led to the generation of the least fragmented 95% PVC,  $h_{ref} - 0.1 * h_{ref}$ , in this case. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

List of vessel categories included in the cumulative noise mode and the corresponding pooled categories used to evaluate SRKW’s levels of noise exposure. Dredgers, marked with #, were not included in the analysis.

Model categories	Broadband SL (db re 1 μPa) <sup>a</sup>	Pooled categories	Model categories	Broadband SL (db re 1 μPa) <sup>a</sup>	Pooled categories
Bulk carriers < 200 m	167.1	Bulkers	Government/Research	146.7	Government/Research
Bulk carriers > 200 m	170.9		Naval Vessels	146.7	Naval vessels
Container ships < 200 m	178.6	Containers	Passenger < 100 m	152.3	Passenger
Container ships > 200 m	178.6		Passenger > 100 m	166.3	
Crude oil tankers < 200 m	161.2	Crude oil tankers	Recreational vessels	144.3	Recreational vessels
Crude oil tankers > 200 m	161.2		Reefers	170.9	
Dredgers#	167.5	-	Tankers	161.2	Tankers
Ferries < 50 m	173.3	Ferries	Tug < 50 m	167.5	Tugboats
Ferries > 50 m	173.3		Tug > 50 m	167.5	
High-speed ferry	166.3	Fishing vessels	Vehicle carriers	170.9	Vehicle carriers
Fishing vessels	146.2		Other	145.8	Other

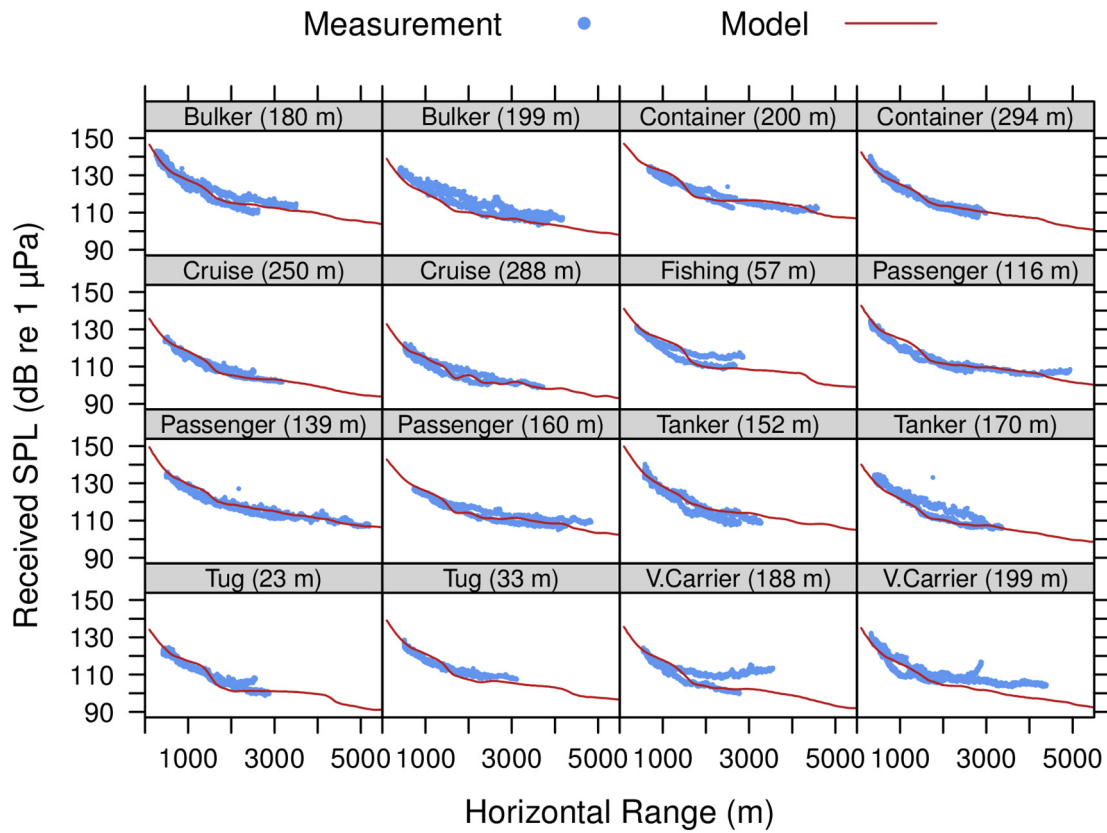
<sup>a</sup> Representative source levels for the different categories of vessels used in the model were compiled from a number of publicly available papers and reports (Austin et al., 2013; Warner et al., 2013; Cybulski, 1977; Arveson and Vendittis, 2000; MCR International, 2011; McKenna et al., 2012; Kipple and Gabriele, 2004; Zykov et al., 2008; Mouy et al., 2012; Breeding et al., 1994; Veirs et al., 2016).

problematic and not immediate. Bootstrapping (Briggs et al., 1997) was used to overcome this limitation, allowing to re-sample animal locations for the creation of confidence intervals. Applying an ArcMap geoprocessing custom model developed for this study and starting from a randomized sample of the original animal’s location, a total of 200 iterations of the KDE analysis were performed for the four summer core area maps. This allowed for the identification of a minimum and a maximum possible extent for each one of the 95% PVCs describing SRKW summer spatial distribution.

2.4. Cumulative noise assessment

A cumulative noise model generated by JASCO Applied Sciences for the NEMES project (O’Neill et al., 2017) was used to determine areas of high levels of noise exposure for SRKW. Vessel broadband source levels for the modeling study were compiled in 1/3 octave bands from 10 Hz to 63.1 Hz (Appendix A.1, Fig. 12 in O’Neill et al., 2017). Broadband vessel Source Levels (SLs) are shown in Table 1. One of the data inputs for the noise model was S-AIS ship movement data provided by exactEarth (<http://www.exactearth.com>). Originally developed as a navigation safety measure, the Automatic Identification System (AIS)

allows for the tracking and modeling of large vessels’ movements. According to Canadian regulations every ship of 500 tons or more, fishing vessels excluded, needs to carry an AIS device. Raw S-AIS data were cleaned and processed by the Institute for Big Data Analytics (Dalhousie University, Canada), resulting in traffic density gridded maps for 22 different vessel categories. Vessel categories were defined using AIS types, when applicable, and using the International Telecommunication Union’s Maritime mobile Access and Retrieval System (MARS) as well as Marine Traffic ([www.marinetraffic.com](http://www.marinetraffic.com)) when the AIS records failed in reporting the class of a vessel. Grids (800 m resolution) recorded vessel counts, the total number of hours with vessels, and the average vessel speed for each cell. Traffic density data (i.e. vessel density, speed, source levels) were used by JASCO to determine ship contributions to ambient sound levels (i.e. background noise level). Vessels sound source levels by category (e.g. tankers, container ships, bulk carriers, fishing vessels) together with the vessel density grids were entered into a sound propagation loss model which then together with other variables (e.g. bathymetry, sea surface pressure, geoacoustics and ambient noise), generated monthly cumulative noise distribution maps of the Salish Sea at an 800 m by 800 m grid scale (O’Neill et al., 2017). Source levels for each vessel class (in dB re 1 μPa @ 1 m) were specified in 1/3-



**Fig. 4.** Comparison of measured and modelled SPL (broadband, 0.01–63 kHz) versus range, from 16 ships of opportunity measured on a cabled hydrophone station located in Georgia Strait. The type and length of each vessel is shown in the strip above the plots. Ships were tracked on AIS as they passed the hydrophone, and SPL was calculated in 1-second intervals from the acoustic data. The measurements show both the approach and departure of each vessel past the hydrophone, with higher levels generally measured during departure (i.e., in the aft direction).

octave frequency bands from 10 Hz to 63.1 kHz. Acoustic transmission loss (TL) for each 1/3-octave band was calculated using a parabolic-equation-based sound propagation model (JASCO's Marine Operations Noise Model, MONM), based on the computationally-efficient split-step Padé algorithm (Collins, 1993). TL was averaged over five frequencies inside each 1/3 octave band and the TL versus range curves were smoothed inside a 200 m window to remove fine-scale interference effects. At high frequencies, mean TL computed by MONM is expected to converge to a high frequency (i.e., ray-theoretical) limit; therefore, TL values for bands above 5 kHz were approximated by adjusting TL at 5 kHz to account for frequency-dependent absorption at higher frequencies (François and Garrison, 1982a, 1982b). MONM was used to pre-calculate curves of TL versus range for twenty different geographic zones, covering the study area, representing four different seabed types (i.e. sand, silt, clayey-silt, and sand-silt-clay) and five different depth ranges (i.e. < 50 m, 50–100 m, 100–150 m, 150–200 m, > 200 m). For each geographic zone, TL was modelled using two different sound speed profiles, representing July and January conditions, and for two source depths, representing the nominal acoustic emission centers of small (2 m) and large (6 m) draft vessels. The 1/3-octave band received SEL in each grid cell was computed as the total time-integrated squared sound pressure originating from all adjacent grid cells not blocked by land within a 75 km radius. For the range-dependent case, where the ray between a source and a receiver traversed more than one zone, the total TL was computed as the range-weighted average of the zone-dependent TL. The monthly  $L_{eq}$  in each grid cell was calculated from the SEL and the number of seconds in a single month,  $T_{mon}$ , as follows:

$$L_{eq} = SEL - 10 \times \log_{10}(T_{mon}). \tag{3}$$

Monthly  $L_{eq}$  was calculated separately for each vessel category. The

relative differences between category-specific  $L_{eq}$  at each geographic location provided a measure of the relative exposure risk from the different types of shipping, based on the overall noise budget.

In order to validate the results of the cumulative noise model, modelled received levels were compared to measured sound levels for several ships of opportunity on a hydrophone station located within the study area. The validation results showed good agreement between the model predictions and received sound pressure levels (i.e. RMS model-data mismatch of 3.53 dB) (Fig. 4). However, due to the opportunistic nature of the validation process, not all the vessel categories could be assessed.

The noise model results for the month of July 2015 were used here for a comparison with SRKW summer distribution. Noise models outputs (Fig. 5) are estimations of cumulative noise expressed in terms of Equivalent Continuous Sound Pressure Level ( $L_{eq}$ ).

Cumulative noise was mapped at 800 m resolution, providing a  $L_{eq}$  value for each vessel category and for all the categories combined. For the purpose of this study, the noise contributions of the initial 22 vessel categories identified in the cumulative noise model were reduced to 15 distinct groups (Table 1) using the dB summation formula:

$$L_{eq(A+B+C+\dots+n)} = 10 \times \log_{10} \left( 10^{\frac{L_{eqA}}{10}} + 10^{\frac{L_{eqB}}{10}} + 10^{\frac{L_{eqC}}{10}} + \dots + 10^{\frac{L_{eqn}}{10}} \right). \tag{4}$$

One of the vessel categories, Dredgers, was excluded from the analysis because of its small AIS aggregated density and its localized contribution to the cumulative noise, resulting in a total of 14 pooled categories included in the noise exposure risk assessment.

### 2.5. Spatial noise exposure risk by vessel categories

The levels of exposure reported in this study represent the spatial

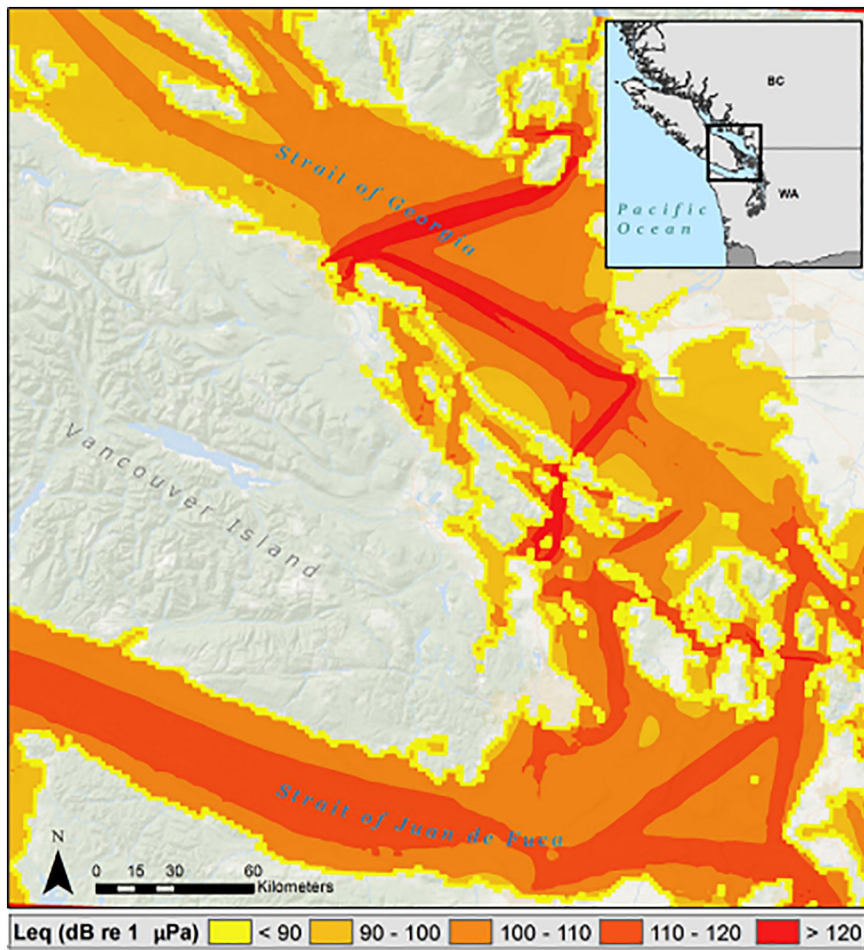


Fig. 5. The output of the cumulative noise model produced by JASCO Applied Sciences. The map shows the cumulative  $L_{eq}$  values relative to all the ship categories combined.

distribution of SRKW's risk of exposure to a certain cumulative noise level, from one of the 14 pooled vessel categories, within its summer core areas. The spatial noise exposure for SRKW pod-groups within their summer core areas was estimated by computing the cumulative distribution function (c.d.f.) of the  $L_{eq}$  values modelled for each vessel category over the KDE relative to the entire population.

Ship traffic within the study area is heterogeneous and varies from one region of the Salish Sea to the other (MacGillivray et al., 2017). Exposure levels were evaluated over three sub-areas (Fig. 6) capturing the different components of vessel traffic transiting through the study area. Located on the southern Gulf Island and outside of the commercial shipping lanes, Zone 1 (Fig. 6) is characterized by the presence of several ferry routes and frequently used by recreational, as well as fishing vessels. Zone 2 (Fig. 6), located in Haro Strait, is an area characterized by high intensity of large commercial traffic. Zone 3 (Fig. 6), located in Boundary Pass and extending into the Strait of Georgia, is also characterized by high intensity of large commercial traffic. Zone 1 included the entire L-group's unique core area (Fig. 11B). Zone 2 included the core area common to all the three groups (Fig. 8B), as well as J-group's unique core area (Fig. 9B). Zone 3 included the entire K-group's unique core area (Fig. 10B).

Cumulative probabilities were computed as follows. First, the probability,  $P_{x,y}$ , of having an animal (or group of animals) in one of the cells constituting the KDE was computed, for each cell, as:

$$P_{x,y} = KDE_{x,y} / \sum_{j=1}^n \sum_{k=1}^m KDE_{j,k} \tag{5}$$

where  $KDE_{x,y}$  was the value of the density estimation stored in cell  $x,y$  of the kernel,  $\sum_{j=1}^n \sum_{k=1}^m KDE_{j,k}$  was the sum of all the KDE values over the entire surface of the kernel density estimation, and  $n$  and  $m$  are the  $x$  and  $y$  dimensions of the KDE, respectively. Using Esri ArcMap 10.3 software, the sum of all the KDE cell values was obtained by multiplying the average value by the total number of cells. For a real random variable,  $X$ , the corresponding c.d.f. is given by:

$$F_X(x) = P(X \leq x), \tag{6}$$

where  $F_X(x)$  represents the probability that the considered random variable,  $X$ , will assume a value equal or less than  $x$  (Nicholson, 2014). By substituting  $X$  and  $x$  with the modelled  $L_{eq}$  values (Eq. (3)) and  $P$  values with the  $P_{x,y}$  values computed from Eq. (5), Eq. (6) was rewritten as:

$$F_{L_{eq}} = \sum P_{x,y}(L') \text{ where } L' \leq L_{eq}, \tag{7}$$

where  $F_{L_{eq}}$  is the cumulative probability of having an animal (or group of animals) exposed to a noise value equal or less than  $L_{eq}$ . To create the c.d.f. for each vessel category,  $v$ , a python script was used to iteratively compute cumulative probability values using Eq. (7) starting from  $L_{eq} = \min(L_{eq,v})$  and proceeding by 1 dB increases until  $L_{eq} = \max(L_{eq,v})$ . This process allowed for the creation of a set of points representing cumulative probabilities and corresponding  $L_{eq}$  values, for each vessel category, as well as for all the categories combined together. From each distribution,  $L_{eq}$  values corresponding to the 5th, the 50th and the 95th percentiles were computed and used to compare vessel categories in terms of levels of exposure (Table 3).

This approach allowed us to identify, within a specific area, the



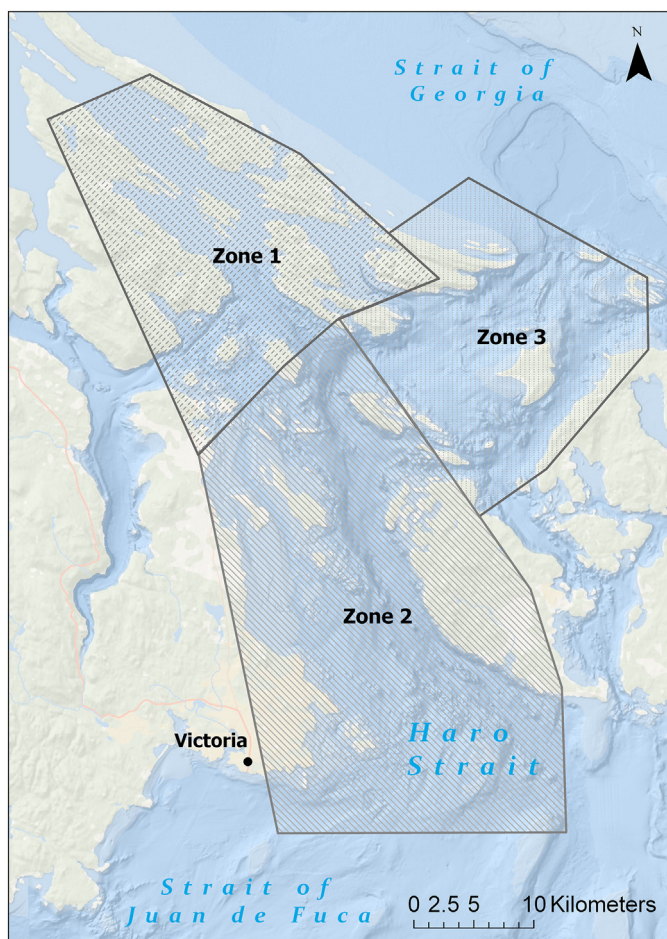


Fig. 6. Zones over which the cumulative distribution functions (c.d.f.) of  $L_{eq}$  values over the KDE describing the entire SRKW population summer core areas were computed.

vessel categories associated with the highest median levels of exposure,  $L_{eq-50^{th}}$ , corresponding to the 50th percentile of the relative c.d.f.. The 5th and 95th percentiles were included to give an indication of the range of variation of the  $L_{eq}$  values attributed to a vessel category within a zone. Since there are no regulations or thresholds relative to the amount of noise from shipping considered to be harmful to SRKW, the  $L_{eq}$  values produced by each category were divided in three exposure level groups:  $L_{eq-50^{th}} < 60 \text{ dB re } 1 \mu\text{Pa}$ ;  $60 < L_{eq-50^{th}} < 90 \text{ dB re } 1 \mu\text{Pa}$ ;  $L_{eq-50^{th}} > 90 \text{ dB re } 1 \mu\text{Pa}$ . The three exposure levels were used to reclassify the noise maps for the categories belonging to the  $L_{eq-50^{th}} > 90 \text{ dB re } 1 \mu\text{Pa}$  group.

### 3. Results

#### 3.1. SRKW sightings

Of the initial 3,150 sightings recorded by Soundwatch volunteers during the summer seasons from 2011 to 2014, only 2,994 were retained for the creation of the KDEs (Table 2). The others ( $n = 156$ ) were removed because they were either incomplete or falling in quadrants with  $E_z = 0$ , thus considered as “off-effort” observations.

SRKW sightings are not evenly distributed within the study area. Out of 444 quadrants, four quadrants (i.e. 175, 180, 183 and 185), located along the west and south-west coasts of San Juan Island, contain approximately 55% of the sightings. The remaining 45% is spread over 131 quadrants, with the majority of the quadrants ( $n = 310$ ) containing no sightings. The three distinct pods; J, K, and L, together

totaled 47% of the sightings, while the pod combinations; JK, JL, KL, and JKL, accounted for 53%. Among the three pods, J (28%) is the most represented, followed by L (15%) and K (4%). Among the pod combinations, JK (22%), is the most represented, followed by JKL (19%), JL (10%) and KL (3%). Spearman's test results showed that the number of contacts and the number of sightings per hour were significantly correlated ( $\rho = 0.88$ ,  $p < 0.05$ ). Quadrants adjacent to the south-west and to the south coast of San Juan Island delineate the area where the number of contacted vessels reached the highest values (Fig. 7A to D). Quadrants located in the immediate vicinity of the abovementioned San Juan area were characterized by an intermediate number of contacts, while the remaining quadrants showed low numbers of vessel contacts (Fig. 7A to D). The effort per unit area derived from Soundwatch boat contacts is variable among years, as well as among zones. 2011 is the year with the highest average effort per unit area ( $E_{z-2011} = 0.433$ ,  $SD_{Ez-2011} = 0.893$ ), followed by 2012 ( $E_{z-2012} = 0.381$ ,  $SD_{Ez-2012} = 0.589$ ), 2013 ( $E_{z-2013} = 0.306$ ,  $SD_{Ez-2013} = 0.685$ ) and 2014 ( $E_{z-2014} = 0.196$ ,  $SD_{Ez-2014} = 0.167$ ). The high standard deviations reflect the wide variability in the effort per unit area among the different zones, ranging from the maximum value of 4.507 contacts per unit area recorded in quadrant 184, to the minimum value of 0.018 recorded in quadrant 122.

#### 3.2. SRKW summer core habitat

Using a bandwidth selection method allowed for the identification of optimal  $h$  values for all four KDEs. The 95% PVC for the K-group was the least fragmented, followed by the entire population, and the J and L groups. The selected 95% PVCs were then used to estimate the full extent of SRKW summer core habitat. The 95% PVC for the entire population (Figs. 8 and 12A) showed the largest extent (i.e., 1805 km<sup>2</sup>). The corresponding minimum and maximum extents obtained from the bootstrap analysis resulted in 864 km<sup>2</sup> and 3333 km<sup>2</sup>, respectively. The J-group 95% PVC (Figs. 9 and 12B) covered an area of approximately 1372 km<sup>2</sup>, with a minimum and maximum extent of 812 km<sup>2</sup> and 2814 km<sup>2</sup>, respectively. The L-group 95% PVC (Figs. 11 and 12C) covered an area of approximately 1142 km<sup>2</sup>, with an estimated minimum and maximum extent of 446 km<sup>2</sup> and 1541 km<sup>2</sup>, respectively. The K-group presented the smallest 95% PVC (Figs. 10 and 12D), covering an area of approximately 1218 km<sup>2</sup>. Minimum and maximum extent for this KDE captured a range of variation between 180 km<sup>2</sup> and 1007 km<sup>2</sup>, indicating that the estimated KDE might not be representative of the K-group core summer area (Fig. 12D).

The south-western coast of San Juan was identified as part of the 50% PVC in each one of the KDEs. The 50% PVCs also included pod specific areas, one for each pod-group. The J-group 50% PVC also included an area of approximately 32 km<sup>2</sup> extending from the northern shore of Stuart Island to the southern shore of Pender Islands. The K group 50% PVC also included an area of approximately 40 km<sup>2</sup> located on the eastern outskirts of Tumbo and Saturna islands. The L-group 50% PVC also included an area of approximately 14 km<sup>2</sup> located between the islands of Salt Spring in the south and Galiano in the north. The KDE of the entire population did not identify these pod-specific areas as high use areas and only identified the South-western coast of San-Juan as SRKW summer core area. The OLS analysis showed a positive correlation between the KDE relative to the entire population and the distribution of the BCCSN sightings-per-unit-effort ( $R^2 = 0.58$ ,  $p < 0.05$ ). Since no pod designation was included in the BCCSN sightings-per-unit-effort map, the test could not be performed for the remaining three KDEs. For this reason, the evaluation of noise exposure levels was limited to the KDE relative to the entire population (Fig. 8A).

#### 3.3. Spatial noise exposure risk by vessel categories

The c.d.f. relative to the total traffic showed median values of 110 dB re 1  $\mu\text{Pa}$  ( $L_{eq-5^{th}} = 95 \text{ dB re } 1 \mu\text{Pa}$ ,  $L_{eq-95^{th}} = 126 \text{ dB re } 1 \mu\text{Pa}$ ),

**Table 2**

SRKW sightings summarized by pod, pod-combination, and pod-group. The number of sightings and percentages relative to the total are reported. The J-group represents 60% of the sightings, with J-pod, JK and JL pod-combinations accounting for 47%, 36% and 17% of the J-group sightings, respectively. The K-group represents 5.5% of the sightings, with K-pod and the KL pod-combination accounting for 62% and 38% of the K-group sightings, respectively. The L-group represents 44% of the sightings, with L-pod and the JKL pod-combination accounting for 44% and 56% of the L-group sightings, respectively. Pod-groups were first defined and used by Hauser et al. (2007).

Pod-group	Pod			Pod combination				Total
	J	K	L	JK	JL	KL	JKL	
J-group	848 (47%)	–	–	660 (36%)	295 (17%)	–	–	1803 (60.23%)
K-group	–	102 (62%)	–	–	–	62 (38%)	–	164 (5.47%)
L-group	–	–	457 (44%)	–	–	–	570 (56%)	1027 (34.30%)
Total (%)	28%	4%	15%	22%	10%	3%	18%	2994

**Table 3**

$L_{eq}$  values corresponding to the 5th ( $p = 0.05$ ), 50th ( $p = 0.5$ ) and 95th ( $p = 0.95$ ) percentiles of the c.d.f. of each vessel category over Zone 1, 2 and 3 (Figs. 12, 13 and 14). For each zone, the assigned exposure levels ( $L_{eq-50^{th}} < 60$ ;  $60 < L_{eq-50^{th}} < 90$ ;  $L_{eq-50^{th}} > 90$ ) are reported. Pooled categories are in bold.

Zone 1				Zone 2				Zone 3						
Category	$L_{eq}$			Exposure Level $L_{eq-50^{th}}$ (dB re 1 $\mu$ Pa)	Category	$L_{eq}$			Exposure Level $L_{eq-50^{th}}$ (dB re 1 $\mu$ Pa)	Category	$L_{eq}$			Exposure Level $L_{eq-50^{th}}$ (dB re 1 $\mu$ Pa)
	0.05	0.5	0.95			0.05	0.5	0.95			0.05	0.5	0.95	
Ferries	70	110	125	> 90	<b>Tugboats</b>	94	101	107	> 90	<b>Tugboats</b>	86	99	106	> 90
<b>Tugboats</b>	80	101	110		<b>Containers</b>	81	98	106		<b>Containers</b>	77	98	106	
Vehicle carriers	59	94	112		<b>Bulkers</b>	73	97	107		<b>Bulkers</b>	76	97	105	
Recreational vessels	75	90	95		Vehicle Carriers	72	93	107		Vehicle Carriers	71	94	104	
Fishing vessels	69	88	95	60–90	Tankers	72	88	99	60–90	Tankers	67	88	98	60–90
Naval vessels	77	86	93		<b>Ferries</b>	76	88	109		Naval Vessels	78	86	94	
<b>Containers</b>	61	85	92		Naval vessels	79	87	96		<b>Ferries</b>	78	85	98	
<b>Bulkers</b>	61	82	97		Recreational vessels	80	87	92		Government/research	65	81	89	
Other	71	81	90		Fishing vessels	76	87	94		<b>Passenger</b>	68	81	89	
Government/research	38	79	93		<b>Passenger</b>	62	80	91		Recreational vessels	62	80	87	
Tankers	44	64	85		Government/research	71	78	88		Fishing vessels	67	79	86	
<b>Passenger</b>	2	56	74	< 60	Other	67	77	86		Other	70	79	88	
<b>Crude oil tankers</b>	24	40	54		<b>Crude oil tankers</b>	45	69	83		<b>Crude oil tankers</b>	34	60	76	
Reefers	22	32	49		Reefers	26	44	55	< 60	Reefers	36	55	65	< 60

107 dB re 1  $\mu$ Pa ( $L_{eq-5^{th}} = 97$  dB re 1  $\mu$ Pa,  $L_{eq-95^{th}} = 114$  dB re 1  $\mu$ Pa) and 105 dB re 1  $\mu$ Pa ( $L_{eq-5^{th}} = 95$  dB re 1  $\mu$ Pa,  $L_{eq-95^{th}} = 112$  dB re 1  $\mu$ Pa) for Zone 1, Zone 2 and Zone 3, respectively. By analyzing the single c.d.f. curves (Figs. 13, 14 and 15), vessel categories were divided into three groups. Vessels having > 50% of their c.d.f. falling under  $L_{eq}$  values < 60 dB re 1  $\mu$ Pa were considered as belonging to a “Low Level” exposure group. Vessels having > 50% of their c.d.f. values falling between 60 dB re 1  $\mu$ Pa and 90 dB re 1  $\mu$ Pa were considered as belonging to a “Medium Level” exposure group. Vessels having > 50% of their c.d.f. values falling above 90 dB re 1  $\mu$ Pa were considered as belonging to a “High Level” exposure group. For example, since 50% of the Crude Oil Tankers' c.d.f. within Zone 1 fell below 60 dB re 1  $\mu$ Pa (Fig. 13), this vessel category was assigned to the low level exposure group in this location. However, since, in Zone 2 and 3, > 50% of the Crude Oil Tankers' c.d.f. was comprised within 60 re 1  $\mu$ Pa and 90 re 1  $\mu$ Pa (Figs. 13 and 14), the category belongs to the medium level exposure group in these two locations. Classification of the modelled vessel categories and corresponding  $L_{eq}$  values are reported in the following paragraphs and in Table 3.

Within Zone 1 (Fig. 13), four vessel categories were identified as

having an  $L_{eq-50^{th}} > 90$  dB re 1  $\mu$ Pa: Ferries ( $L_{eq-50^{th}} = 110$  dB re 1  $\mu$ Pa); Tugboats < 50 m ( $L_{eq-50^{th}} = 101$  dB re 1  $\mu$ Pa), Vehicle Carriers ( $L_{eq-50^{th}} = 94$  dB re 1  $\mu$ Pa) and Recreational Vessels ( $L_{eq-50^{th}} = 90$  dB re 1  $\mu$ Pa). Of the remaining 10 categories, seven (i.e. Fishing Vessels, Naval Vessels, Containers, Bulkers, Government/Research, Tankers, Other) were identified as having  $L_{eq-50^{th}}$  values comprised between 60 and 90 dB re 1  $\mu$ Pa, while 3 (i.e. Passenger, Crude Oil -tankers, Reefers) showed  $L_{eq-50^{th}} < 60$  dB re 1  $\mu$ Pa. Within Zone 2 (Fig. 14), four vessel categories were identified as having an  $L_{eq-50^{th}} > 90$  dB re 1  $\mu$ Pa: Tugboats ( $L_{eq-50^{th}} = 101$  dB re 1  $\mu$ Pa), Containers ( $L_{eq-50^{th}} = 98$  dB re 1  $\mu$ Pa), Bulkers ( $L_{eq-50^{th}} = 97$  dB re 1  $\mu$ Pa), Vehicle Carriers ( $L_{eq-50^{th}} = 93$  dB re 1  $\mu$ Pa). Of the remaining 10 categories, nine (i.e. Tankers, Ferries, Naval Vessels, Recreational Vessels, Fishing Vessels, Passenger, Government/Research, Crude Oil Tankers, Other) were identified as having  $L_{eq-50^{th}}$  values comprised between 60 and 90 dB re 1  $\mu$ Pa, while only Reefers showed  $L_{eq-50^{th}} < 60$  dB re 1  $\mu$ Pa. Within Zone 3 (Fig. 15), four vessel categories were identified as having an  $L_{eq-50^{th}} > 90$  dB re 1  $\mu$ Pa: Tugboats ( $L_{eq-50^{th}} = 99$  dB re 1  $\mu$ Pa), Containers ( $L_{eq-50^{th}} = 98$  dB re 1  $\mu$ Pa), Bulkers ( $L_{eq-50^{th}} = 97$  dB re 1  $\mu$ Pa), Vehicle Carriers ( $L_{eq-50^{th}} = 94$  dB re 1  $\mu$ Pa). Of the remaining 10

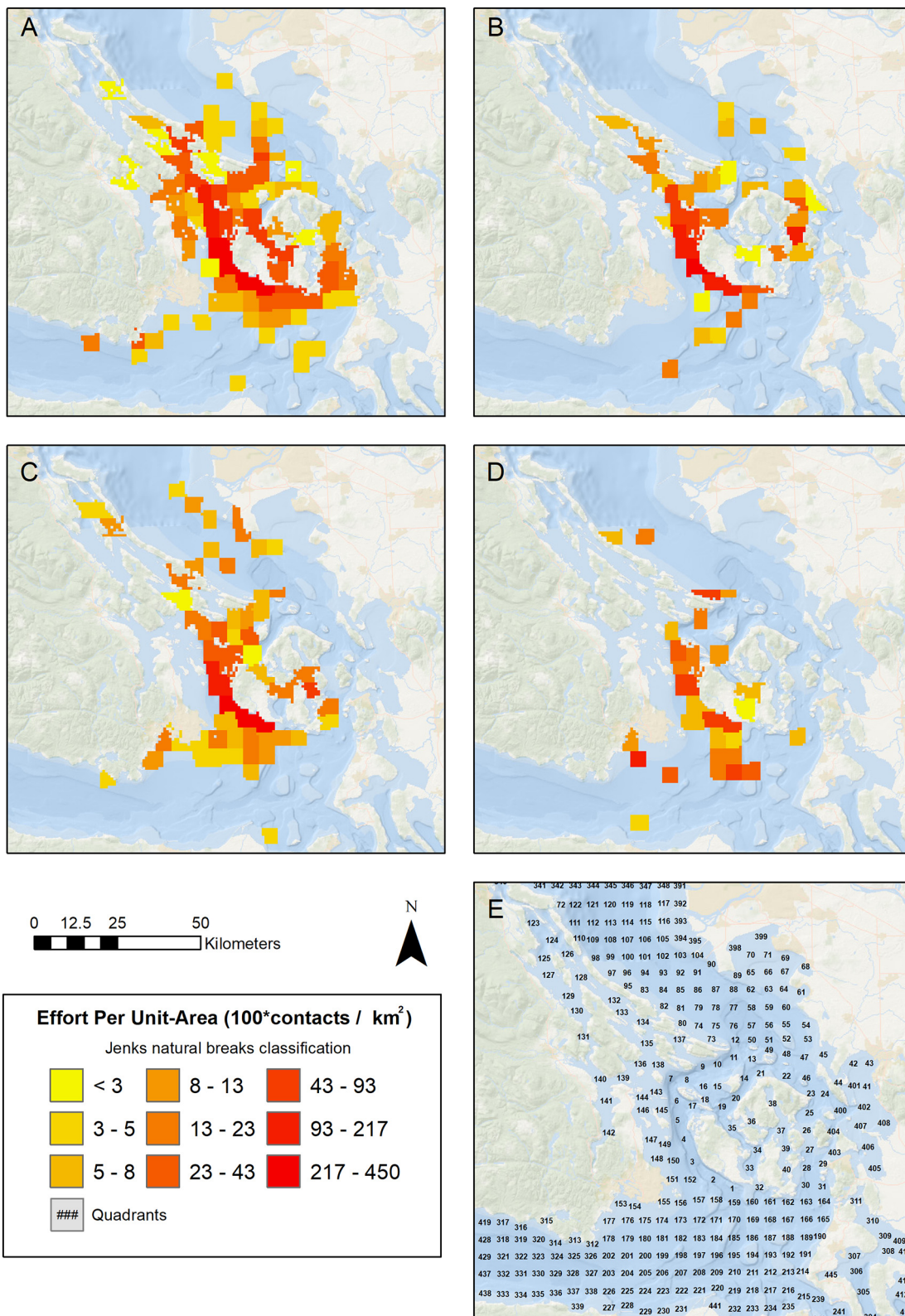
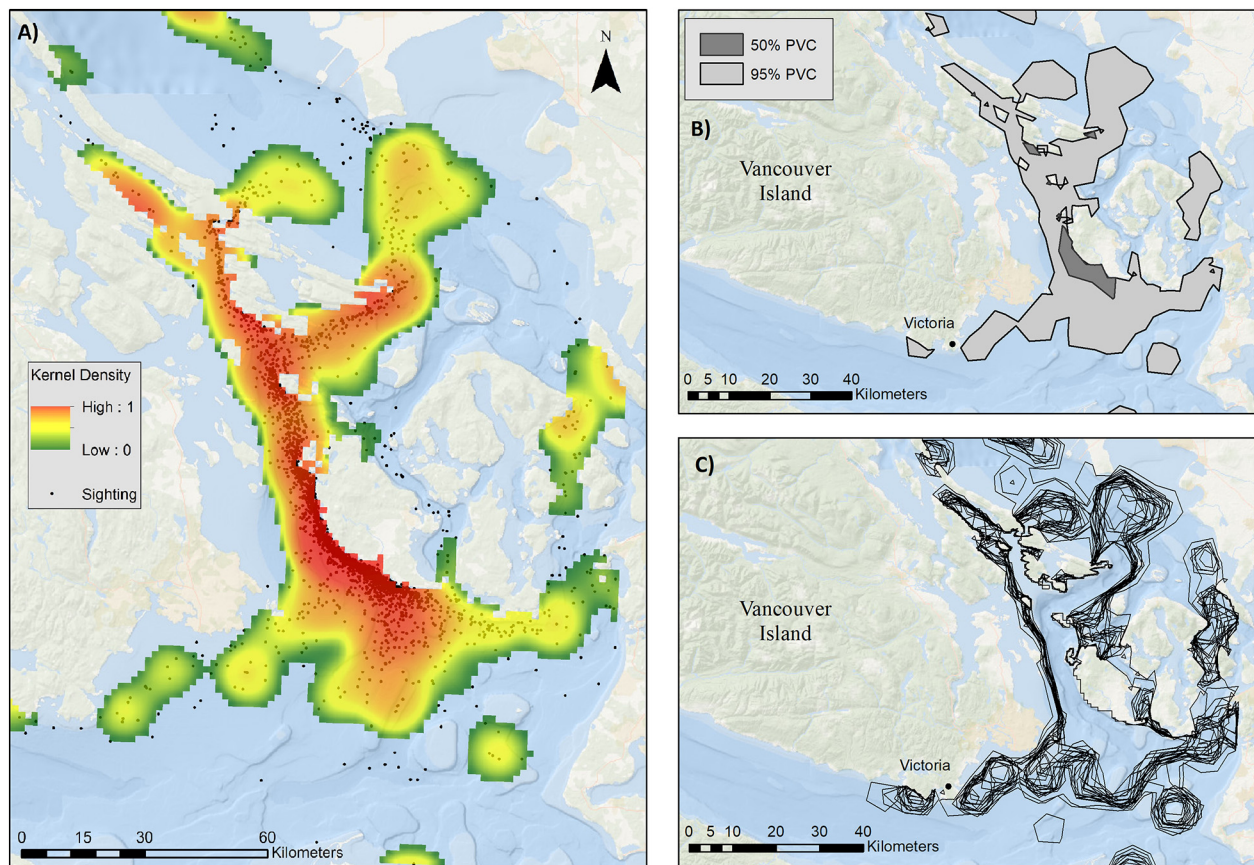


Fig. 7. Distribution of Soundwatch effort across the study area for the years 2011 (A), 2012 (B), 2013 (C) and 2014 (D). Quadrants used to compile the Southern Resident Sighting Compilation (E).

categories, nine (i.e. Tankers, Naval Vessels, Ferries, Government/Research, Passenger, Recreational Vessels, Fishing Vessels, Crude Oil Tankers, Other) were classified as medium exposure categories, while only Reefers were identified as a low exposure categories.

### 3.4. Exposure maps

Exposure maps were produced for the six vessel categories belonging to the “High Level” exposure group (Fig. 16). Some of these categories showed analogous *L<sub>eq</sub>* distribution patterns, while others



**Fig. 8.** Results of the kernel density analysis for the entire SRKW population. A) KDE values within the 95% PVC and SRKW sightings. B) The extent of the 95% (light gray) and 50% (dark gray) PVCs. C) Results of the bootstrap procedure, for visualization purposes only the first 20 iterations are displayed.

displayed a unique pattern. Containers (Fig. 16E) and Bulkers (Fig. 16F), were characterized by high exposure levels ( $L_{eq-50^{th}} > 90$  dB re 1  $\mu$ Pa) covering approximately 50% of both Zone 2 and 3 and by medium exposure levels ( $60 < L_{eq-50^{th}} < 90$  dB re 1  $\mu$ Pa) within Zone 1.

Ferries (Fig. 16A) were characterized by high exposure levels concentrated in Zone 1 and in the northern portion of Zone 2, while the central portion of Zone 2 and the majority of Zone 3 displayed medium exposure levels. Recreational Vessels (Fig. 16C) displayed high exposure levels concentrated in the center of Zone 1 and along the western portion of Zone 2. When compared to other classes, areas with high exposure values from Recreational Vessels showed the smallest extent. High exposure levels from tugs (Fig. 16B) covered the majority of all the three zones, with only small portions characterized by a medium or low exposure level. Showing a similar pattern, vehicle carriers (Fig. 16D) displayed high exposure levels over approximately half of each one of the three zones.

#### 4. Discussion

Findings in this study complement and update findings from previous studies that identified the same SRKW summer core areas (Hauser et al., 2007, Fisheries and Oceans Canada (DFO), 2011). However, the high spatial resolution of the KDEs produced in this study and the large number of observations considered for their computation allowed us to describe current SRKW summer areas at a finer spatial scale. By combining these distributions with vessel noise maps, we also provide a first insight into the locations of areas characterized by high levels of noise exposure for part of the SRKWs critical habitat within the central Salish Sea. Such information can help support the management of this endangered population.

##### 4.1. SRKW summer core areas

A large core area, commonly used by all three pods as evinced by the 50% PVCs, was identified along the south-western shore of San Juan Island (Fig. 1C). Foraging on Chinook salmon is the main activity undertaken by members of SRKW within the boundaries of this core area (Hanson et al., 2010; Scott-Hayward et al., 2015) and vessel traffic off the coast of San Juan has been associated with the disruption of SRKW feeding behavior (Lusseau et al., 2009). This area in the Haro Strait borders international shipping lanes, making it likely that individuals belonging to all three pods, when feeding here, will at times be exposed to high levels of noise from vessel sources. Moreover, potential disturbance from noise may vary among different groups. For example, the current San Juan core area for the L-group extends southwards into the Strait of Juan de Fuca, reaching the northern end of Hein Bank, while the K and J groups current core areas are between Eagle Point and Hanbury Point, representing the southern and northern ends, respectively. Looking at the pod-specific areas identified by the 50% PVCs, the J and K specific core areas (Figs. 9B and 10B) overlap with the international shipping lane, while the L-group specific core area (Fig. 11B) is located in a portion of the Salish Sea characterized by relatively low levels of traffic from large vessels. Pod-groups include multiple pods formed by SRKW. For example, the J-group includes observations of individuals all belonging to the J-pod, but also mixed groups such as JK and JL. These mixed groups are usually short-term associations between members of different pods (Hauser et al., 2007). Our approach did not allow us to draw pod-specific conclusions. However, as noted by Hauser et al. (2007), the long-lasting social associations (i.e. J, K, and L) may be driving the movement and space use of the less frequent mixed groups. For example, the J-pod appeared to be driving the spatial distribution of the JK and JL pod combinations, and similar observations

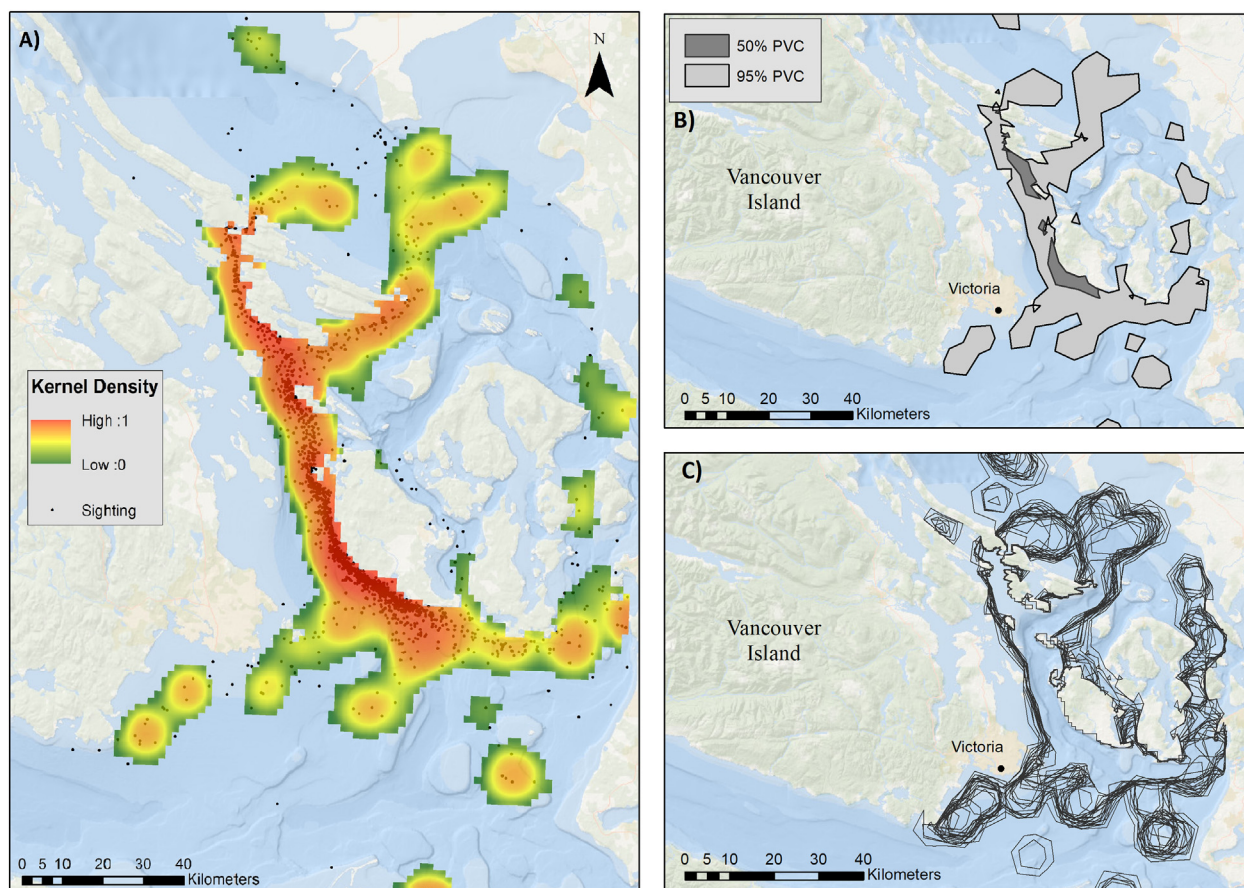


Fig. 9. Results of the kernel density analysis for the J-group. A) KDE values within the 95% PVC and J-pod sightings. B) The extent of the 95% (light gray) and 50% (dark gray) PVCs. C) Results of the bootstrap procedure, for visualization purposes only the first 20 iterations are displayed.

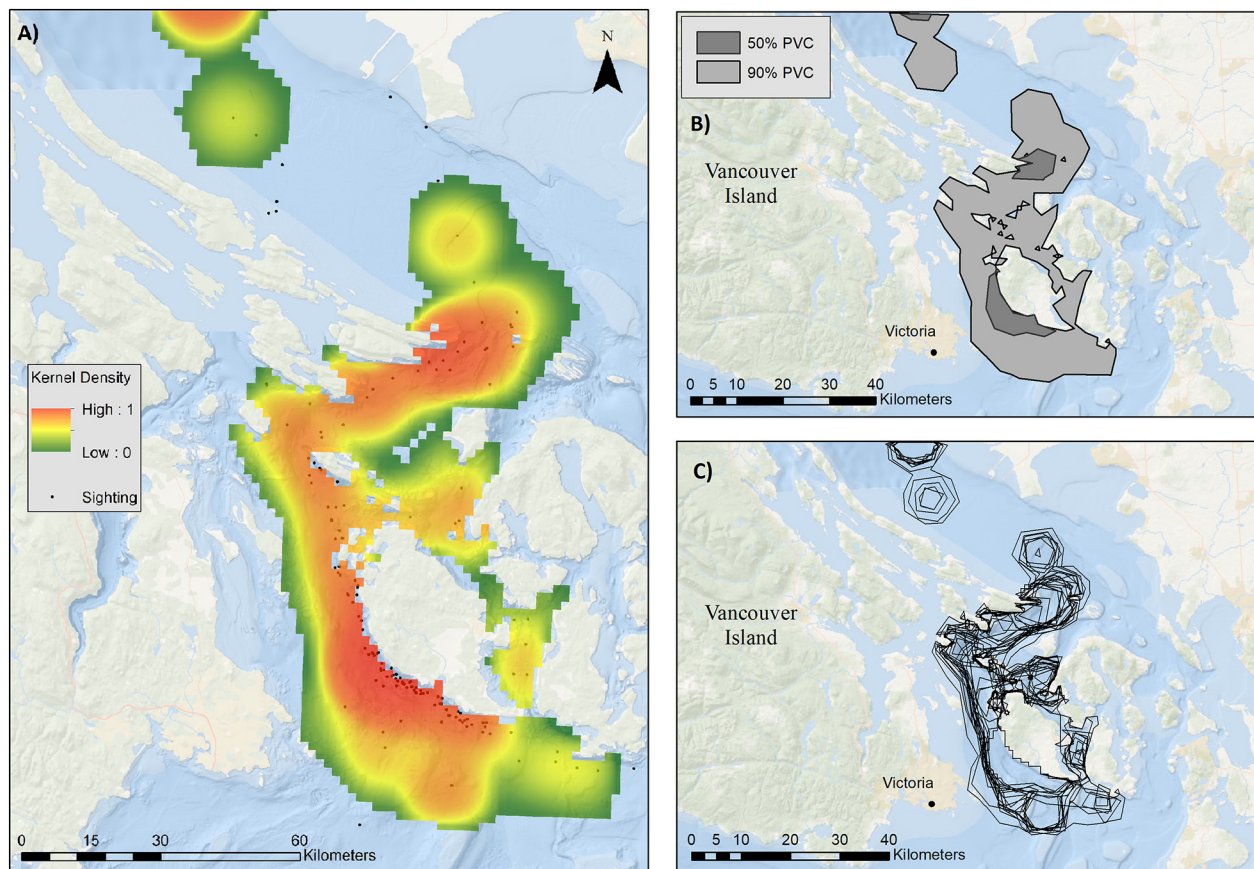
were made for the K and L groups.

Estimating data uncertainty is thought to be fundamental for incorporating species distribution studies into conservation planning (De Ornellas et al., 2011; McShea, 2014; Scott-Hayward et al., 2015). In this study, the bootstrap iteration allowed for an estimation of uncertainty related to the KDEs, providing upper and lower boundaries of the summer core areas for which there has been Soundwatch activity. According to the results of the bootstrap iteration (Fig. 12D), the KDE representing the K-group (Fig. 10C) overestimated the extent of the corresponding core area. This is probably associated with the relatively low number of K-group sightings available for this study (Table 2). However, this overestimate is not only influenced by biases in the methodology, but also a result of SRKW's peculiar population structure. K-pod is the least numerous of the three pods, made up of only four matriline, comprising of only 18 individuals, consequently, further data needs to be collected to improve the quality of this pod's core area estimation. Since the Strait of Juan de Fuca, the Strait of Georgia and the Northern Gulf Islands are rarely frequented by Soundwatch, the KDEs are probably unreliable across these areas. For this reason, none of the three analyzed zones included portions of the KDEs extending over these three areas. Biases related to the uneven spatial and temporal distribution of sightings effort could also have influenced the reported location of the pod-specific core areas. Soundwatch mainly operates where private boaters are more likely to encounter members of SRKW, and, in some years the activity is limited to the South-west coast of San Juan Island (Fig. 7). Similarly, most of Soundwatch activities are undertaken within US waters, a bias that might have caused underestimations of the extent of SRKW summer areas within Canadian waters. Data from Straitwatch, the Canadian counterpart of Soundwatch, could not be accessed and included in our study, but could be used in

the future to refine our analyses. The positive correlation observed between the KDE relative to the entire population and the BCCSN sightings-per-unit-effort map indicates that the KDE effectively depicts SRKW summer distribution within the study area. The low  $R^2$  value obtained from the OLS analysis might be due to the different spatial resolution of the two maps: 800 m and approximately 5 km for the KDE and the BCCSN sightings-per-unit-effort map, respectively. Another factor affecting the level of correlation between the two estimates could be related to the inclusion, in the BCCSN dataset, of both the resident (i.e. northern and southern) and transient (Bigg's) killer whale ecotypes occurring in the Salish Sea. Due to these limitations, noise exposure levels were evaluated only for the KDE describing the entire population summer core area. Nonetheless, the identification of pod-specific areas suggests that the three pods constituting SRKW could be exposed to different levels of noise from shipping.

#### 4.2. Spatial noise exposure risk by vessel categories

This study considered cumulative noise expressed as unweighted equivalent time-averaged sound pressure level ( $L_{eq}$ ), resulting from the long-term integration of time-varying sound exposure. More specifically, in this study  $L_{eq}$  represents the average rate of accumulation of sound exposure over a period of a month. When computed over prolonged periods of time,  $L_{eq}$  will tend toward an asymptotic value. Assuming that the daily vessel traffic is broadly similar throughout the month, the monthly accumulation rate will be comparable to the daily accumulation rate of sound exposure experienced by SRKW within the study area.  $L_{eq}$  is a commonly used metric for the assessment of human exposure to continuous, non-physically damaging noises (Maling Jr., 2007). Analogous to the measurement of human noise exposure, the  $L_{eq}$



**Fig. 10.** Results of the kernel density analysis for the K-group. A) KDE values within the 95% PVC and K-pod sightings. B) The extent of the 95% (light gray) and 50% (dark gray) PVCs. C) Results of the bootstrap procedure, for visualization purposes only the first 20 iterations are displayed.

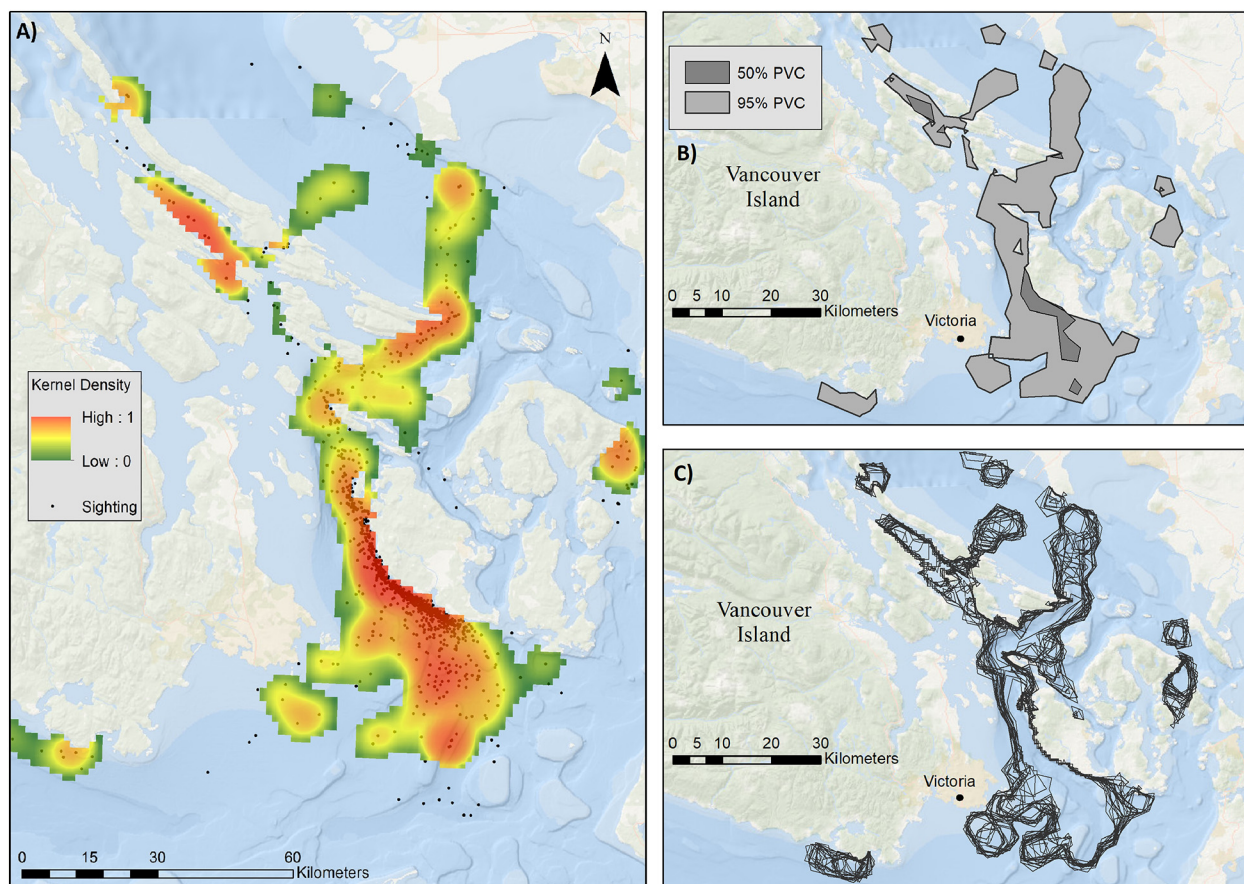
maps from this study may be understood as a measure of typical daily noise exposure for whales at different geographic locations within the study area. An animal (or group of animals), occupying a cell of the model may be exposed to higher or lower sound levels at any particular instant, but the long-term exposure will tend toward the average value (i.e.  $L_{eq}$ ). Since animals are known to move within the study area, having a member of SRKW continuously occupy a single cell for a day would be very unlikely. The results presented, therefore, should be seen as the maximum exposure an animal would receive if it were to stay within the same general area. The  $L_{eq}$  at a given percentile level (e.g.  $L_{eq-50\%}$ ), therefore, expresses the probability for a pod (or group) to accumulate a certain amount of daily noise exposure within such an area. Thus, while the modelled  $L_{eq}$  values used in the present study were not intended to provide a cause-effect relationship between noise exposure and its impacts on the population, it is nonetheless a useful proxy to identify areas characterized by a higher risk of exposure for SRKW on the basis of the spatial distribution of vessels as sources of noise and killer whales as receivers. Furthermore, a study measuring variation in stress hormones in North Atlantic Right Whales showed that after the events of September 11, 2001 resulting in fewer commercial vessels travelling through Right Whale habitat causing a 6 dB drop in sound levels, stress hormones in whale fecal samples were reduced (Rolland et al., 2012). The authors, however, did not differentiate between the potential effects of ship presence and noise presence in their study.

The computation of the c.d.f. allowed taking into account the probability of observing SRKW within a specific cell of the KDE during the summer months. Furthermore, the use of c.d.f. suggests that both the spatial and temporal components of commercial shipping should be considered when introducing management solution aimed at the reduction of chronic noise pollution.

The various ship categories considered in this study were characterized by different cumulative distribution functions which could be grouped based on their 50th percentiles. Ferries, Tugboats, Vehicle Carriers and large commercial ships (i.e. Container Ships, Bulkers) produced the highest levels of sound exposure for SRKW within their summer core areas. Ferries, Tugboats, and large commercial ships are also responsible for the vast majority of the sound energy input by commercial vessels in the Salish Sea (MacGillivray et al., 2017).

The modelled  $L_{eq}$  values are driven by the source levels (SL) (Table 1), the SPL scaled to nominal distance of 1 m from the source, estimated for each vessel category. Container ships are the category of commercial ships that produces the highest SLs. SLs reaching 178 dB re 1  $\mu$ Pa have been estimated from container ships transiting through Haro Strait (Veirs et al., 2016). Source levels of 183 dB re 1  $\mu$ Pa and of 185 dB re 1  $\mu$ Pa have been estimated from container ships navigating the waters of Puget Sound (Bassett et al., 2012), both in the Salish Sea, and in Santa Barbara Channel (McKenna et al., 2012), along the coast of California. Tugboats show lower estimated source levels: 170 dB re 1  $\mu$ Pa (Bassett et al., 2012; Veirs et al., 2016). Tugboats navigate at relatively constant low speeds, one of the main factors influencing the amount of noise produced by a vessel (McKenna et al., 2013), but their cargo, can be highly variable. Therefore, source levels estimated from a small sample of Tugboats or limited to a small area, might not capture the full extent of Tugboats' noise emissions. One of the factors making ferries one of the main contributors to the cumulative noise within SRKW summer core areas is that ferries travel the same route several times a day while other vessel categories are less frequent.

The use of estimated SL also introduces an element of uncertainty in the modelled  $L_{eq}$  values. A recent study (Veirs et al., 2017) demonstrated how approximately half of all noise energy released in Haro Strait is produced by approximately 15% of the total commercial fleet.



**Fig. 11.** Results of the kernel density analysis for the L-group. A) KDE values within the 95% PVC and L-pod sightings. B) The extent of the 95% (light gray) and 50% (dark gray) PVCs. C) Results of the bootstrap procedure, for visualization purposes only the first 20 iterations are displayed.

These “large” noise polluters are characterized by SLs > 179 dB re 1  $\mu$ Pa, indicating that a small population of particularly loud vessels might be affecting the average SL attributed to a category. The SL of a ship is highly variable depending on speed, draught, maintenance, as well as several other factors, and actual cumulative noise levels could only be established through the use of models validated for particular ships navigating in a specific environment. In order to validate the results of the cumulative model, the modelled received levels were compared with the available vessel noise measurements in the Salish Sea (Fig. 4).

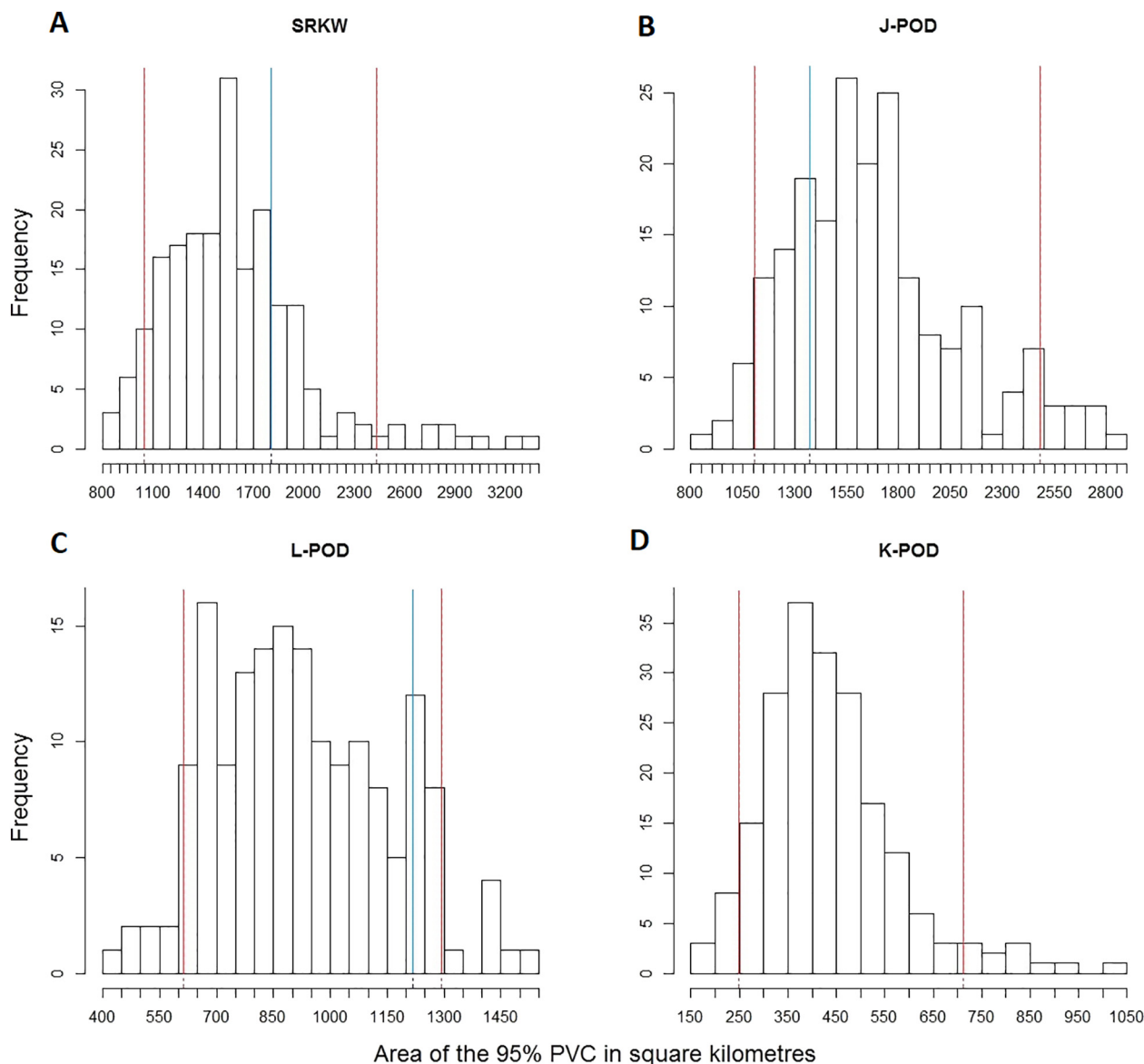
Another limitation of the cumulative noise model used in this study is that AIS data inevitably underestimates the actual density of ships in the Salish Sea, as not all the categories considered in this study are equipped with mandatory AIS devices. This is particularly true for recreational vessels which resulted to be a category associated with high levels of exposure within Zone 1 (Fig. 16C and Table 3). This result might be underestimating the actual contribution of recreational traffic to the cumulative noise experienced by SRKW because only a small fraction of the private pleasure crafts, fishing vessels and whale watching boats are equipped with AIS transponders. Consequently, an analysis of these specific sources of noise is highly recommended.

#### 4.3. Management implications

Our results can help inform decisions relative to ship traffic within the study area and help design scenarios that could reduce noise from shipping within SRKW summer core areas. From August 7 until October 6th, 2017, the Vancouver Fraser Port Authority introduced a voluntary speed limit of 11 kn for all the traffic transiting within SRKW summer core area (VFPA ECHO Program). Since most of the large commercial

ships transiting through Haro Strait move at speeds of approximately 8 m/s (i.e. 15.5 kn) and since the traffic is concentrated within the international shipping lane, this management solution aims to reduce the noise produced by these vessel categories. However, within the study area, Tugboats move at speeds below 6 m/s (i.e. 11.5 kn) and showed, for the month of July 2015, a volume of traffic approximately 4 times larger than the traffic volume of large commercial ships (MacGillivray et al., 2017). The imposition of an 11 kn speed limit to this category might not reduce its contribution to the cumulative noise within SRKW core areas. Even for those categories which are affected by the slow-down protocol, reducing vessel speed increases the duration of noise exposure (albeit, at a lower sound level). Thus, it remains uncertain to what extent slowdown mitigations reduce acoustic impacts on SRKW. Future work should investigate how the introduction of slow-downs affects the duration of noise exposure. A possible approach could be the estimation of noise exposure from a SEL perspective, as reported by McKenna et al. (2013) in the Santa Barbara Channel.

A possible application of these results could be the implementation of speed and density limits for the six vessel categories identified as causing high levels of exposure for SRKW. Vessel density could be controlled by re-routing part of the traffic toward other areas, as well as by imposing a limit on the number of vessels allowed to navigate through an area at the same time. Re-routing vessels navigating through a complex system of narrow seaways and islands, such as the Salish Sea, where there are few alternatives to re-routing vessels, could be challenging. Another possible approach could be the adoption of what DFO defined as “lateral displacement”, the introduction of small changes in the routes typically followed by vessels to avoid ecologically vulnerable areas (Fisheries and Oceans Canada (DFO), 2017b). Although lateral displacement would most likely not be an efficient solution for the



**Fig. 12.** Frequency distribution of the 95% PVCs extent obtained from 200 iterations of the KDE bootstrap procedure for the entire population (A), the J-pod (B), the L-pod (C) and the K-pod (D). Red lines indicate the 5th and 95th percentiles of the distribution, blue lines represent the area of the 95% PVCs obtained from the full dataset for the entire population as well as for each pod. The K-pod (D) 95% PVC area resulted to be greater than the upper limit of the distribution, indicating a possible overestimation of the extent. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

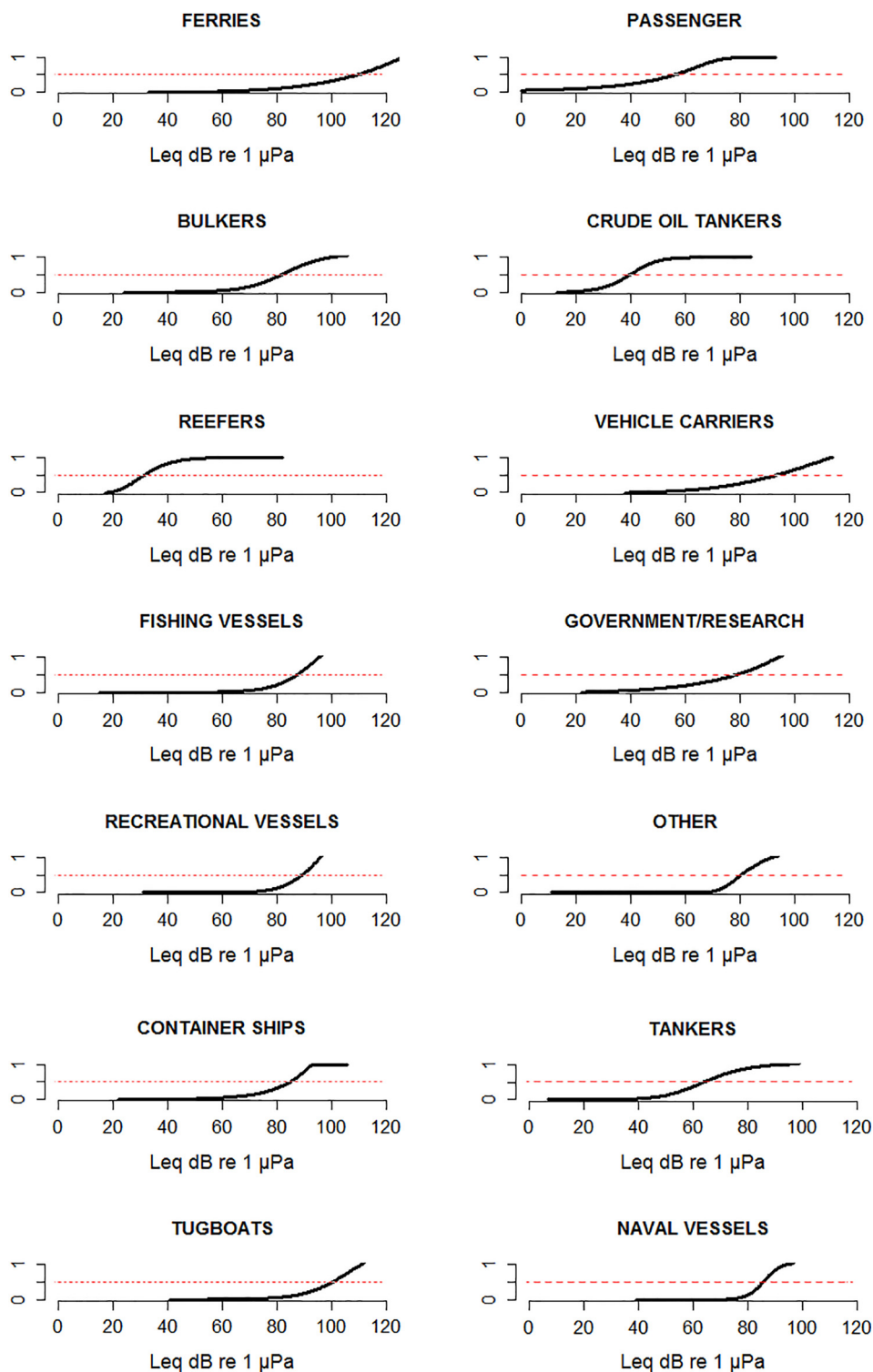
abatement of low-frequency noise, it could lead to a reduction of the amount of high-frequency noise released within SRKW core areas. Furthermore, re-routing and lateral displacement options could be feasible in ports where shipping lanes are not too geographically constrained. Speed limits and avoidance areas have already been implemented to address lethal ship strikes for the North Atlantic Right Whale (NARW) in both the US (Laist et al., 2014) and Canada (Daoust et al., 2017), aiming to achieve a reduction in the number of vessel-caused deaths for this endangered population. Along with the risk of ship strike and entanglement, chronic noise pollution is thought to be a limiting factor for the recovery of the NARW population (Petruny et al., 2014). Ports that are not as geographically constrained, such as Boston's Harbor (US), could more easily adopt re-routing and lateral displacement as strategies to reduce the risk of exposing endangered cetacean species to vessel noise pollution. However, in other areas re-routing would not be challenging, but rather impossible. Representing the main point of access for the Gulf of St. Lawrence and the St. Lawrence Seaway, the Cabot Strait is characterized by a considerable amount of

vessel traffic. In this context, other solutions such as real-time notifications of whale presence, convoying, and the creation of “quiet” periods where navigation is forbidden could be adopted (Fisheries and Oceans Canada (DFO), 2017b). Nonetheless, as recognized by the International Maritime Organization (2014), the ideal long-term solution for the reduction of shipping noise is the adoption of quiet design practices for the construction of commercial vessels.

## 5. Conclusions

In the narrow seaways of the Salish Sea, killer whales are frequently in close proximity to ships, and are therefore exposed to both noise in low- and high-frequencies generated by propeller cavitation (Veirs et al., 2016). For these endangered odontocetes, this might have the dual effect of masking communication, as well as the reception of echolocation signals, thus affecting the feeding success and the social interactions of SRKW. It is important, however, to consider noise pollution as only one of the many anthropogenic impacts affecting this





**Fig. 13.** The c.d.f. curves of the  $L_{eq}$  values modelled within Zone 1 (Fig. 6). A curve was computed for each vessel category producing noise emissions within Zone 1. Cumulative probabilities are on the y axes while the corresponding  $L_{eq}$  values are on the x axis. The red dashed line marks the  $L_{eq-50th}$  for each class (i.e.  $F_{L_{eq}} = 0.5$ ) (Eq. (7)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

marine species. Impact at the population level is likely the result of cumulative impacts from several different stressors interacting with each other. For example, the SRKW population was considered to have 71 individuals in 1973 (Olesiuk et al. 1990), while 76 were reported by the Center for Whale Research in September 2017. In between the population rose to over 90 individuals and declined again and repeated this cycle a few times. The population numbers in one year appeared to

be directly connected to the availability of their main prey, the Chinook salmon (*Oncorhynchus tshawytscha*) during the year before (Ford and Ellis, 2006; Hanson et al., 2010) and periods of decline in the abundance of chinook have been associated with periods of increased mortality rates for SRKW (Ford et al., 2010). The interdependency of these two species is considered so strong that, without the implementation of adequate conservation measures, a full recovery of SRKW might

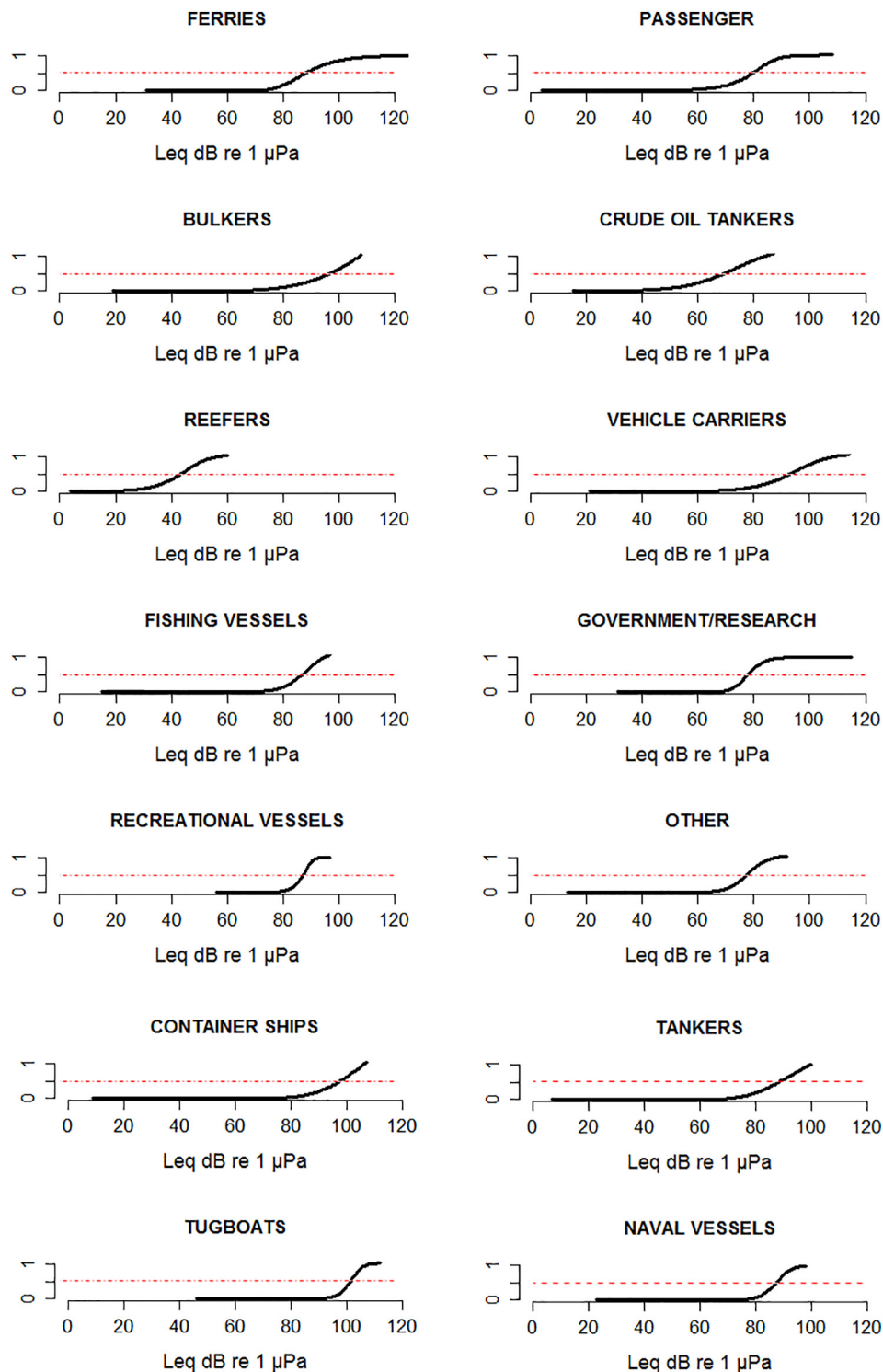
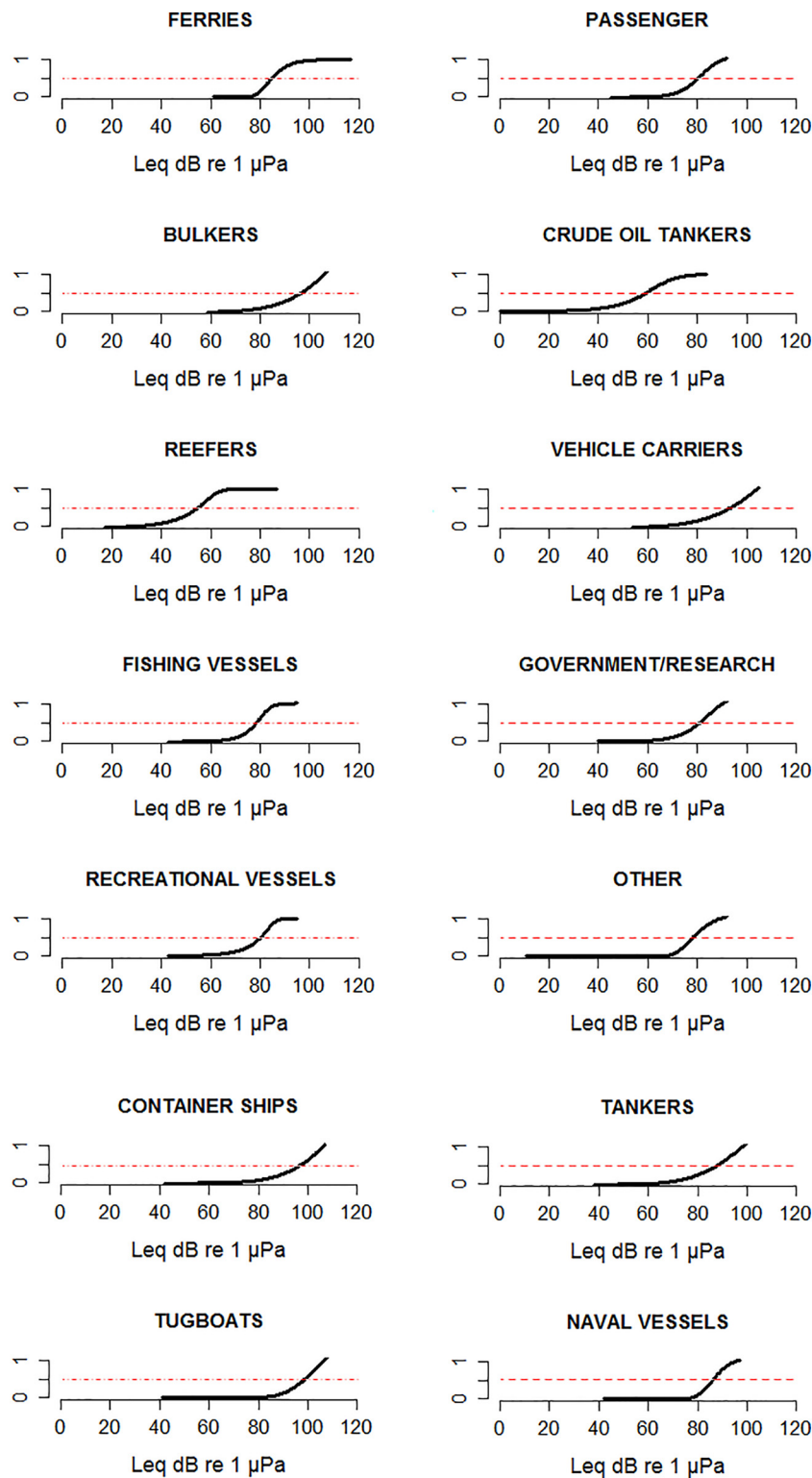


Fig. 14. The c.d.f. curves of the  $L_{eq}$  values modelled within Zone 2 (Fig. 6). A curve was computed for each vessel category producing noise emissions within Zone 2. Cumulative probabilities are on the y axes while the corresponding  $L_{eq}$  values are on the x axis. The red dashed line marks the  $L_{eq-50\%}$  for each class (i.e.  $F_{L_{eq}} = 0.5$ ) (Eq. (7)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

compromise the recovery of Chinook salmon populations (Williams et al., 2011). All killer whales in the North-eastern Pacific also show high levels of contaminants, such as polychlorinated biphenyl (PCB), as well as other pollutants, which have been associated with reduced survival and reproduction rates (Buckman et al., 2011; Lachmuth et al., 2011; Alava et al., 2016). Disturbance from small vessel traffic near the whales may represent another relevant threat to the recovery of SRKW, with positive correlations between increases in small vessel presence

around the animals and reduced foraging rates in this population (Lusseau et al., 2009). Moreover, over the period 2011–2016, the Soundwatch Boaters Education program recorded > 13,300 negative interactions between boats and killer whales that had the potential to damage the animals or interfere with their behavior (Eisenhardt, 2012; Eisenhardt & Koski, 2011, 2013 and 2014; Seely, 2015 and 2016). During 2016 each one of the 77 members of SRKW (Center for Whale Research, 2016) experienced on average approximately 30 negative

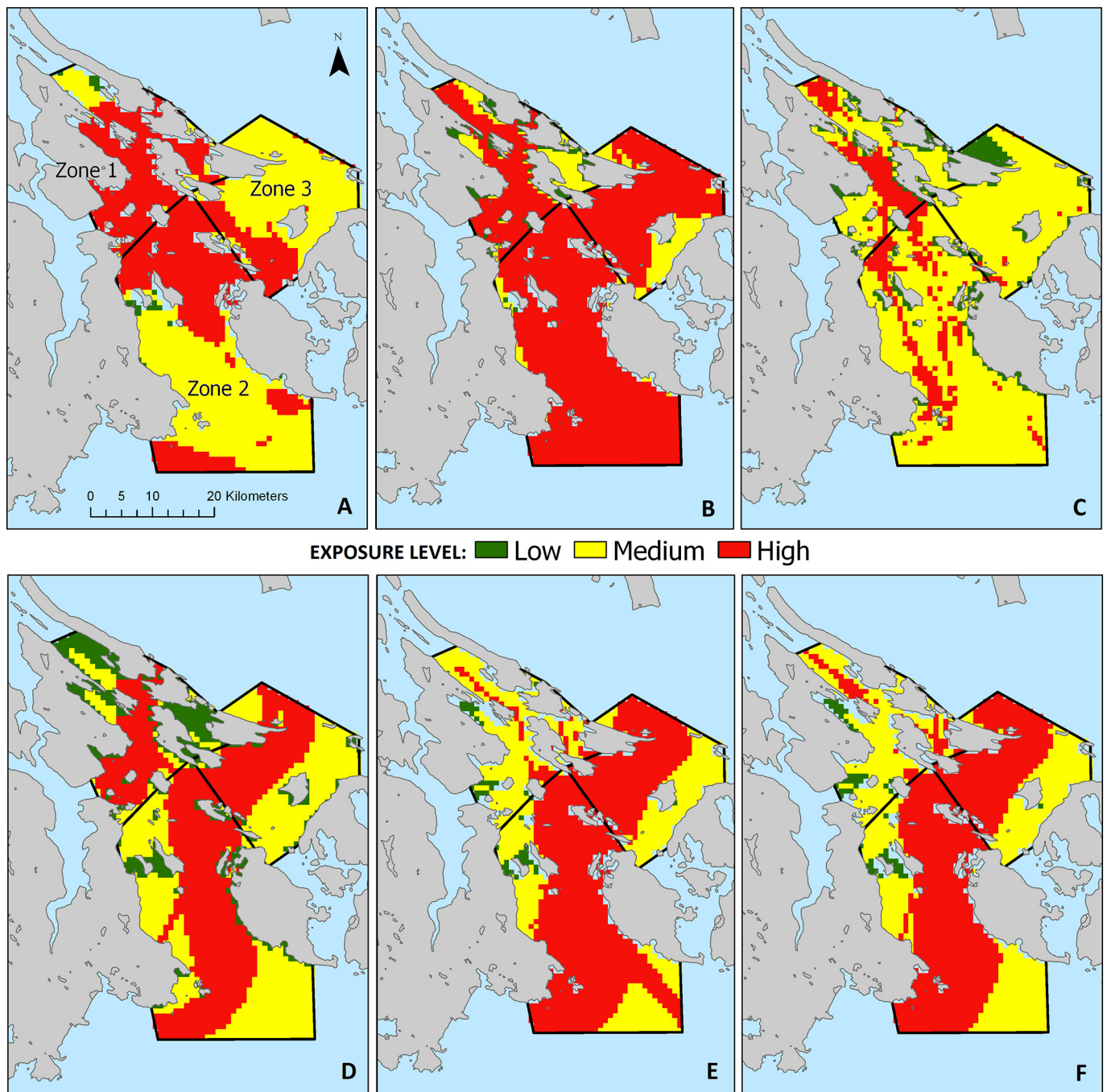


**Fig. 15.** The c.d.f. curves of the  $L_{eq}$  values modelled within Zone 3 (Fig. 6). A curve was computed for each vessel category producing noise emissions within Zone 3. Cumulative probabilities are on the y axes while the corresponding  $L_{eq}$  values are on the x axis. The red dashed line marks the  $L_{eq-50\%}$  for each class (i.e.  $F_{L_{eq}} = 0.5$ ) (Eq. (7)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

interactions with boats. Furthermore, at least one of the six deaths that occurred in 2016, taking SRKW back to population sizes recorded in the late 1980s, was suspected to be the consequence of a ship strike, an unprecedented threat to the survival of this population (Lopes, 2016).

These concurring threats highlight the need for comprehensive adaptive management strategies, in order to ensure the survival of the

SRKW population and to improve the habitat for other marine life. Adaptive management goes beyond the trial and error approach and requires the exploration of alternative strategies including modeling simulations of effects, as well as the systematic evaluation and modification of those strategies through continuous monitoring of effects and outcomes (Aldridge et al., 2004; Allen and Garmestani, 2015). For



**Fig. 16.** Maps showing exposure levels for ferries (A), tugboats (B), recreational vessel (C), vehicle carriers (D), containers (E) and bulkers (F). Low exposure levels (green) correspond to  $L_{eq} \leq 60$  dB re 1  $\mu$ Pa, medium exposure levels (yellow) correspond to  $60 < L_{eq} \leq 90$  dB re 1  $\mu$ Pa while high exposure levels (red) correspond to  $L_{eq} > 90$  dB re 1  $\mu$ Pa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

these reasons, appropriate adaptive management measures for the reduction of cumulative noise from shipping in the Salish Sea should be adopted. For example, although speed is generally correlated with the noise emitted by commercial ships, the relationship between speed and noise varies among vessel types and propulsion systems (Wales and Heitmeyer, 2002; McKenna et al., 2012), suggesting that the effectiveness of improving SRKW habitat via vessel slowdown needs to be tested and compared with other methods. It may turn out that, in addition to slowdowns, other strategies are needed to address this complex issue. For example, modifying existing shipping routes, as suggested by IMO's guidelines (International Maritime Organization, 2014), represents another possible strategy for the reduction of vessel

noise.

However, in the absence of a regulatory framework addressing the issue of oceanic anthropogenic noise and its impacts, the successful application of quieting measures is dependent on voluntary compliance by noise producers. Although noise has been included in SRKW recovery strategy as a source of disturbance (Fisheries and Oceans Canada (DFO), 2016), currently no law limiting chronic anthropogenic noise output in the ocean exists in Canada. Yet, a regulatory infrastructure that recognizes noise as a marine pollutant already exists. The United Nations Convention on the Law of the Sea (UNCLOS) is at the core of many national and international regulations for the protection of marine environments (Boyes and Elliott, 2014; Firestone and Jarvis,

2007). UNCLOS defines pollution as the: “introduction by man, directly or indirectly of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living sources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities” (UNCLOS, supra note 21, at article 1(4)). Considering that high amplitude sound as a byproduct of anthropogenic activities is recognized to be potentially harmful to humans and other terrestrial species (Fritschi et al., 2011; Luo et al., 2015; Ware et al., 2015), all countries that ratified UNCLOS should adopt measures to regulate the emission of underwater sound in order to reduce its impact. Furthermore, other jurisdictions have already introduced legislative frameworks aimed at reducing the output of underwater sound energy. The EU’s Marine Strategy Framework Directive (MSFD) (2008/56/EC) identifies annual thresholds for low-frequency continuous sounds and level thresholds for impulsive sounds introduced into the waters around its member states (Erbe et al., 2012). The MSFD explicitly refers to underwater noise as a form of pollution and required member states to implement ambient noise monitoring programs by 2015 (Dekeleing et al., 2016).

In conclusion, the absence of national regulations and the slow implementation of international regulations might jeopardize the conservation efforts for SRKW, as well as for many other species inhabiting our oceans.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2018.08.050>.

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