Analysing marine vessel noise impacts on endangered Southern Resident killer whale acoustic behaviour during transits of Boundary Pass in the Salish Sea

by
Olivia Beth Murphy

Bachelor of Science in Biology – Vancouver Island University, 2020

Project Submitted in Partial Fulfilment of the
Requirements for the Degree of
Master of Science

in the
Ecological Restoration Program
School of Environmental Science (SFU)
and
School of Construction and the Environment (BCIT)

SIMON FRASER UNIVERSITY
BRITISH COLUMBIA INSTITUTE OF TECHNOLOGY
2023

Declaration of Committee

Name:	**Olivia Murphy**
Degree:	**Master of Science**
Title:	**Analysing marine vessel noise impacts on endangered Southern Resident killer whale acoustic behaviour during transits of Boundary Pass in the Salish Sea**
Examining Committee:	**Chair: Dr. Ruth Joy** Supervisor Faculty, SFU **Dr. Anayansi Cohen-Fernandez** Examiner Faculty, BCIT

Abstract

This research aims to determine the effectiveness of Southern Resident killer whale (SRKW) management measures including a commercial vessel slowdown, and an interim sanctuary zone in an area of heavy vessel traffic. The SRKW have been documented to increase their communication effort to be heard over vessel noise – a phenomenon termed the Lombard effect. Between 1 June – 25 October 2022, along the inshore waters of Boundary Pass, acoustic data was analysed from 13 SRKW transit events. Pulsed call types were extracted and tested for differences in SRKW vocal behaviour. There were significant differences in call duration, frequency, and call types used between loud and quiet ambient noise levels. Given that these acoustic behaviour differences were documented under high management measure compliance, more research on how to further reduce the acoustic footprint of marine vessels is required to increase the effectiveness of reducing vessel noise in endangered SRKW critical habitat.

Keywords: killer whales; marine vessels; underwater acoustics; Boundary Pass; Salish Sea

Acknowledgements

This research took place on the traditional and unceded territories of the Coast Salish peoples. The data for this research project was collected on the land and waters of the Tsawout and Tseycum Nations. Additionally, this project was formed and completed on the land of the xwməθkwəy̓ əm (Musqueam), Sḵwx̱ wú7mesh Úxwumixw (Squamish), and səl̓ilw̓ ətaʔɬ (Tsleil-Waututh) Nations.

I would like to express my utmost gratitude to my supervisor, Dr. Ruth Joy. Thank you for giving me your guidance, support, and knowledge as I entered into the world of researching whale acoustics. I especially appreciated your regular assurances that I would get everything done on time! To my research assistant, Lauren Laturnus, thank you for the immeasurable effort, support, and enthusiasm you have given to this project. From racing to East Point at any time of day (or night) to catch a glimpse of the whales, to learning the language of the SRKW, you took on the role better than I would have. To Paul Nguyen Hong Duc, thank you for lending me your invaluable coding skills in analysing the ambient noise levels and call parameters. Thank you to our team of whale acoustics specialists, Dr. Amalis Viera, April Houweling, Dr. Scott Veirs, and Madie Bouvier-Brown for sharing your invaluable knowledge and guidance on the subject.

To the Saturna Island Marine Research and Education Society (SIMRES), in particular, Maureen Welton, Susie Washington-Smyth, Dr. Martin Wale, thank you for your partnership, support, and commitment to this research project. I am very grateful for the financial support from SIMRES, the Port of Vancouver, and a MITACS NSERC Alliance Grant for making this research happen. Thank you to the members of the Southern Gulf Islands Whale Sighting Network for your warm welcome, invaluable whale observations, and heads up when the whales were coming our way.

To the ‘whale gals’ that came before me, Lucy Quayle, Kaitlin Baril, and Azadeh Gheibi, thank you for your guidance, friendship, and great research that I was able to build upon. Thank you to my family, friends, roommates, and partner for your endless support, healthy distractions, and regular reminders that I was more than capable of pulling off this research project. Lastly, thank you to the whales for allowing me a small glimpse into your world.

Table of Contents

List of Tables

List of Figures

List of Acronyms

ANL	Ambient Noise Level
SRKW	Southern Resident killer whale
NRKW	Northern Resident killer whale
ISZ	Interim Sanctuary Zone
SIMRES	Saturna Island Marine Research and Education Society
AIS	Automatic Identification System
SGIWSN	Southern Gulf Islands Whale Sighting Network


L Laturnus 2022


L Quayle 2022

Chapter 1. Introduction

Anthropogenic impacts on the natural world are increasing in intensity and scope as the human population and its footprint expand across the world. One such repercussion of this expansion is an increase in human activity in marine environments. Marine vessel disturbance includes both direct vessel strikes and indirect effects stemming from noise pollution on marine life (Raverty et al. 2020). Ambient noise levels (ANL) have been steadily increasing in the world's oceans, and noise is projected to continue increasing (Hildebrand 2009, Erbe et al. 2019). With increasing numbers of both large commercial tankers and container vessels to small private motorboats (Erbe et al 2019), there has been a 3.3-dB increase in ANL per decade between 1950 and 2007 (Frisk 2012). In the Salish Sea, the broadband (across multiple frequencies) ANL have increased significantly due to commercial vessels, including noise in the frequency range that killer whales use for communication and echolocation (10-40 kHz band) (Veirs et al. 2016). Amplified noise levels are capable of disrupting animal behaviour and eliciting a stress response across many marine taxa (Buxton et al. 2017, Celi et al. 2015, Filliciotto et al. 2014, Wang et al. 1987). However, the effects are more acute in killer whales. Killer whales are a highly acoustic species, with a hearing range of 100 Hz to 160 kHz (Branstetter et al. 2017). For comparison, human hearing ranges from 20 Hz to only 17 kHz (Purves et al. 2001). Responses to higher levels of noise range from changes in behaviour, increases in stress hormones, and cause temporary and permanent hearing loss (Erbe 2011).

The killer whale (*Orcinus orca*), includes two distinct ecotypes that range across areas of high vessel use in the Salish Sea, including the Transient (or Bigg's) and the Resident ecotypes (Cominelli et al. 2018) (Figure 1). The Transient (or Bigg's) killer whale inhabits the coastal waters from Alaska to Oregon and is genetically distinct, having diverged 700 000 years ago (Ford 2017). Despite the distant genetic relationship, there are minor morphological differences between the Transient (Bigg's) and Resident ecotypes (Ford 2017). The most apparent difference between these ecotypes are their diets. Transient killer whales feed on marine mammals, whereas Resident killer whales feed on fish, primarily Chinook salmon (*Oncorhynchus tshawytscha*) (Ford 2017, Ford & Ellis 2006). The other main difference between these ecotypes are their acoustic repertoires (Ford 1987). The Transient (or Bigg's) ecotype has a relatively simple acoustic repertoire due to their smaller pod sizes (Ford 1987; Ford 2017). This is in contrast to the Resident ecotype populations, which have extensive acoustic repertoires made up of whistles, echolocation clicks, and pulsed calls which they use to maintain communication between members of relatively large pods (Ford 1987, Ford 2017). Of these types of acoustic signals, pulsed calls are the most complex. Calls are further categorized as monophonic and biphonic, depending on the number of tones produced by the whale during a call (Foote et al. 2008).

The Resident killer whales are made up of two genetically distinct populations (Barrett-Lennard & Ellis 2001; Riesch & Deecke 2011). These populations are the Southern Resident killer whale (SRKW), ranging from Washington state to central Vancouver Island, and the Northern Resident killer whale (NRKW), ranging from central Vancouver Island to Alaska (Krahn 2002). These Resident communities are organized into clans and pods (Ford 1991). The NRKW population comprises the A, G, and R clans while the SRKW entire population is made up of J clan and further classified into: J, K, and L pods (Ford 1991). Acoustic repertoires are identical within a pod but become less alike across different pods and become completely separate across clans (Ford 1991).

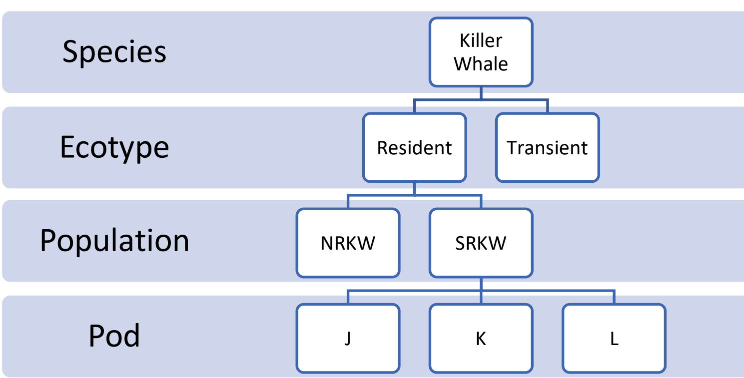


Figure 1. Taxonomic distinctions between killer whales found in the Salish Sea.

The SRKW has experienced a recent dramatic decline from 98 individuals in 1995 to 73 individuals (as of September 2022; Center for Whale Research 2022) and was classified as an endangered species in Canada in 2003 (Department of Fisheries and Oceans Canada 2018). This legal protection under the *Species at Risk Act* and the SRKW reliance on the acoustic conditions of the underwater environment (Joy et al. 2019, Williams et al. 2021) leads to heightened concern for this population to be negatively affected by marine vessels. The SRKW have been documented to change physical behaviours in response to marine vessels. This can occur through changes in foraging, resting, socializing, or travelling activity states that result in increased energy expenditure or decreased time and effort afforded to prey capture (Williams et al. 2009; Lusseau et al. 2009, Holt et al. 2021, Williams et al. 2021). Surface-active behaviours result in increased energy expenditure through the occurrence of breaching, fin and tail slapping, and spy hopping (Noren et al. 2009, Williams et al. 2009). Additionally, vessel noise has reduced the majority of SRKW available communication space, resulting in a need to increase the loudness and duration of communications coupled with an increase in energy expenditure to be heard - a phenomenon termed the Lombard effect (Williams et al. 2014; Holt et al. 2009). This documented increase in communication effort is through pulsed call amplitude (loudness) and call duration (Holt et al. 2008, Holt et al. 2009, Holt et al. 2012; Foote et al. 2004). At extreme noise levels, SRKW may display avoidance behaviours and/or experience temporary or permanent hearing loss (Erbe 2002). These behavioural changes are suspected to be one of the main factors contributing to the lack of recovery of SRKW in the Salish Sea (Williams et al. 2021).

In response to the established sensitivity of SRKW to underwater noise and vessel disturbance, the Department of Fisheries and Oceans and the Port of Vancouver have introduced various management measures to reduce vessel impacts in the SRKW designated Critical Habitat, located in waters around the southern end of Vancouver Island, BC (Government of Canada 2021). Under these implemented management measures, all marine vessels must maintain a minimum of 400 m approach distance from SRKW year-round. Additionally, there is a voluntary large commercial vessel slowdown and lateral displacement system in select critical zones along this commercial shipping route to limit noise pollution. Bulkers, tankers, and general cargo ships are asked to slow to 11 knots and containers, car carriers, and cruise ships are asked to slow to 14.5 knots in two slowdown zones within the Salish Sea, Haro Strait and Boundary Pass. Historically, Boundary Pass, a narrow 5 km wide channel and the surrounding waters of the Salish Sea were important foraging areas for the SRKW, as they were frequently observed foraging here throughout the summer months (Hauser et al. 2007; Olson et al. 2018). These factors led to the area being included in the designated Species-at-Risk Critical Habitat in 2009 by the Department of Fisheries and Oceans Canada (Department of Fisheries and Oceans Canada 2018). This area also contains a portion of the busiest shipping route in the Salish Sea and is a destination for commercial fishing vessels, recreational pleasure craft, and ecotourism (or whale watching) vessels (Cominelli et al. 2018). Lastly, there are three Interim Sanctuary Zones (ISZ) with legislated vessel restrictions that restrict vessel access between June 1 to November 30 in coastal BC waters; one of which is found along the north shoreline waters of Boundary Pass, on the southern shores of Saturna Island. There is evidence to suggest that there is variable success in compliance between the management measures in place in Boundary Pass (Baril 2022, Burnham et al. 2021).

While the compliance rates as well as potential impact reductions of the management measures have been studied, there has been no research assessing the realized efficacy of these management measures on SRKW directly (Baril 2022, Burnham et al. 2021). This project aims to fill this knowledge gap and determine whether the current management measures are effective at minimizing the impact of vessels on SRKW acoustic behaviour. As the number of SRKW individuals continues to decline, more research on vessel disturbance - one of the main stressors responsible for the lack of SRKW recovery - is crucial (Williams et al. 2021). Boundary Pass is ideally situated for research based on the SRKW acoustic response to vessels as it is a home to a busy commercial shipping lane and home to an interim sanctuary zone. Lastly, more research is needed on the acoustic and behavioural response of killer whales to noise from smaller vessel engines, as the majority of these studies have been based on mysticetes (baleen whales, such as Humpback whales (*Megaptera novaeangliae*) - and their acoustic response to larger ships (Erbe et al. 2019).

1.1 Goals and Objectives

This project aims to assess whether the Interim Sanctuary Zone and the Commercial Vessel Slowdown are effective at eliminating the effect of vessels on SRKW acoustic behaviour. This project aims to assess SRKW acoustic behaviour around vessels in Boundary Pass. This project will add to the collective research in establishing the restoration of the endangered SRKW in the Salish Sea. Through the following objectives, this project aims to assess whether or not the current management measures are sufficient in removing the impact of vessel noise on SRKW acoustic behaviour.

1) How does marine vessel noise affect SRKW acoustic behaviour in Boundary Pass?

Goal: Identify SRKW acoustic behaviour and marine vessel noise in Boundary Pass.

- Quantify the SRKW call types used during SRKW transits.
- Quantify the durations of SRKW calls during SRKW transits.
- Quantify the peak and bandwidth frequencies of SRKW calls during SRKW transits.
- Quantify the background ambient noise levels from marine vessels during SRKW transits.

2) How often are the management measures followed?

Goal: Identify instances of vessel compliance and non-compliance of measures in Boundary Pass.

- Identify the interim sanctuary zone compliance of vessels present during SRKW transits.
- Identify the commercial vessel slowdown compliance of vessels present during SRKW transits.

Chapter 2. Methods

2.1 Site Description

The observation site for this study was located along an outlook point established at Tekteksen on Wsanec First Nation traditional territory, also known as East Point Park on Saturna Island. This study site permitted unobstructed views to observe the waters of Boundary Pass. Boundary Pass is a channel located in the Salish Sea along the international border of the Canadian Southern Gulf Islands and the American San Juan Islands. Saturna Island is located approximately 55 km south of Vancouver and 40 km northeast of Victoria, British Columbia, Canada. The primary observation site is positioned within the Gulf Islands National Park Reserve at East Point Park (48°46'58.55" N, 123°2'44.03" W) approximately 19 m above sea level (Figure 2). Supplementary whale observations were made from various locations along the southern end of Saturna Island by volunteers from the Southern Gulf Islands Whale Sighting Network (SGIWSN). A hydrophone was used to continuously record the underwater acoustic environment approximately 500 m southwest of the observation site (48°46’49.7532” N, 123°3’5.544” W) (Figure 2). The hydrophone array is permanently mounted at a water depth of approximately 18 m near shore in the Interim Sanctuary Zone.

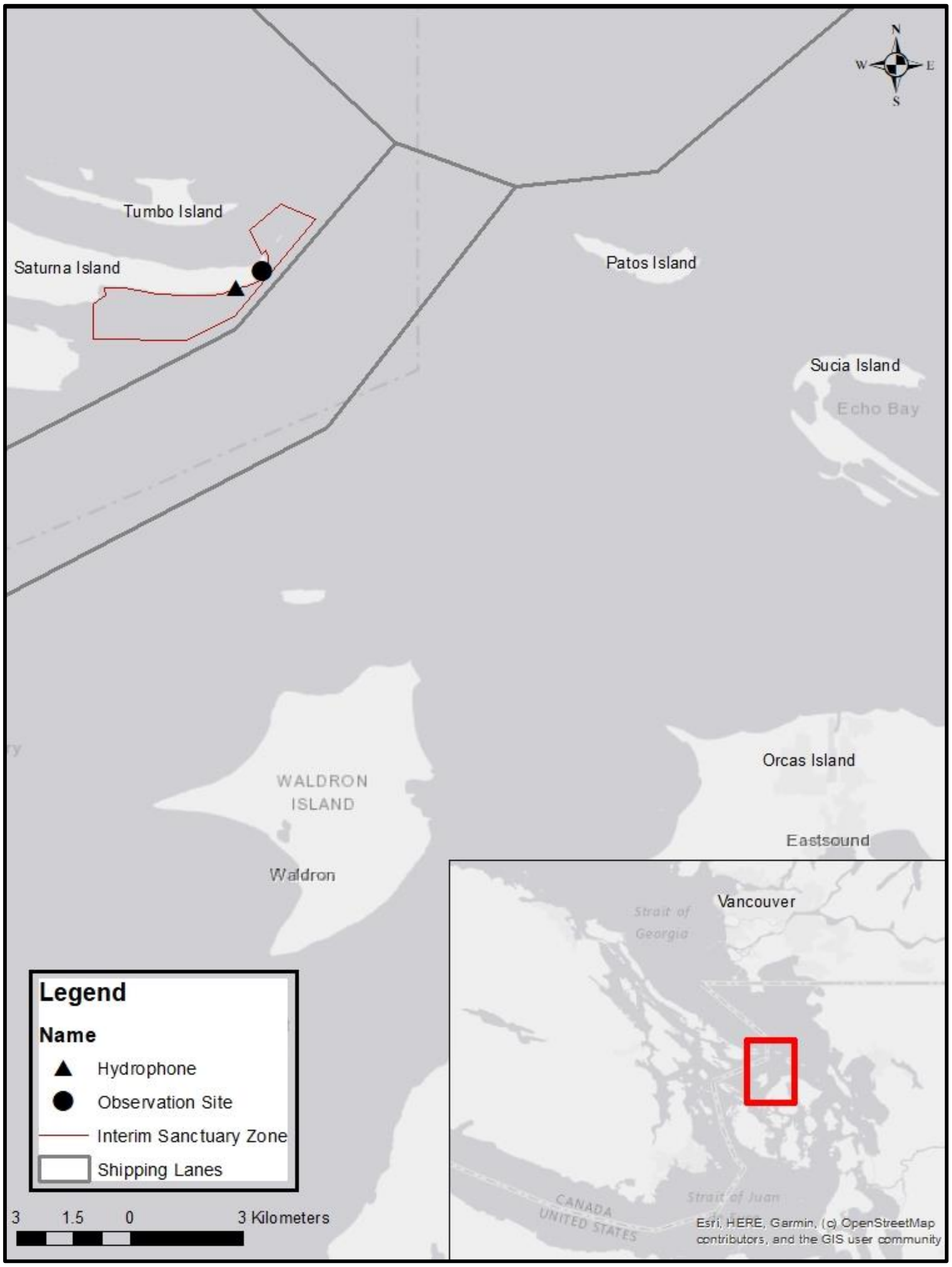


Figure 2. Boundary Pass study site indicating the primary observation site, hydrophone, shipping lanes, and Interim Sanctuary Zone.

2.2 Data Collection

Visual and acoustic data were collected in partnership with Saturna Island Marine Research and Education Society (SIMRES) from 1 June through 25 October 2022 (Murphy et al. 2022). Systematic visual observations of whales and marine vessels were recorded nearly daily from 9:00 am to 4:00 pm at the observation site (Figure 3). These observations were conducted using a 15-minute visual scan using binoculars (Nikon 10 x 42, Zeiss 10 x 42) in a northeast to southwest to northeast sequence, for a total of two scans of the study site, following methods pioneered by (Lusseau et al. 2009) in Haro Strait and following prior survey efforts in Boundary Pass (Le Baron et al. 2019, Quayle & Joy 2021, Gheibi et al. 2021). Additionally, the site was set up for equipment that would allow for the collection of highly accurate spatial data of vessels and whales for future years of research. This data is collected using a Topcon DT-200 theodolite with Mysticetus software and methods developed by the Department of Fisheries and Oceans Canada (2021) field protocol (Appendix A). Continuous acoustic data was passively recorded and stored for the duration of the data collection period.

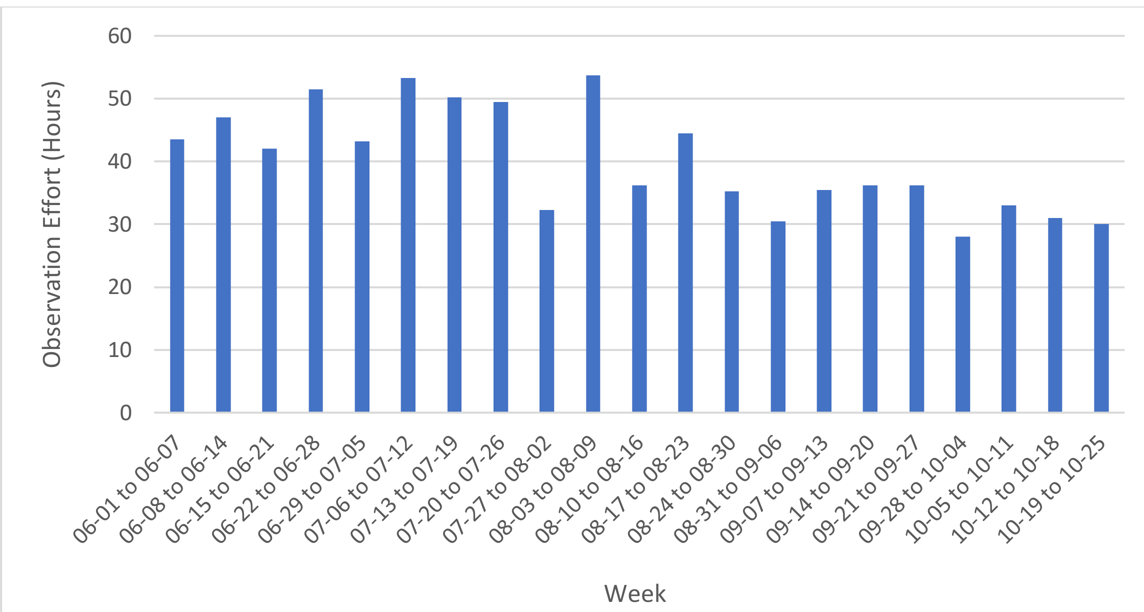


Figure 3. Hourly observation effort by week from 1 June – 25 October 2022.

2.3 Marine Vessel Management Measures Compliance Survey

Data were recorded on marine vessels upon their entrance into the study area. First, the MarineTraffic application (MarineTraffic.com 2022) was opened for live updates on the Boundary Pass area (Appendix B). This application shows the real-time locations of marine vessels that are using Automatic Identification System (AIS) tracking. This application was used to assess whether an individual vessel was using an AIS tracking system. For vessels using AIS, this data is automatically archived and was accessed after the field season. For vessels not using AIS tracking, observers collected the data visually. Vessels were visually categorized to type as motorboat, sailing, ecotourism (whale-watching), commercial fishing, commercial shipping, or unknown vessels. The total time a vessel remained in the area was recorded upon the appearance and disappearance of the vessel from the observers' field of view in the study site. Lastly, ISZ compliance was recorded. A laser rangefinder (Newcon LRM 3500M-35BT) and the position of the vessel in relation to known landmarks were used to identify the position of the vessel in relation to the ISZ. Vessels that were transiting or fishing in the ISZ were recorded as non-compliant. A DSLR camera (Sony α7R IV) with a telephoto lens (Sony 200-600 mm) was used to photograph ISZ infractions as well as identify any visible vessel registration. Fishing and transit infractions in the ISZ were reported and submitted to Transport Canada daily.

As for vessels that were using AIS tracking, data such as the vessels position and speed at certain archived using an AIS receiver antenna from Quayle Consulting Ltd mounted on a building near the observation site. The data is archived and accessed on AISHub. Data was accessed and downloaded at times of visual SRKW events in Boundary Pass. The vessel types were filtered for commercial vessels to assess compliance of the commercial vessel slowdown. The data including the iterative positions and speeds of the vessels were tracked on Google Earth software to assess vessel speed in both 'transition zones' and 'slowdown zones'. Non-compliance was deemed as vessels travelling in the 'slowdown zones' more than 2 knots over the slowdown target speed to account for the difference in speed over land and speed through water (Baril 2022).

To determine infractions (or non-compliance) of the ISZ, data was filtered on the specific spatial extent of the ISZ boundaries. Vessel types that are exempt from the ISZ regulations (government vessels, Indigenous fishing vessels) were filtered out of the dataset. These data on the AIS vessels were combined with the visually documented non-AIS vessels for the total number of ISZ infractions. The visual documentation of the ISZ infractions follow the same methods between years. However, because of differences in data collection methods for compliant vessels differed, the compliance rates are not comparable between years. Compliance rates were calculated using a specific area of Boundary Pass called the ‘compliant zone’ in 2020 and 2021. For 2022, vessels entering ‘compliant zone’ were not recorded and no compliance rate can be calculated. Instead, all vessels that were sighted anywhere in Boundary Pass were recorded.

2.4 Citizen Science Whale Sightings Data

In the days or hours preceeding the majority of sightings, SRKW would first appear along the west side of the American San Juan Island before their appearance in Boundary Pass hours or days later. For this reason, it was helpful to consult the Facebook group titled “Whale Sightings in the San Juan Islands”, a page ran and moderated by the Orca Behavior Institute on San Juan Island, to be aware that SRKW were in the general area. On the Canadian side of the border, the Southern Gulf Islands Whale Sightings Network (SGIWSN) is made up of volunteer members that reside on North and South Pender Islands, Mayne Island, and Saturna Island. Members are trained in whale identification and their sightings are uploaded to the British Columbia Cetacean Sightings Network WhaleReport application. Sightings of SRKW from SGIWSN members on other Gulf islands gave observers an idea of which direction and when SRKW would appear in Boundary Pass. Photograph-confirmed sightings of SRKW by SGIWSN members on Saturna Island allowed SRKW transit events in Boundary Pass that occurred on observer off-days or after hours to be included in this project as well. However, this data was opportunistic as sighting effort varied between members, weather, and sighting conditions. While systematic observing hours occurred nearly daily from 9:00 am to 4:00 pm, when SRKW were reported to be in the area from the above listed sources, observers stayed at the observation point for as long as possible during daylight hours.

2.5 Southern Resident Killer Whale Survey

For the majority of SRKW sightings, observers would hear the whales exhaling at the surface as they approached the study site before getting a visual observation. Data were recorded upon the visual appearance of whales into the study area. The approximate number of whales were visually estimated and recorded. The time of the visual SRKW transit event was recorded upon their entrance to and exit from the study site or more than 20 minutes passing since the last surfacing event. If more than twenty minutes passed between surfacing events, these were counted as two separate sighting events. Lastly, SRKW presence in the commercial shipping lanes and/or the ISZ were visually estimated and recorded. The positions of the whales were estimated in relation to known landmarks.

Due to the minor morphological differences between the Transient and Resident killer whale ecotypes, photographs of individual whales were taken on a DSLR camera (Sony α7R IV) with a telephoto lens (Sony 200-600 mm) to be reviewed for identification after the field day. Identification was made using distinguishing features such as an open or closed saddle patch and the presence of nicks and scratches on the dorsal fin and surface (Figure 4). These features were compared to photographs in whale catalogues for verified identification (Center for Whale Research 2019, Towers et al. 2019).

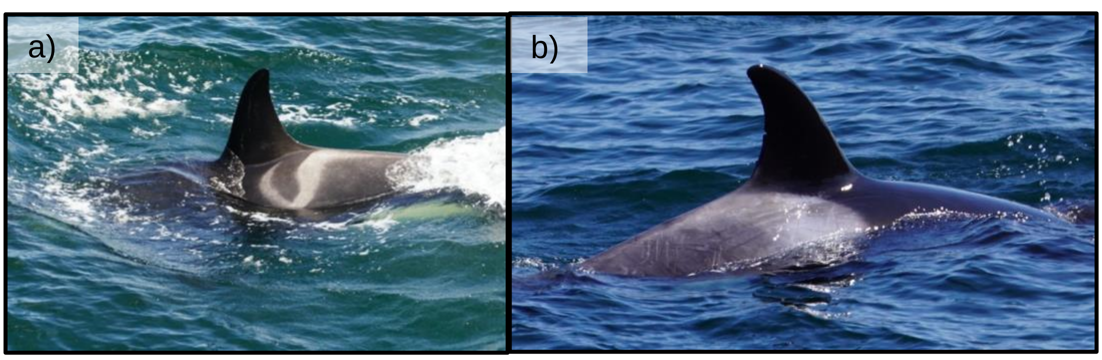


Figure 4. **Physical features used to distinguish between killer whale ecotypes. (a) Southern Resident killer whale with 'open' saddle patch behind dorsal fin (Identified individual: J42) (b) Transient killer whale with 'closed' saddle patch, nick in dorsal fin, and scratches on dorsal surface (Identified individual: T124A2B).**

2.6 Acoustic Data

Underwater acoustic data is passively recorded on the SIMRES hydrophone near East Point Park on Saturna Island, BC. SIMRES first installed a permanent placement for an underwater hydrophone array at an approximate depth of 18 m in July 2014. The hydrophone is run from an underwater cable connecting the placement and a power source and acoustic processing equipment in the shoreline adjacent house of an individual member of SIMRES. Sea to Shore Systems regularly maintains and replaces the individual hydrophones. The specific hydrophone that recorded the data used in this study was deployed 15 March 2022. The hydrophone used is an Ocean Sonics icListen Smart Hydrophone (RB9-ETH) with Ethernet and a 900 m depth rating. Testing of this hydrophone showed calibration levels of -178.0 ± 1.2 dB re 1 μPa (10 kHz to 100 kHz) and -179.3 ± 2.4 dB re 1 μPa (10 kHz to 200 kHz) (Ocean Sonics 2015). Acoustic data was continuously recorded during the field season and stored as 5-minute .wav audio files.

2.7 Acoustic Analysis

The recorded times of SRKW transit visual observations in Boundary Pass were cross-referenced to the corresponding underwater audio files for audio file selection. The files that overlapped with the SRKW visual transit in addition to a 30-minute buffer period at both the beginning and end of the SRKW transits were selected for acoustic analyses. The corresponding 5-minute files were converted to compressed .flac audio files and downloaded for analysis.

Acoustic files were modified for optimal listening for SRKW pulsed call detection by applying a high pass audio filter that minimized low frequency vessel noise (frequencies from 0-200 Hz with a 24 dB roll-off) and applying an amplification effect of 25.0 dB to the files using RStudio (S. Veirs, personal communication, August 12, 2022). Individual audio files were opened in the RavenPro desktop with standardized pre-set spectrogram settings (Appendix C). Instances of SRKW acoustic signals were manually annotated with a selection box drawn as tightly as possible around the signature on the spectrogram (Figure 5). If a signal is visually faint, the brightness and contrast setting were adjusted as needed and then set back to the standardized settings. Once all annotations were made, the file was given a final playthrough to catch any previously missed signals. Each selection box measures various acoustic parameters, the specific parameters of interest for this study are peak frequency (Hz), duration (seconds), maximum frequency (Hz), and minimum frequency (Hz). All SRKW signals were annotated including pulsed calls, the beginning sequence of echolocation clicks, buzzes, whistles, and rasps, however only pulsed calls were used for this study due to time constraints.

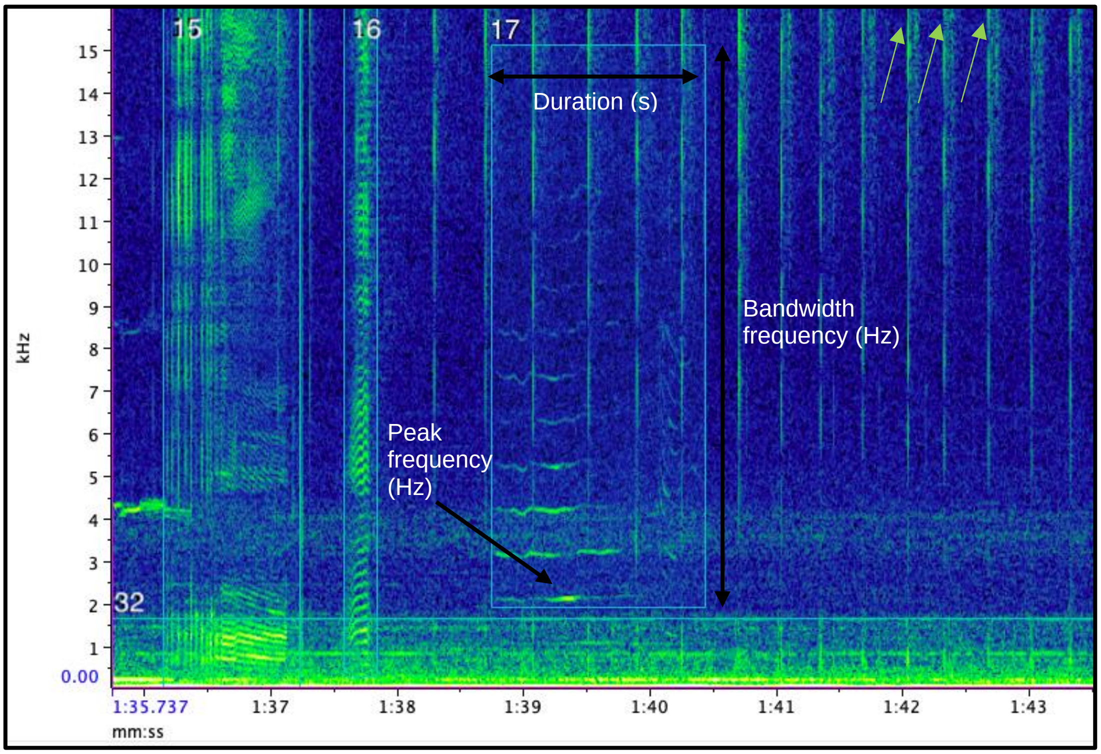


Figure 5. **Acoustic analysis of an 8-second audio recording from the hydrophone during an SRKW transit in Boundary Pass in RavenPro software. Selection boxes 15-17 show SRKW call type S04, S05, and S03, respectively. Selection box 32 showing low frequency vessel noise presence from approximately 0-1.7 kHz over the entire 8-second audio clip. Selection box 17 is used to show how the three call parameters (bandwidth frequency, peak frequency, and duration) are calculated. Note: green arrows indicate SRKW echolocation clicks, these are not associated with pulsed calls.**

Pulsed calls were further classified to call type. Calls were identified by comparing similarities of both the unique visual signature on the spectrogram and the unique acoustics of the call to examples in an unpublished call catalogue from the Department of Fisheries and Oceans Canada, adapted from Ford 1991 (Figure 5). Each call annotation was assigned ‘low’, ‘medium’, or ‘high’ identification confidence levels based on how alike both the visual spectrogram and acoustic signature were to the call catalogue. For instances in which there was no confidence in a discernable call type, it was left as ‘unknown’. Calls assigned a ‘low’ identification confidence were excluded from the dataset. Bioacousticians from both JASCO Applied Sciences Ltd. and the University of Victoria specializing in SRKW call identification provided mentorship and confirmation for particularly challenging annotations.

In the audio files that contain SRKW pulsed calls, selection boxes were also drawn to measure background ANL. A 5-second-long selection box was made every 100 seconds spanning the frequency range from 0-15 kHz. During instances when there were calls present at these set times, the selection box was made at the first instance of call absence. This normally occurred within 10 seconds before or after these set times, however a few instances required going further away than 10 seconds due to a high density of calls. Broadband noise analyses for background ANLs (logarithmic scale) were measured as sound pressure level (dB re 1 µPa) using PAMGuide software in RStudio for each ANL selection box (Merchant et al. 2015). A Hamming window of length 12800 samples and an overlap of 50% between time windows were used to compute sound pressure levels over 0.5-15 kHz, the frequency range in which vessel noise and SRKW calls overlap (Williams et al. 2014). Sound pressure levels were averaged over the entire selection box. Using an average across multiple selection boxes was not completed due to the high variation in ANL within acoustic events. This is a typical noise parameter measurement of background vessel noise (Bouvier 2022, Holt et al. 2009). Hydrophone-specific calibration data was used to accurately measure the sound pressure levels across the 10-100 kHz frequency bands, the most relevant for SRKW calls and vessel noise (Ocean Sonics, 2015). The mean sound pressure level per background noise selection box was added as the ANL parameter for each SRKW call that occurred within that 100 second window.

The SRKW call parameters of interest for this study, bandwidth frequency, peak frequency, and duration, were measured from the SRKW call selection boxes in RavenPro and analysed in RStudio. Bandwidth frequency is defined as the range of frequencies that the call spans (maximum frequency – minimum frequency) in Hz (Figure 5). Duration is defined as the time span of the call in seconds (Figure 5). Peak frequency is defined as the frequency point of the call that possesses the maximum power or energy in Hz (Figure 5). The usual parameter of interest in SRKW call analyses of the Lombard effect is call amplitude (or loudness) (Holt et al. 2009), however this study was not able to measure this parameter. The Lombard effect is more loosely defined as an increase in communication effort of any kind and has been used to describe an increase in SRKW call duration as well (Foote et al. 2004). A literature review showed that call frequency parameters have not been studied in SRKW specifically but have been studied in bottlenose dolphins whistles around marine vessels (Heiler et al. 2016).

2.8 Statistical Analysis

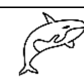
Statistical analyses were performed using RStudio Version 2022.12.0+353 for macOS. A Levene's test tested the data for normality. An ANL mean was not calculated per file due to the quick and drastic changes in ANL that occur in Boundary Pass. Instead, the mean ANL across each 5-second annotation was used for further analyses. Pulsed calls were matched up to the corresponding background ANL. The threshold between loud and quiet ANL conditions was set at 95 dB re 1 μPa because of a natural separation of the distribution of the data at this point (Appendix D). Call types in which had less than ten instances of either loud or quiet calls were not included in these analyses to maintain statistical power. Log-transformed two-way ANOVA tests were performed to analyse differences in pulsed call parameters (peak frequency, bandwidth frequency, and call duration) between loud and quiet ANL. Post-hoc Tukey's tests were performed to infer the call types for which differences in call parameters occurred. Lastly, Fisher's exact tests for count data were performed to analyse associations between call types used and background ANL and associations between the use of biphonic (two-voices and frequencies produced at one time) or monophonic (one voice and frequency produced at one time) calls and background ANL.

Chapter 3. Results

3.1 SRKW Transit Events

The SRKW were documented in Boundary Pass on 15 days from June 1 – October 25, 2022. All three pods (J, K, and L) were identified on at least one occasion throughout the field season (Table 1). Thirteen of the fifteen SRKW events contained pulsed calls and were included in this study (Table 1). Positive identification of killer whale ecotype and pod was made primarily from visual sightings. When this was not possible, acoustic identification was made, which occurred for one event (3 October 2022). There were two events (28 June and 4 August) in which there were subsequent killer whale sightings after confirmed SRKW and Transient (or Bigg's) killer whale sightings that same day. The whales in these subsequent sightings were far away from the observation site and therefore the ecotype of these killer whales remained unidentified. Only the confirmed sighting times were used for acoustic analysis.

Table 1. **SRKW pod presence per Boundary Pass transit event during the 2022 field season. SRKW events that contained SRKW pulsed calls that were included in the acoustic analysis are indicated by ***

Date of SRKW transit event	**SRKW Pod(s) Present**		
	J	K	L
June 24			
June 28*			
July 10*			
July 11*			
July 12*			
July 23*			
July 25*			
July 26*			
July 28*			
July 29*			
August 4*			
August 5			
August 9*			
September 3*			
October 3*			

3.2 SRKW Acoustic Data

There were 433 5-minute audio files analysed, within which contained approximately 13 hours and 40 minutes of SRKW acoustic activity were identified. The duration of the acoustically active segments of SRKW events ranged widely from 5 minutes to 190 minutes in duration (Figure 6). This amounted to 1188 annotations of pulsed calls that could be identified to call type with medium or high confidence. 444 annotations of low identification confidence were removed from the dataset. There were 3133 annotations of unidentified calls also removed from the dataset. These calls were either of low acoustic quality and were not identifiable to call type or were variable and aberrant calls. These types of calls are often modified versions of known pulsed calls (Ford 1989). The maximum number of calls identified from one event was 402 (11 July 2022), the minimum was 4 (3 September 2022), and the average number of calls identified per event was 114 $\pm$ 33.9 calls. There were 26 different call types identified out of the 30 unique call types recognised in the SRKW call catalogue (Ford 1987). The three most common call types found were S04 (n= 533, 36.0% of total), S01 (n= 213, 14.4% of total), and S19 (n= 165, 11.2% of total) (Figure 7). 11 of these call types were identified as monophonic and 15 were identified as biphonic or two-voiced (Table 2). Twenty call types were removed from the dataset because they had less than ten instances of calls in either quiet or loud conditions and would have low statistical power. The six remaining call types were statistically analysed (Table 2).

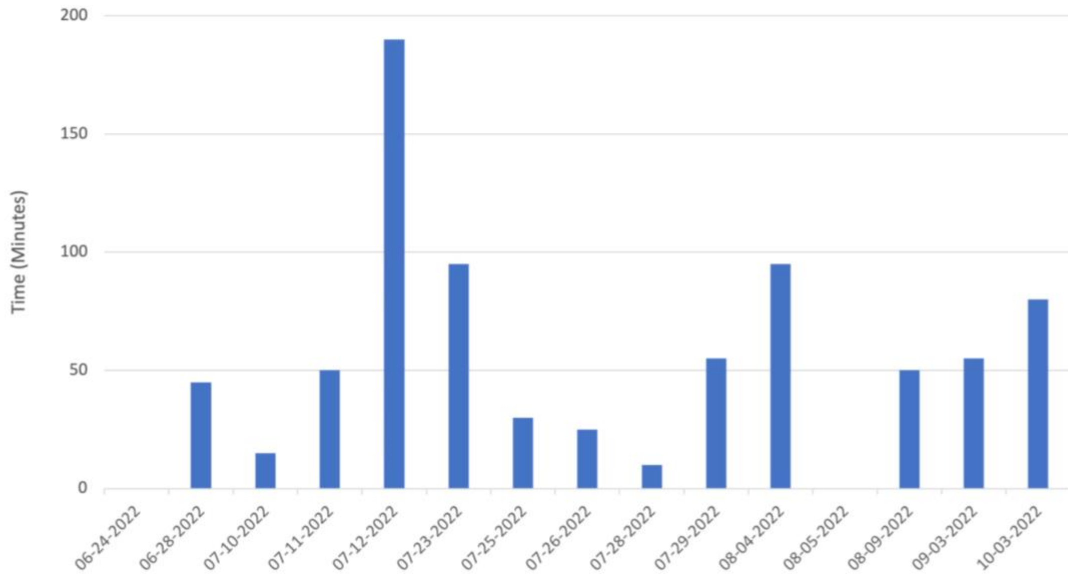


Figure 6. **Duration of acoustically active segment of SRKW transit events in Boundary Pass in 2022.**

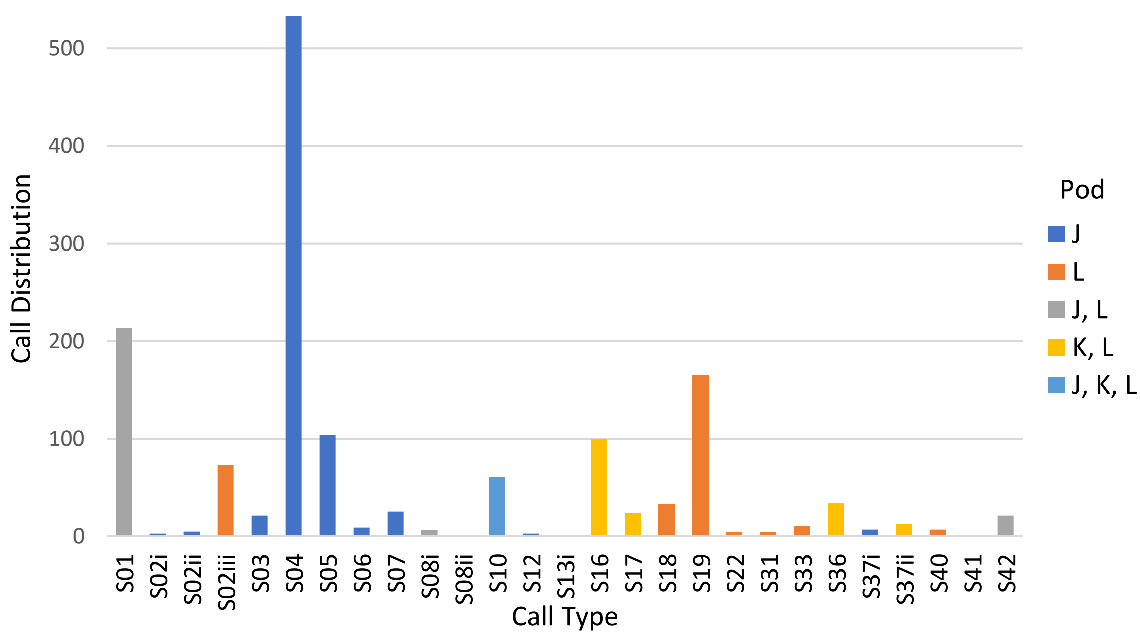


Figure 7. **SRKW call type distribution across recorded transit events in Boundary Pass in 2022. Colours indicate pod(s) use of each call type**.

Table 2. Total numbers of SRKW pulsed call types from recorded acoustic files over the 13 acoustically active whale events in Boundary Pass in 2022. Call types are ordered by total count of occurrence.

Call Type	Monophonic or Biphonic Call Type	Number of Calls in Quiet conditions	Number of Calls in Loud conditions	Pod(s)
S04*	M	523	10	J
S01*	M	168	45	J, L
S19*	B	75	90	L
S05*	M	94	10	J
S16*	M	72	28	K, L
S02iii*	B	33	40	L
S10	M	51	9	J, K, L
S36	B	34	0	K, L
S18	B	24	9	L
S07	M	25	0	J
S17	M	20	4	K, L
S03	M	12	9	J
S42	B	0	21	J, L
S37ii	B	12	0	K, L
S33	B	4	6	L
S06	M	8	1	J
S37i	B	7	0	J
S40	B	1	6	L
S08i	B	1	5	J, L
S02ii	B	0	5	J
S31	M	0	4	L
S22	B	2	2	L
S12	M	2	1	J
S08ii	B	1	0	L
S13i	B	0	1	J
S41	B	1	0	J

* Indicates which call types were included in statistical analyses

3.3 Marine Vessel Data

There were on average 10.6 ± 2.4 (n=14) marine vessels present in Boundary Pass during a visual SRKW transit event. The lowest number of vessels seen during an SRKW transit was 1 (10 July 2022) and the highest number of vessels seen was 29 (4 August 2022) (Figure 8). Additionally, twelve of the fifteen events had more than one vessel type present. The most common types of vessels included small motorboats (n=64), sailing vessels (n=44), and ecotourism (whale-watching) vessels (n=20) (Figure 8).

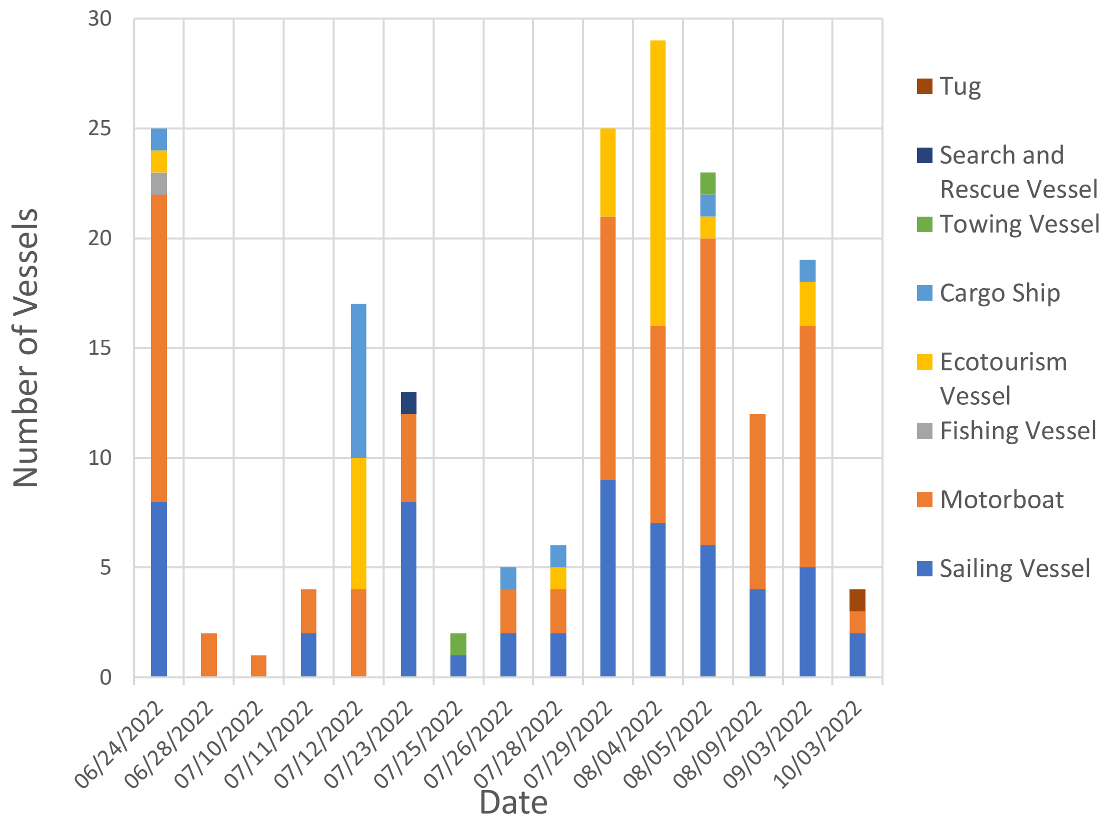


Figure 8. **Total numbers of marine vessels present during SRKW transit events in Boundary Pass in 2022.**

3.4 Ambient Noise Level Data

The average ANL received at the point of the hydrophone over all SRKW acoustically active events was 88.61 ± 0.16 dB re 1 μPa. The lowest ANL was 79.7 dB re 1 μPa recorded on 11 July 2022 and the highest ANL received was 107.6 dB re 1 μPa recorded on 4 August 2022 (Figure 9). During the acoustically active portions of SRKW events, four out of the thirteen events had one or more commercial vessels present (Figure 9). There is a nearly strong positive correlation between ANL and total number of vessels present during an SRKW event (R is 0.68, $p < 0.05$) (Figure 10).

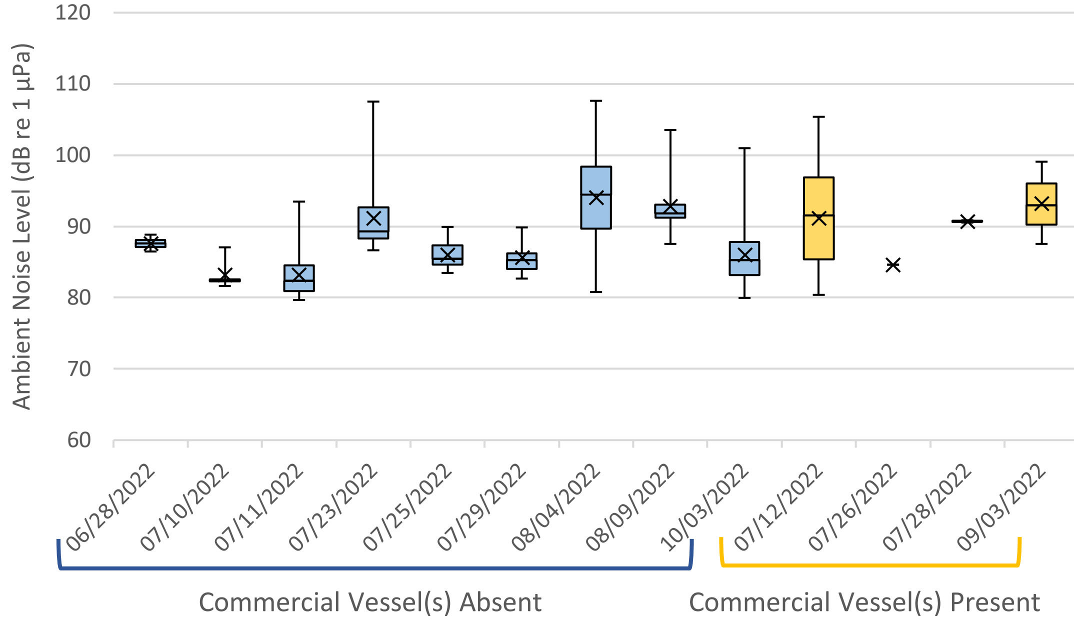


Figure 9. Boxplots depicting average background ambient noise levels during recorded SRKW acoustic events in Boundary Pass in 2022. X represents the mean over each event.

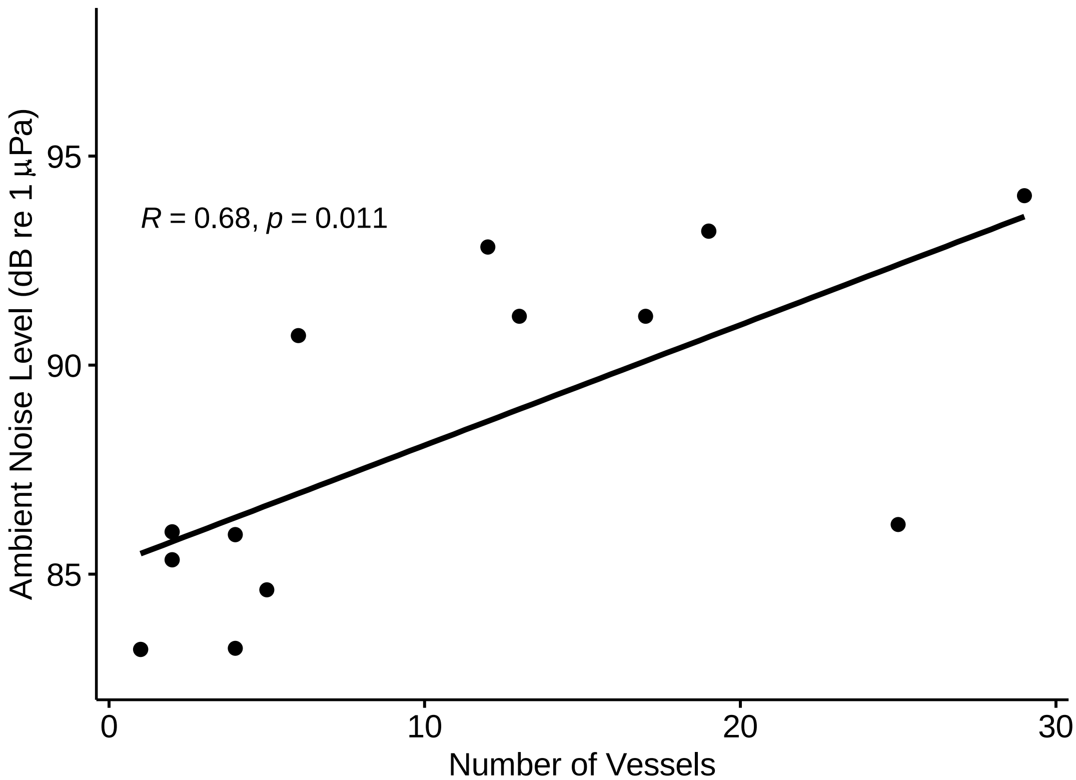


Figure 10. Relationship between average ambient noise levels (dB re 1 µPa) and number of marine vessels present during each SRKW event.

3.5 Management Measure Compliance

The commercial vessel voluntary slowdown returned a compliance rate of 79% when commercial vessels were present in Boundary Pass during a visual SRKW event. There were 15 vessels that remained at compliant speeds while transiting Boundary Pass. There were 2 bulk carriers and 2 general cargo non-compliant ships that transited at a speed above the 11-knots speed threshold for their vessel category. Only looking at the portion of the event that SRKW were acoustically active, the commercial vessel compliance rate is 100% (Table 3). The commercial vessel voluntary slowdown compliance rates over the entire field season were not calculated due to time constraints. While this study did not focus on visual behaviour of SRKW around marine vessels, SRKW were visually sighted passing through the shipping lanes on 11 of the 15 SRKW events (Murphy et al. 2022).

Table 3. Compliance for the commercial vessel voluntary slowdown during SRKW transit events in Boundary Pass.

SRKW Event Date	Number of commercial vessels present	Number of slowdown compliant vessels
Jun 24	1	1
Jun 28	2	1
Jul 10	2	2
Jul 11	1	1
Jul 12 ^	7	7
Jul 26 ^	1	1
Jul 28 ^	1	1
Jul 29	1	0
Aug 5	1	0
Aug 9	1	0
Sep 3 ^	1	1
Total Vessels during entire visual SRKW Events	19	15 (79%)
Total Vessels during only acoustic SRKW Events ^	10	10 (100%)

^ Indicates vessels were present during the acoustically active segment of the SRKW event

There were infracting marine vessels that entered the Interim Sanctuary Zone along the southern shore of Saturna Island during five of the 15 visual SRKW events. Over the course of these five events, there were 11 vessel infractions while SRKW were visually present in Boundary Pass. Seven of these vessels were small motorboats, three were sailing vessels, and one was an ecotourism (or whale-watching) vessel. One of the small motorboat infractions was a transit and fishing violation while the rest of the infractions were transiting violations. Nine of these infractions occurred during the acoustically active segments of three SRKW events (Table 4).

For the entire observation period, from June 1 – October 25, there were a total of 487 ISZ infractions. These include 456 small motorboats, 17 ecotourism (or whale-watching) vessels, 8 fishing vessels, 5 unknown vessel types, and 1 dredging or underwater operations vessel. The most infractions occurred during the month of August with 176 infractions and the least infractions occurred during the month of October with 14 (Figure 11).

For the field seasons of 2020 and 2021, ISZ infraction data had also been collected. For 2020, there were 427 infracting vessels and a compliance rate of 0.368 (Quayle 2021) For 2021, there were 251 infracting vessels and a compliance rate of 0.669 (Baril 2022). Comparing the data from this study over the same time period as these past studies, June 1 – August 31, there were 370 infracting vessels visually and automatically documented in the ISZ. As previously stated, no compliance rate can be calculated for 2022 due to differences in data collection methods.

Table 4. Infractions for the Interim Sanctuary Zone during SRKW transit events in Boundary Pass.

SRKW Event Date	Number of vessel infractions	Types of vessels
Jun 24	1	Motorboat
Jul 29 ^	3	Motorboat
Aug 4 ^	5	2 Motorboat, 2 Sailing, 1 Ecotourism
Aug 5	1	Sailing
Aug 9 ^	1	Motorboat
Total infractions during entire visual SRKW events	11	
Total infractions during only acoustic SRKW events ^	9	

^ Indicates vessels were present during the acoustically active segment of the SRKW event

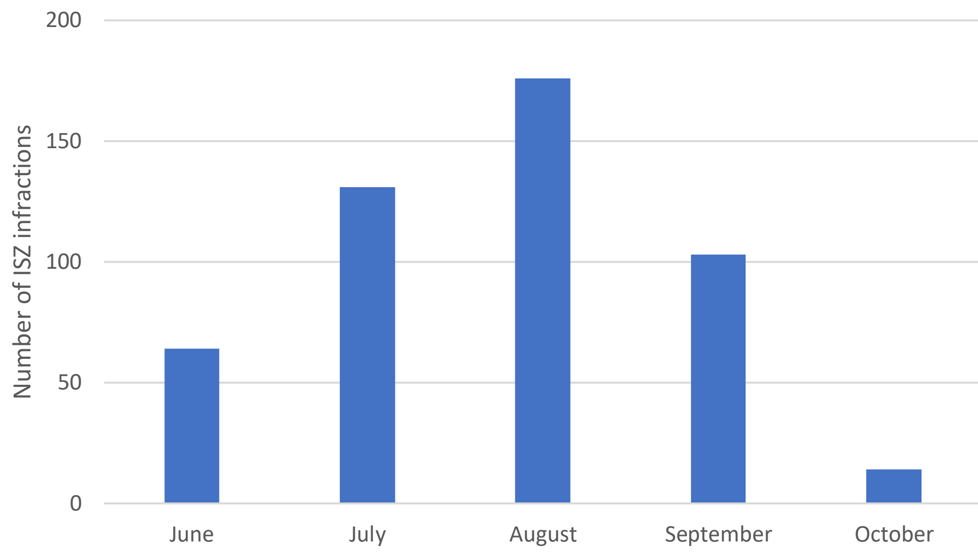


Figure 11. **Saturna Island Interim Sanctuary Zone infractions by month from June 1 – October 25, 2022.**

3.6 Call Parameter Data

The measurements of the three SRKW call parameters (peak frequency, bandwidth frequency, and duration) from the East Point hydrophone location were obtained using the RavenPro software representative selection boxes for calls in loud and quiet ANL conditions (Figure 12). The peak frequency of SRKW calls ranged from 156.25 Hz (S01 call type) to 23000 Hz (S04 call type). The bandwidth frequency of SRKW calls ranged from 340.4 Hz (S04 call type) to 56161.62 Hz (S05 call type). The duration of SRKW calls ranged from 0.1232 seconds (S05 call type) to 2.6654 seconds (S19 call type). The call parameter means at loud and quiet ANL conditions of call types that showed a statistically significant difference are provided in section 3.7.

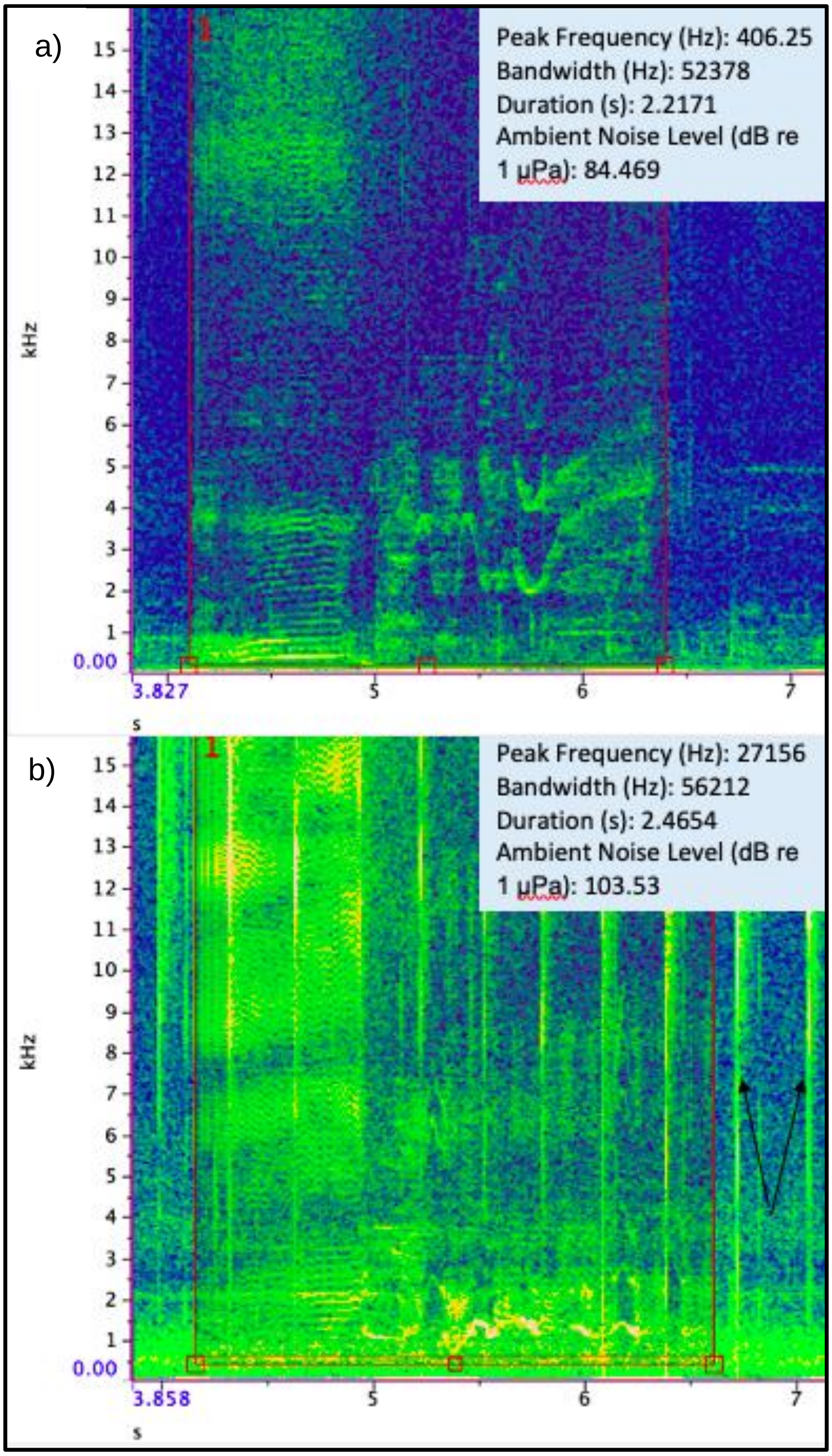


Figure 12. **Acoustic analysis of a 3-second audio recordings from the hydrophone during an SRKW transit in Boundary Pass in RavenPro software a) representative S10 call in “Quiet” ANL conditions b) representative S10 call in “Loud” ANL conditions. Black arrows indicate SRKW echolocation clicks not associated with pulsed calls.**

3.7 Statistical Analyses

A Levene's test indicated that the ANL data were not normally distributed, but after log transformations the data were normally distributed. The results of a log-transformed two-way ANOVA indicated there were significant differences in call duration among ANL conditions and call types (F statistic of ANL main effect is 317.08 (df1=1), p value <0.001, F statistic of call type main effect is 543.32 (df=5), p value <0.001, and F statistic of the interaction effect is 11.37 (df=5), p value <0.001). A post hoc Tukey's test indicated that there were significant differences in call duration between loud and quiet conditions for the call types S02iii (p value <0.001) and S19 (p value <0.001). The mean duration of the S02iii call in quiet conditions is 0.8300 [95% C.I. = (0.7370, 0.9231)] seconds and loud conditions is 1.081 [95% C.I. = (1.002, 1.160)] seconds (Figure 13). The mean duration of the S19 call in quiet conditions is 0.8933 [95% C.I. = (0.8300, 0.9567)] seconds and in loud conditions is 1.166 [95% C.I. = (1.097, 1.236)] seconds (Figure 13).

The results of a log-transformed two-way ANOVA indicated there were significant differences in call bandwidth frequency (range between maximum and minimum frequency ridges) among ANL conditions and call types (F statistic of ANL main effect is 274.365 (df1=1), p value <0.001, F statistic of call type main effect is 77.431 (df=5), p value <0.001, and F statistic of interaction effect is 4.615 (df=5), p value <0.001). A post hoc Tukey's test indicated that there were significant differences in call bandwidth frequency between loud and quiet conditions for the call types S01 (p value <0.001), S05 (p value 0.058), and S19 (p value <0.001). While the Tukeys test indicated a p value of 0.058 for the call type S05, the log-transformed ANOVA model, with a higher degree of accuracy, indicated a significant difference. The mean bandwidth frequency of the S01 call in quiet conditions is 6917 [95% C.I. = (6303, 7531)] Hz and loud conditions is 18476 [95% C.I. = (13607, 23344)] Hz (Figure 14). The mean bandwidth frequency for the S05 call in quiet conditions is 12043 [95% C.I. = (-16027, 40114)] Hz and loud conditions is 18549 [95% C.I. = (4680, 32417)] Hz (Figure 14). The mean bandwidth frequency for the S19 call in quiet conditions is 10627 [95% C.I. = (9006, 12249)] Hz and loud conditions is 25350 [95% C.I. = (21614, 29085)] Hz (Figure 14).

The results of a log-transformed two-way ANOVA indicated there were significant differences in call peak frequency among ANL conditions and call types (F statistic of ANL main effect is 142.518 (df1= 1), p value <0.001, F statistic of call type main effect is 53.499 (df=5), p value <0.001, F statistic of interaction effect is 7.163 (df=5), p value <0.001). A post hoc Tukey's test indicated that there were significant differences in call peak frequency between loud and quiet conditions for the call types S01 (p value 0.101) and S05 (p value <0.001). Again, while the Tukeys test indicated a p value of 0.101 for the call type S01, the log-transformed ANOVA model, with a higher degree of accuracy, indicated a significant difference. The mean peak frequency of the S01 call in quiet conditions is 1373 [95% C.I. = (1125, 1621)] Hz and loud conditions is 1857 [95% C.I. = (1708, 2254)] Hz (Figure 15). The mean peak frequency of the S05 call in quiet conditions is 2363 [95% C.I. = (1485, 3241)] Hz and loud conditions is 7741 [95% C.I. = (4053, 11428)] Hz (Figure 15).

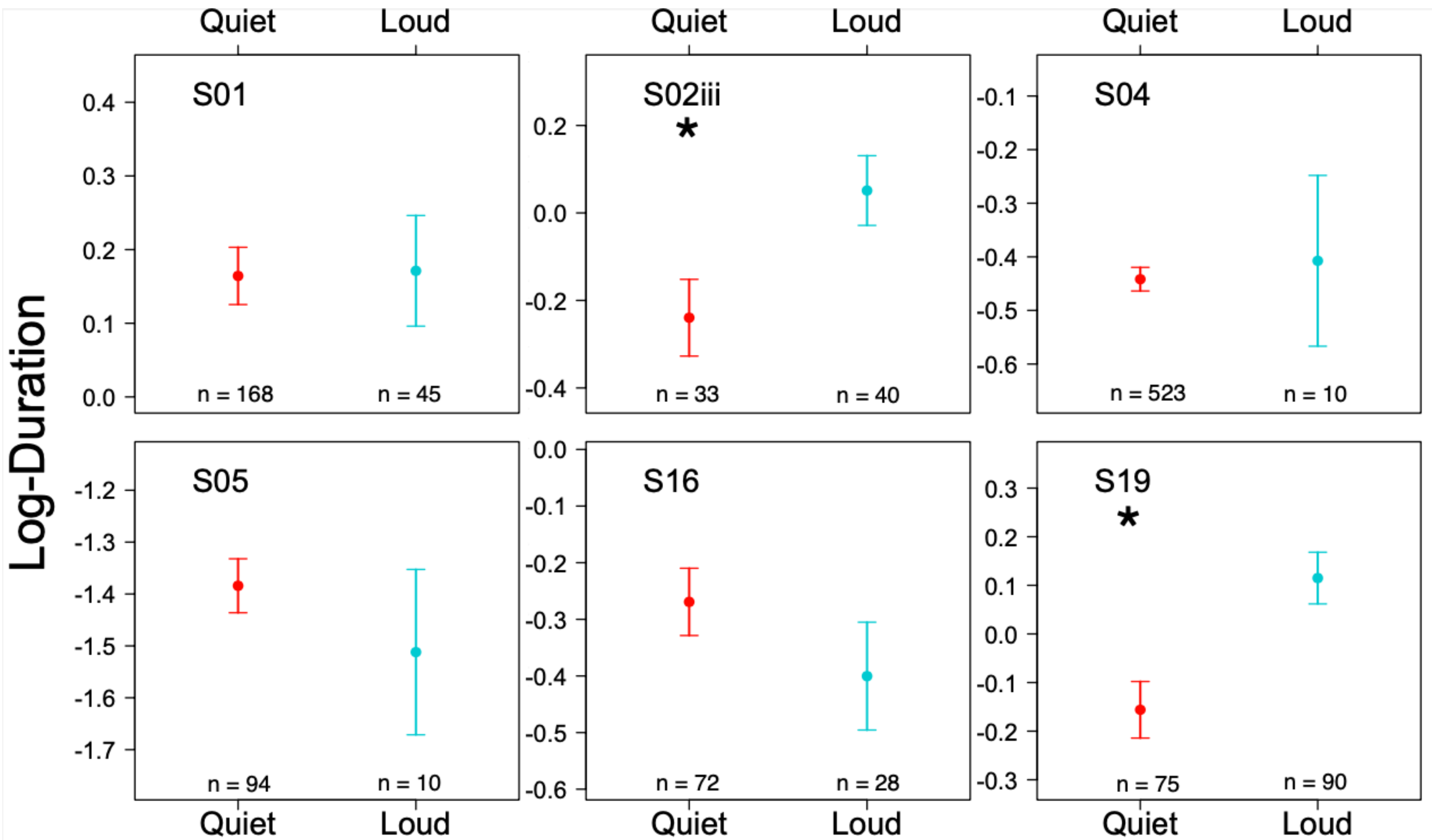


Figure 13. **Boxplots of SRKW call types indicating log-transformed duration of SRKW calls during "Quiet" and "Loud" background ambient noise level (dB re 1 μPa) conditions. Noise threshold is 95 dB re 1 μPa. Error bars indicate 95% confidence interval. Asterisks indicate <0.05 significance level.**

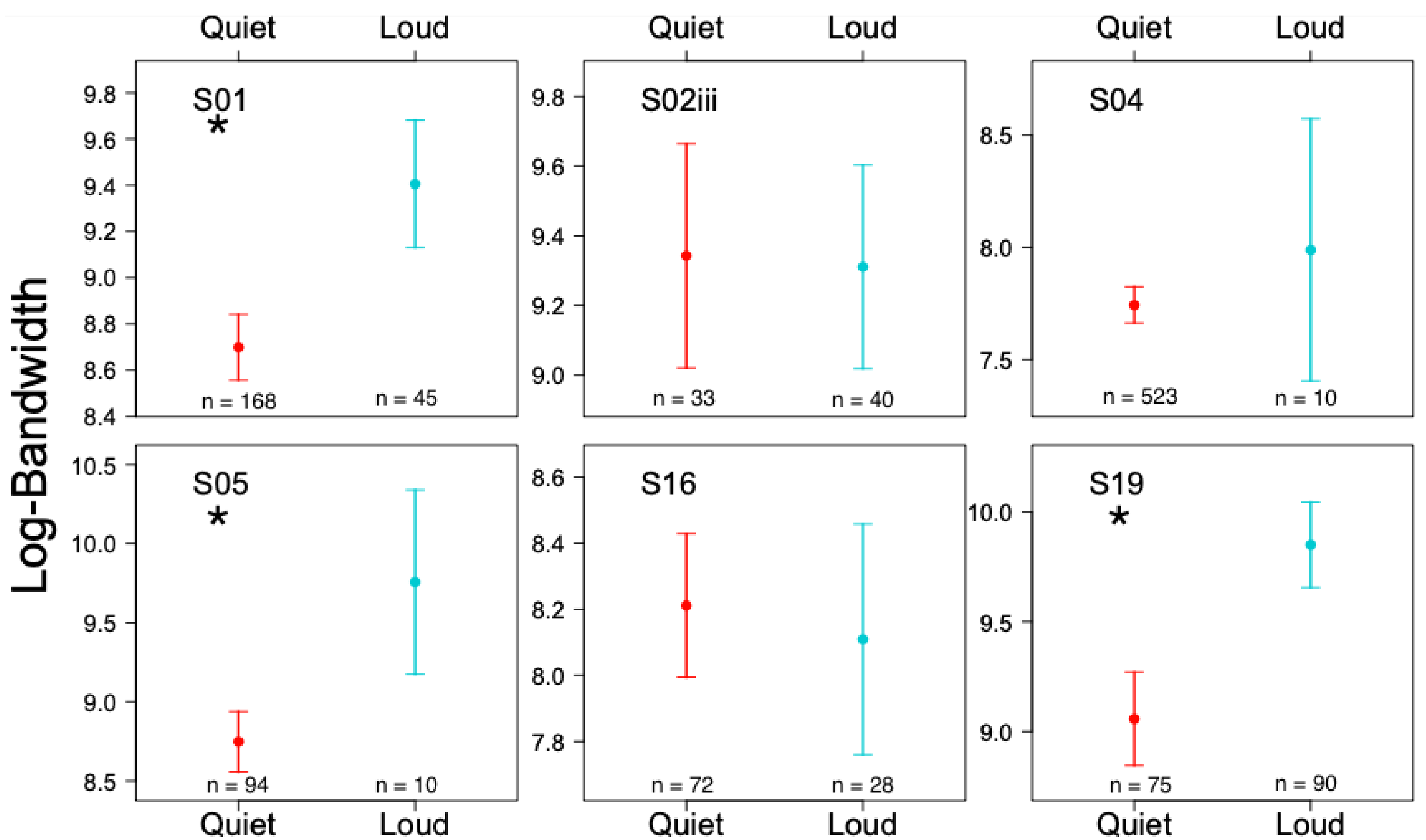


Figure 14. **Boxplots of SRKW call types indicating log-transformed bandwidth frequency of SRKW calls during "Quiet" and "Loud" background ambient noise level (dB re 1 µPa) conditions. Noise threshold is 95 dB re 1 µPa. Error bars indicate 95% confidence interval. Asterisks indicate <0.05 significance level.**

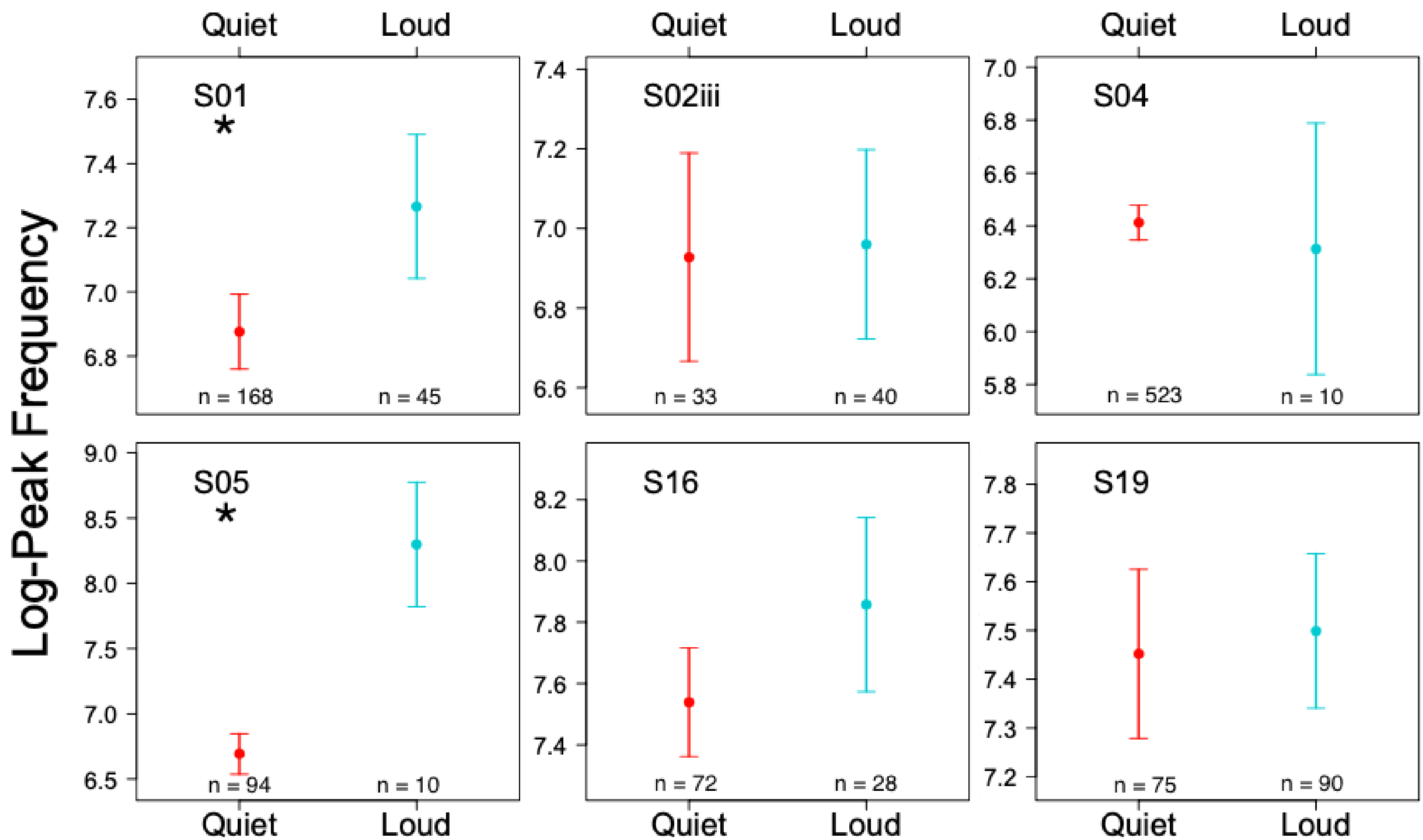


Figure 15. **Boxplots of SRKW call types indicating log-transformed peak frequency of SRKW calls during “Quiet” and “Loud” background ambient noise level (dB re 1 μPa) conditions. Noise threshold is 95 dB re 1 μPa. Error bars indicate 95% confidence interval. Asterisks indicate <0.05 significance level.**

In quiet conditions (<95 dB re 1 μPa), there were 108 (11.2% of total) biphonic calls and 857 (88.8% of total) monophonic calls. In loud conditions, there were 130 (58.3% of total) biphonic calls and 93 (41.7% of total) monophonic calls. A Fisher's exact test for count data showed there was a significant association between call types used and background ANL (p value <0.001) (Figure 16). Additionally, a Fisher's exact test for count data showed there was a significant association between the tonal characteristic of call types (biphonic vs monophonic) and background ANL (p value <0.001) (Figure 16).

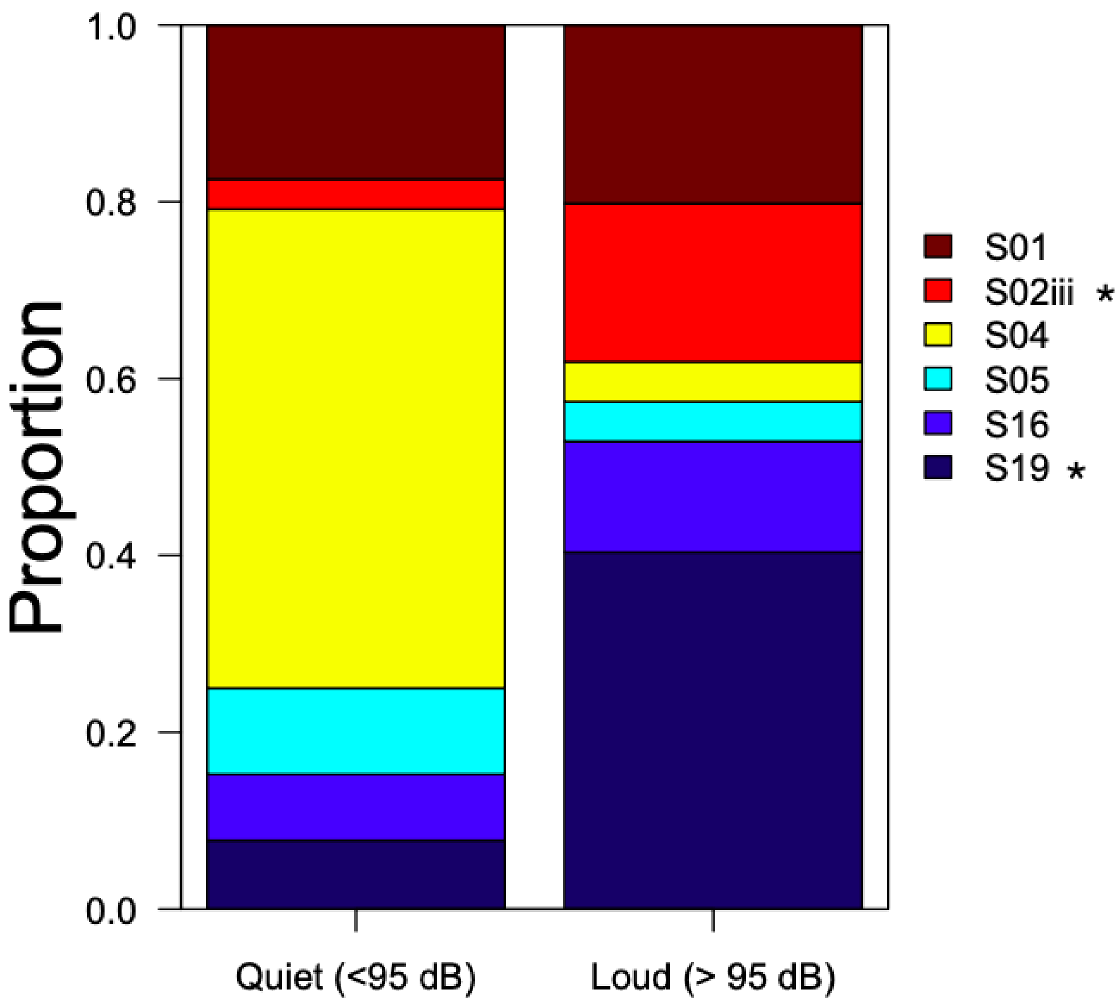


Figure 16. Proportions of call instances that occurred under "Quiet" and "Loud" conditions by call type. Noise threshold is 95 dB re 1 μPa. Asterisks indicate biphonic call types.

Chapter 4. Discussion

4.1 Call Type Distributions

The two most frequently identified call types were S04 (n= 533) and S01 (n= 213) (Table 2). This is a departure from historic patters. Traditionally, S01 has been the most common call type recorded in the Salish Sea, while S04 has been the fourth or fifth most common call type (Foote et al. 2008). This result of more than double the number of S04 than S01 is unexpected because the S01 call type is used by both J and L pods and the S04 call is made exclusively by J pod, meaning there are less individuals that are able to produce this call. This increase in number of S04 calls could be in part due to the high prevalence of J pod acoustic recordings (n= 13) relative to that of K pod (n= 3) and L pod (n= 3) in Boundary Pass. There has also been some recent evidence of J pod exclusively using S04 calls for relatively long sequences, although there has been no proposed reason for this (S. Veirs, personal communication, December 2022).

Of the S01 calls identified, 79% occurred during quiet conditions. It's possible that this call was particularly masked in loud conditions, resulting in a sample size lower than the actual number of calls made. However, this is unlikely as the most common call type, S04, occurred in predominately quiet conditions (98%) and this call resulted in a relative increase in call use from previous studies (Foote et al. 2008). Anecdotally, the minimum frequency of S04 was generally lower than that of S01, therefore S01 would be less likely to be masked by the low frequency vessel noise during loud conditions than S04. Overall, this result suggests that SRKW are currently increasing their use of S04 and decreasing their use of S01 compared to previous studies. Ford 1991 suggests that call repertoire use can change over time.

The call occurrence distributions of S19 (n= 165), S16 (n= 100), and S02iii (n= 73) are in line with historical call distributions and the relatively low number of sightings of K and L pods. Historically, the most commonly used calls by L pod have been S19 and S02iii (Foote et al. 2008). Historically, the most common calls used by K pod have been S16 and S17. The commonality of S17 (n= 24) is unexpectedly low relatively to instances of S16 (n= 100), but due to the low number of acoustic recordings from K pod (n= 3), no strong conclusions can be drawn from this result.

4.2 Effects of Ambient Noise Levels on Call Parameters

The Lombard effect has been described as an increase in communication effort to be heard over loud background conditions (Holt et al. 2009). This effect has been described in birds as a shift in call amplitude (volume) to compensate for a shift to louder anthropogenic noises in urban compared to rural environments (Sementili-Cardoso & Donatelli 2021). The Lombard effect has also been documented in SRKW as a positive relationship between background ANL and SRKW call amplitude (or volume) and duration (Holt et al. 2009; Foote et al. 2004). The results of this project corroborate the Lombard effect- that ANL increased SRKW call duration in the S02iii and S19 call types. The increase in duration of these SRKW calls may be an attempt to increase their communication effort to be heard in loud vessel conditions. In many species, increasing call duration has been associated with an improved sound perception threshold by other individuals of that species (Heil and Neubauer 2003). The energetic cost of increasing communication effort for SRKW remains unknown, however, birds have shown an increased metabolic rate with an increase in song production (Oberweger and Goller 2001).

Other call parameters not explicitly associated with the Lombard effect may also be affected by background vessel noise. The results of this study suggest that ANL may have an effect on peak frequency in S01 and S05 call types and an effect on bandwidth frequency in S01, S05, and S19 call types. Upon a review of the literature, call frequency parameters have not been included as being part of the Lombard effect or been studied in SRKW. A positive relationship between vessel presence and whistle frequency parameters has been documented in Bottlenose dolphins (*Tursiops truncatus)* (Heiler et al. 2016). There is an overlap between SRKW communication frequencies and marine vessels frequencies (Williams et al. 2014). This overlap may be causing an upwards call frequency shift in loud ANL conditions in an attempt to use available acoustic communication space (Heiler et al. 2016). The increase in bandwidth frequency, or frequency range, of SRKW calls in loud conditions may also be due to the overlap of SRKW communication and marine vessel frequencies. SRKW may be using calls over a wider range of frequencies in an attempt to be heard in loud conditions. These frequency call parameters seem to be changing in response to background vessel noise; however, it is unknown if changes in these parameters are associated with an increase in communication effort.

There also seem to be effects on the particular types of calls used in relation to background ANL. SRKW are using significantly different proportions of monophonic and biphonic calls in quiet and loud conditions. In quiet conditions, the majority of calls used are monophonic and in loud conditions, monophonic and biphonic calls are used in approximately equal proportions. Biphonic calls are two-toned in nature. SRKW are able to make these calls using two voices at the same time by pushing air through phonic lips (Madsen et al. 2023). These tones occur over different frequencies, therefore a possible cause for the increased use of them at loud conditions is the ability to call over a variety of frequencies at one time, gaining a higher likelihood of being heard.

Biphonic calls have been documented in other animals such as the Dhole (a canid) and two species of penguin for recognition purposes (Volodina et al. 2005, Aubin et al 2000). Aubin et al. 2000 mentions that for penguins, these biphonic calls are robust and propagate the sound through the entire penguin colony. Foote et al. 2008 showed that SRKW biphonic calls were used more in multi-pod settings and postulated that these biphonic calls are important for recognition of individuals in other pods too. Perhaps biphonic calls are more distinct and easily heard by other individuals as they are likely used for recognition of other pods far distances away. Perhaps loud underwater conditions make it difficult to use monophonic calls and therefore SRKW must default to using the more distinct biphonic calls, normally used to recognize individuals from other pods, to recognize individuals from their own pod too.

Miller (2002) showed that the high frequency component of SRKW biphonic calls have higher energy when the whale is approaching the hydrophone than travelling away from it, suggesting that there is a directionality associated with these recognition calls too. Perhaps SRKW are using these calls more frequently in loud conditions to be able to identify the direction other pods members are travelling in order to deduce and avoid a collision with the vessel itself. Additionally, the two significantly different call durations between loud and quiet conditions, S02iii and S19, are both biphonic call types. This could further support the idea that SRKW are using biphonic calls more often and for longer in loud conditions to be more easily recognizable by other individual whales.

Different call types may exert different communication effort to use them; however, it is unknown if this is the case.

For SRKW, heightened anthropogenic noise levels have the potential to change and even stop certain behaviours (Holt et al 2009, Foote et al. 2004; Holt et al. 2021). This could result in behavioural changes to the SRKW ecology – resulting in possibly negative effects on individuals. SRKW rely on communication between pod and clan members to serve vital roles for the population such as prey sharing, navigation, and reproduction. If this available acoustic communication space is changed due to vessel noise at the same frequencies as SRKW communication, a new selective pressure may drive change in vocalisation behaviour toward switches in dominant call types, as well as within call modifications such as higher frequency and longer duration calls. If individuals, or the entire SRKW population, are unable to adapt to changing ANL conditions, they may be unable to maintain communication with their pod and would cause detrimental effects on this endangered population.

4.3 Management Measure Implications

This study occurred within the critical habitat of the endangered SRKW (Government of Canada 2021). Within this critical habitat, the behaviour of SRKW is being affected by vessel noise to an unknown degree. This is an indication of the destruction of this critical habitat, which is a violation of the *Species at Risk Act* (Government of Canada, 2002). The management measures in place to minimize the destruction of this critical habitat caused by vessel noise are the Interim Sanctuary Zone and the commercial vessel slowdown. These measures have been documented to reduce the ANL in Boundary Pass by 4.3 dB for the slowdown and 2.4 dB for the ISZ, both within the 500 – 15000 Hz frequency range (Burnham et al. 2021).

Given the high compliance rates of the slowdown and the low number of ISZ infractions relative to the durations of the SRKW acoustic events, it seems as though SRKW are still being affected by vessel noise under measure compliance. This could be an indication that these measures are not reducing vessel noise enough to completely avoid impacting SRKW. There is also evidence to suggest that there are significant additional sources of ANL contributing to the soundscape in addition to commercial vessels. Four of the thirteen acoustically active events had at least one commercial vessel present (Figure 9). These four events are among the loudest events, however two events in which commercial vessels were absent were louder. This may suggest that other sources of ANL, such as smaller recreational or ecotourism vessels are being overlooked as a significant contributor of ANL in the area. Future studies assessing the efficacy of the current management measures and useful options for potential amendments to the management measure regulations are vitally needed.

While compliance rates of the management measures are somewhat high during SRKW events, instances of ISZ infractions and slowdown non-compliance are still occurring. While no compliance rate is available for 2022, a comparison of the number of infractions can be made over the past three years of study in Boundary Pass. There were 427 infractions in 2020, 251 in 2021, and 370 in 2022. This may indicate that ISZ compliance is decreasing between the years 2021 and 2022. However, we may not be able to assume that the number of vessels using Boundary Pass is approximately the same over the past three study years due to the COVID-19 pandemic and fluctuating numbers of vessels allowed to cross the Canada-USA border. Nevertheless, the fact that instances of non-compliance are still occurring indicates that participation and enforcement of measures could be improved, especially when SRKW are in the area. The current or future measures would be most effective as compulsory and effectively enforced regulations.

4.4 Study Limitations

While certain biases and limitations were accounted for in this study, the results still have limitations. The data for this project represent the background ANL and SRKW call parameters at the point of the hydrophone in which these sounds were recorded. In this project, the data is used as the background ANL and call parameters at the point of the SRKW individuals. Although the path of the SRKW was directly over top of the hydrophone location for most of the events, this was not the case for the entire event or every event. This may have introduced some inaccuracies in the data. Future studies are advised to build a sound propagation model to account for this issue. Another limitation is the pseudoreplication and Type II error present in this data. This is due to multiple data points being used from the same SRKW events (under similar conditions) and even the same individuals in the same events. One specific example is the heightened use of the S04 call. This call type was perhaps overrepresented in this study due to the long sequences of exclusively S04 calls that were found in some audio files. Future studies are advised to use an autocorrelation function to account for this during data analysis. These steps were not taken in this study due to timeline constraints. Another limitation stems from lower frequency sounds travelling further than higher frequency sounds. For this reason, there could be underlying confounding factors such as intensified masking of calls depending on the direction of travel and distance between the calling whales and the hydrophone when low frequency vessel noise is present. Additionally, for the peak frequency data in particular, the low frequency vessel noise could be masking the true peak frequency in the lower frequencies, resulting in an increased peak frequency in loud ANL conditions.

Chapter 5. Conclusion

This study aimed to answer how the vocal behaviour of SRKW is being affected by marine vessel noise, and if the current management measures, the Interim Sanctuary Zone, and the commercial vessel slowdown are effective at minimizing any possible vessel related effects on SRKW behaviour. Acoustic data from 13 SRKW transits of Boundary Pass yielded results suggesting that shifts in measured call parameters of some SRKW call types are being affected by marine vessel noise- some of these parameters are evidence of the Lombard effect. Call duration, peak frequency, and bandwidth frequency all exhibit an increase with background ANL. Additionally, the data suggest that certain call types used are being affected by ANL. Particularly, biphonic or two-toned call types are being used more in loud conditions. Both of these lines of evidence suggest that vessel noise is causing a change in the behaviour of SRKW- at an unknown cost to the whales.

This study also aimed to answer the efficacy of the current management measures, the Interim Sanctuary Zone, and the commercial vessel slowdown at minimizing any possible vessel related effects on SRKW behaviour. When vessels were present during an acoustic SRKW event, there was high compliance of both management measures. This suggests that the current measures are perhaps not enough to minimize vessel noise for the SRKW. More research is required on the efficacy of these management measures in Boundary Pass and other regions of SRKW critical habitat.

References

Aubin T, Jouventin P, Hildebrand C (2000) Penguins use the two-voice system to recognize each other. Proceedings of the Royal Society of London. Series B, Biological Sciences 267: 1081-1087

Baril KM (2022) Marine Restoration in Boundary Pass: Evaluating Management Strategies for Conserving Canada's Coastal Whale Populations. MSc Thesis, Simon Fraser University

Barrett-Lennard LG, Ellis GM (2001) Population structure and genetic variability in Northeastern Pacific Killer Whales: Towards an assessment of population viability. DFO Canadian Science Advisory Secretariat Research Document 2001/065

Bouvier MIM (2022) Playgrounds by a highway: Understanding the effects of increased ambient noise levels on Northern Resident killer whales *(Orcinus orca)* during beach rubbing. MSc Thesis, Simon Fraser University

Burnham RE, Vagle S, O'Neill C, Trounce K (2021) The Efficacy of Management Measures to Reduce Vessel Noise in Critical Habitat of Southern Resident Killer Whales in the Salish Sea. Frontiers in Marine Science 8: e664691

Buxton RT, Mckenna MF, Mennitt D, Fristrup K, Crooks K, Angeloni L, Wittemeyer G (2017) Noise pollution is pervasive in U.S. protected areas. Science 356(6337): 531-533

Branstetter BK, St. Leger J, Acton D, Stewart J, Houser D, Finneran JJ, Jenkins K (2017) Killer whale (*Orcinus orca*) behavioral audiograms. Journal of the Acoustical Society of America 141(4): 2387-2398

Celi M, Filliciotto F, Maricchiolo G, Genovese L, Quinci EM, Maccarrone V, Mazzola S, Vazzana M, Buscaino G (2015) Vessel noise pollution as a human threat to fish: assessment of the stress response in gilthead sea bream (*Sparus aurata*, Linnaeus 1758). Fish physiology and biochemistry 42(20): 631-641

Center for Whale Research (2019) Orca Survey Southern Resident Killer Whales ID Guide. Washington, USA

Center for Whale Research (2022) Southern Resident Orca (SRKW) Population https://www.whaleresearch.com/orca-population (accessed 4 October 2022)

Cominelli S, Rodolphe D, Yurk H, MacGillivray A, McWhinnie L, Canessa R (2018) Noise exposure from commercial shipping for the southern resident killer whale population. Marine Pollution Bulletin 136: 177-200

Department of Fisheries and Oceans Canada (2018) Recovery Strategy for the Northern and Southern Resident Killer Whales (Orcinus orca) in Canada [proposed]. Species at Risk Act Recovery Strategy Series, Fisheries and Oceans Canada, Ottawa.

Department of Fisheries and Oceans Canada (2021) Northern resident killer whale Eagle Eye field protocol. OPP MEQ Pacific. Vancouver, British Columbia, Canada

Erbe C (2002) Underwater noise of whale-watching boats and potential effects on killer whales (Orcinus orca), based on acoustic impact model. Marine Mammal Science 18(2): 394-418

Erbe C (2011) Underwater acoustics: noise and the effects on marine mammals. A Pocket Handbook 164(9): 10-35

Erbe C, Marley SA, Schoeman RP, Smith JN, Trigg LE, Embling CB (2019) The effects of ship noise on marine mammals- a review. Frontiers in Marine Science 6

Filliciotto F, Vazzana M, Celi M, Maccarrone V, Ceraulo M, Buffa G, Stefano VD, Mazzola S, Buscaino G (2014) Behavioural and biochemical stress responses of *Palinurus elephas* after exposure to boat noise pollution in tank. Marine pollution bulletin 84(1-2): 104-114

Foote AD, Osborne RW, Hoelzel AR (2004) Whale-call response to masking boat noise. Nature 428: 910

Foote AD, Osborne RW, Hoelzel AR (2008) Temporal and contextual patterns of killer whale (*Orcinus orca*) call type production. Ethology 114: 599-606

Ford JKB (1987) A catalogue of underwater calls produced by killer whales (Orcinus orca) in British Columbia. Department of Fisheries and Oceans, Nanaimo, British Columbia, Canada

Ford JK (1991) Vocal traditions among resident killer whales (Orcinus orca) in coastal waters of British Columbia. Canadian Journal of Zoology 69(6): 1454-1483

Ford JKB (2017) Marine Mammals of British Columbia. Royal BC Museum, Victoria, Canada.

Ford JKB, Ellis GM (2006) Selective foraging by fish eating killer whales Orcinus orca in British Columbia. Marine Ecology 316: 185-199

Frisk GV (2012) Noiseonomics: the relationship between ambient noise levels in the sea and global economic trends. Scientific Reports 2(1): 437

Gheibi A, Baril K, Quayle L, Joy R (2021) Boundary Pass 2021 Land-based Cetacean Observations. Technical report prepared by the School of Environmental Science, Simon Fraser University for the Vancouver Fraser Port Authority

Government of Canada (2002) Species at Risk Act https://laws-lois.justice.gc.ca/PDF/S-15.3.pdf (accessed 6 March 2023)

Government of Canada (2021) Fisheries and Oceans Canada https://www.pac.dfo-mpo.gc.ca/fm-gp/mammals-mammiferes/whales-baleines/srkw-measures-mesures-ers-eng.html (accessed 13 December 2021)

Hauser DDW, Logsdon MG, Holmes EE, VanBlaricom GR, Osborne RW (2007) Summer distribution patterns of southern resident killer whales Orcinus orca: core areas and spatial segregation of social groups. Marine Ecology Progress Series 351: 301-310

Heil P and Neubauer H (2003) A unifying basis of auditory thresholds based on temporal summation. Proceedings of the National Academy of Sciences of the United States of America 100(10): 6151-6156

Heiler J, Elwen SH, Kriesell HJ, Gridley T (2016) Changes in bottlenose dolphin whistle parameters related to vessel presence, surface behaviour and group composition. Animal Behaviour 117: 167-177

Hildebrand JA (2009) Anthropogenic and natural sources of ambient noise in the ocean. Marine Ecology Progress Series 395: 5-20

Holt M, Veirs V, Veirs S (2008) Investigating noise effects on the call amplitude of endangered Southern Resident killer whales (*Orcinus orca*). The Journal of the Acoustical Society of America 123(5): 2985

Holt MM, Noren DP, Veirs V, Emmons CK, Veirs S (2009) Speaking up: Killer whales (Orcinus orca) increase their call amplitude in response to vessel noise. Journal of the Acoustical Society of America 125(1): EL27–EL32.

Holt MM, Veirs V, Veirs S (2012) Noise effects on the call amplitude of southern resident killer whales (Orcinus orca). Bioacoustics 17(1-3): 164-166

Holt MM, Tennessen JB, Hanson MB, Emmons CK, Giles DA, Hogan JT, Ford MJ (2021) Vessels and their sounds reduce prey capture effort by endangered killer whales *(Orcinus orca).* Marine Environmental Research 170: 105429

Joy R, Tollit D, Wood J, MacGillivray A, Li Z, Trounce K, Robinson O (2019) Potential benefits of vessel slowdowns on Endangered Southern Resident Killer Whales. Frontiers in Marine Science 6

Krahn MM (2002) Status review of the southern resident killer whale under the endangered species act. National Oceanic and Atmospheric Administration, Seattle, Washington, USA

Le Baron N, McWhinnie L, Frouin-Mouy H (2019) Boundary Pass 2019 Land-based Cetacean Observations: ECHO 2019 Slowdown Evaluations. Document 01906, Version 3.0. Technical report by JASCO Applied Sciences and University of Victoria for Vancouver Fraser Port Authority

Lusseau D, Bain DE, Williams R, Smith JC (2009) Vessel traffic disrupts the foraging behavior of southern resident killer whales *Orcinus orca.* Endangered Species Research 6:211-221

Madsen PT, Siebert U, Elemans CP (2023) Toothed whales use distinct vocal registers for echolocation and communication. Science 379(6635): 928-933

MarineTraffic.com (2022) MarineTraffic (version 4.0.35) [Mobile application software] Play store

Merchant ND, Fristrup KM, Johnson MP, Tyack PL, Witt MJ, Blondel P, Parks SE (2015) Measuring acoustic habitats. Methods in Ecology and Evolution 6: 257-265

Miller PJO (2002) Mixed-directionality of killer whale stereotypes calls, a direction of movement cue? Behavioural Ecology Sociobiology 52: 262-270

Murphy O, Laturnus L, Gheibi A, Baril K, Quayle L, Joy R (2022) Boundary Pass 2022 Land-based Cetacean Observations. Technical report prepared by the School of Environmental Science, Simon Fraser University for the Vancouver Fraser Port Authority

Noren DP, Johnson AH, Rehder D, Larson A (2009) Close approaches by vessels elicit surface active behaviors by southern resident killer whales. Endangered Species Research 8:179-192

Oberweger K, Goller F (2001) The metabolic cost of birdsong production. The Journal of Experimental Biology 204(19): 3379-3388

Ocean Sonics (2015) Certificate of Calibration. Ocean Sonics, Ltd. Truro, Nova Scotia

Olson JK Wood J, Osborne RW, Barrett-Lennard L, Larson S (2018) Sightings of southern resident killer whales in the Salish Sea 1976-2014: the importance of a long-term opportunistic dataset. Endangered Species Research 37: 105-118

Purves D, Augustine GJ, Fitzpatrick D, Katz LC, LaMantia A, McNamara JO, Williams SM (2001) Neuroscience, 2nd edition. Sinauer Associates

Quayle LS (2021) Assessing Vessel Related Threats on Whales in Boundary Pass. MSc Thesis, Simon Fraser University

Quayle L, Joy R (2021) Boundary Pass 2020 Land-based Cetacean Observations: ECHO 2020 Slowdown Evaluation. Technical report by SMRU and Simon Fraser University for Vancouver Fraser Port Authority

Raverty S, St. Leger J, Noren DP, Huntington KB, Rotstein DS, Gullard FMD, Ford JKB, Hanson MB, Lambourn DM, Huggins J, Delaney MA, Spaven L, Rowles T, Barre L, Cottrell P, Ellis G, Goldstein T, Terio K, Duffield D, Rice J, Gaydos JK (2020) Pathology findings and correlation with body condition index in stranded killer whales *(Orcinus orca)* in the northeastern Pacific and Hawaii from 2004 to 2013. Plos One 15(12): e0242505. https://doi.org/10.1371/journal. pone.0242505

Riesch R, Deecke VB (2011) Whistle communication in mammal-eating killer whales (*Orcinus orca*): further evidence for acoustic divergence between ecotypes. Behavioural Ecology and Sociobiology 56: 1377-1387

Sementili-Cardoso G, Donatelli RJ (2021) Anthropogenic noise and atmospheric absorption of sound induce amplitude shifts in the songs of Southern House Wren (Troglodytes aedon musculus). Urban Ecosystems 24: 1001-1009

Towers JR, Sutton GJ, Shaw TJH, Malleson M, Matkin D, Gisborne B, Forde J, Ellifrit D, Ellis GM, Ford JKB, Doniol-Valcroze T (2019) Photo-identification Catalogue, Population Status, and Distribution of Bigg's Killer Whales known from Coastal Waters of British Columbia, Canada. Canadian Technical Report Fish and Aquatic Sciences 3311(6): 299 p

Veirs S, Veirs V, Wood JD (2016) Ship noise extends to frequencies used for echolocation by endangered killer whales. PeerJ 4: e1657

Volodina EV, Volodin IA, Isaeva IV, Unck C (2005) Biphonation may function to enhance individual recognition in the Dhole (*Cuon alpinus*). Ethology 112: 815-825

Wang Z, Akamatsu T, Duan P, Zhou L, Yuan J, Li J, Lei P, Chen Y, Yang Y, Wang K, Wang D (1987) Underwater noise pollution in China's Yangtze River critically endangers Yangtze finless porpoises (*Neophocaena asiaeorientalis asiaeorientalis*). Environmental Pollution 262: 114310

Williams R, Bain DE, Smith JC, Lusseau D (2009) Effects of vessels on behavior patterns of individual southern resident killer whales *Orcinus orca.* Endangered Species Research 6:199-209

Williams R, Clark CW, Ponirakis D, Ashe E (2014) Acoustic quality of critical habitats for three threatened whale populations: Acoustic quality of critical whale habitats. Animal Conservation 17(2): 174-185

Williams R, Ase E, Yruretagoyena L, Mastick N, Siple M, Wood J, Joy R, Langrock R, Mews S, Finne E (2021) Reducing vessel noise increases foraging in endangered killer whales. Marine Pollution Bulletin 172: 112976

Appendix

Appendix A

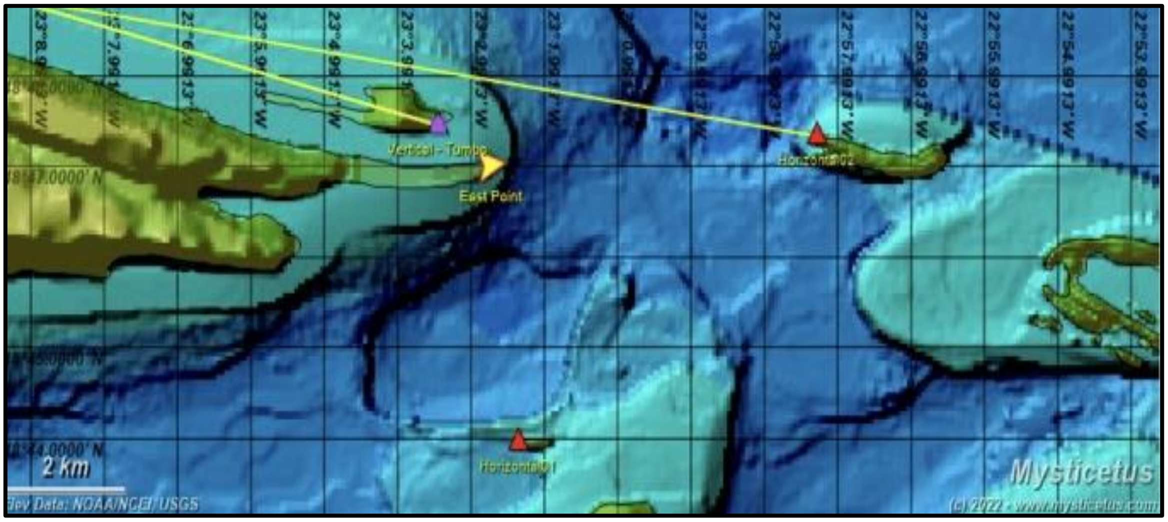


Figure A1. **Screenshot of the Mysticetus software positioned on the study area in Boundary Pass, British Columbia. Yellow marker represents the land-based observation platform, red markers represent horizontal waypoints established at specific unique points on Skipjack Island (Horizontal01) and Patos Island (Horizontal02), purple marker represents vertical waypoint established at a specific unique point on Tumbo Island.**

Appendix B

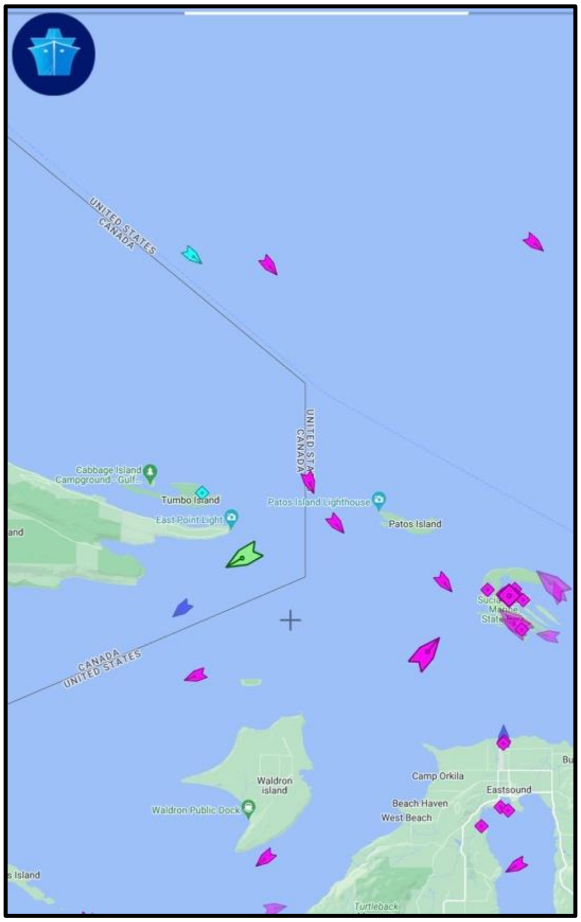


Figure B1. **Screenshot of MarineTraffic application software dashboard positioned on Boundary Pass.**

Appendix C

Table C1. Standardized pre-set RavenPro software spectrogram settings

Brightness	50
Contrast	56
FFT	3053
Frequency View Range	0-15 kHz
Time Frequency Range	9s
Volume Gain	10.62

Appendix D

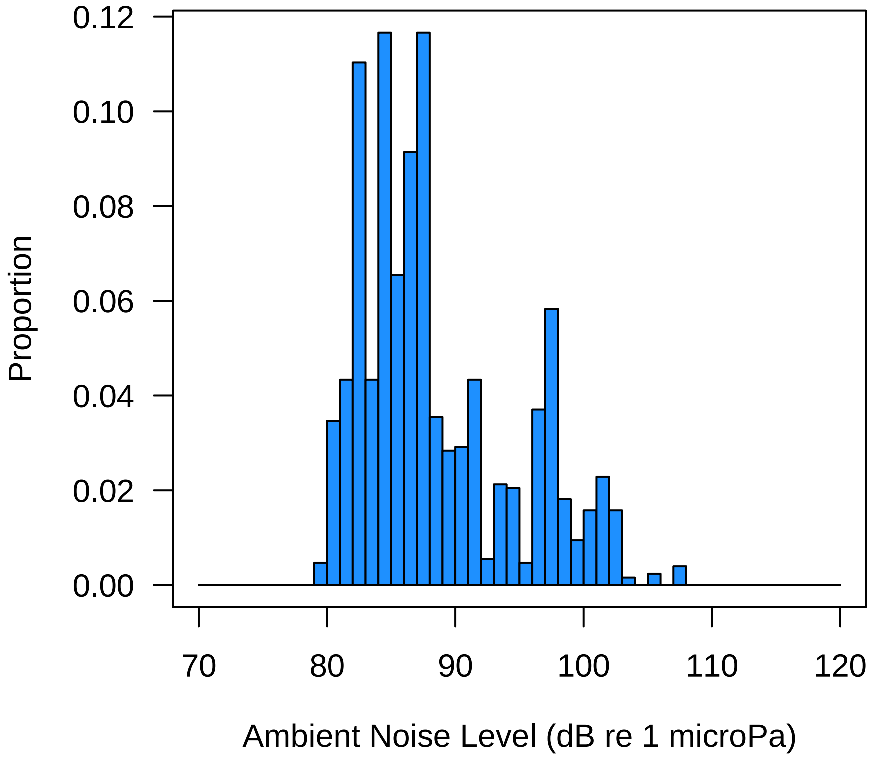


Figure D1. **Proportion of ambient noise levels (dB re 1 μPa) during SRKW calls. Grey line indicates noise threshold between "Quiet" and "Loud" conditions at 95 dB re 1 μPa.**