

NoiseTracker: Tracking vessel noise and its implications for Southern Resident killer whales in the Salish Sea

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Executive summary

Underwater noise is a primary threat limiting the recovery of critically endangered Southern Resident killer whales (SRKW). Degraded acoustic conditions can reduce communication efficiency and foraging success, with potential consequences for body condition, fecundity, and survival. In response, several mitigation measures have been implemented within SRKW habitat in the Salish Sea, including seasonal Vessel Restricted Zones (VRZs) and a voluntary commercial vessel slowdown program. This study evaluated long-term changes in underwater noise and SRKW occurrence in the Salish Sea over the past decade using hydrophone data from Pender and Saturna Islands. We quantified changes in vessel-related noise across biologically relevant frequency bands and compared acoustic trends with SRKW detection records and vessel traffic data from 2017 to 2025.

Results indicate a sustained degradation of the acoustic environment, with consistent increases in underwater noise across all metrics and frequency bands relevant to SRKW. Despite existing management measures, these increases correspond with rising vessel traffic and changes in vessel composition and operation. Current management measures appear insufficient to offset cumulative vessel noise exposure in critical SRKW habitat, highlighting the need for more effective, enforceable, and biologically relevant reduction targets.



1. Introduction

1.1 Conservation context

Southern Resident killer whales (SRKW) are an endangered ecotype - a genetically and behaviorally distinct form - of killer whales (*Orcinus orca*) found in the northeast Pacific Ocean. Critical habitat has been designated throughout the coastal waters of the Salish Sea under Canada's Species at Risk Act (Species at Risk Act 2002; Fisheries and Oceans Canada 2018). As of July 2025, the population numbered 74 individuals (Center for Whale Research 2025). Declines in their primary prey, Chinook salmon, combined with anthropogenic stressors including vessel noise and disturbance and chemical contaminants, undermine population recovery (Fisheries and Oceans Canada 2018; Lusseau et al. 2009; Tennessen et al. 2024).

SRKW are highly social cetaceans that rely on pulsed calls and echolocation clicks to communicate, forage, and navigate (Barrett-Lennard et al. 1996). Elevated underwater noise levels can mask these signals, disrupting information transfer and reducing foraging efficiency (Tennessen et al. 2024). Behavioural responses to vessel presence and noise include altered movement patterns, changes in call type and frequency, and displacement from preferred foraging locations (Williams et al. 2006; Holt et al. 2021a). Chronic acoustic disturbance has been linked to declines in foraging efficiency, forcing whales to work harder to meet their energetic demands (Lacy et al. 2017; Fisheries and Oceans Canada 2019; Holt et al. 2021a; Thornton et al. 2022; Tennessen et al. 2024). These cumulative pressures have prompted targeted management actions to reduce disturbance within critical habitat.

1.2 Management context

In the heavily trafficked waters of the Salish Sea, both commercial and recreational vessels collectively contribute to underwater noise, resulting in a louder habitat for marine mammals. Regional management actions have been implemented to mitigate vessel disturbance to SRKW in Canadian waters. Two Vessel Restricted Zones (VRZs; formerly Interim Sanctuary Zones) were established in 2019 off North Pender Island and eastern Saturna Island (Figure 1). These locations were selected based on long-term sightings data indicating consistent SRKW use of Swanson Channel and Boundary Pass (Olson et al. 2018). Under current regulations, vessel entry into these zones is prohibited from June 1 through November 30, corresponding with peak SRKW presence. However, vessel compliance

remains difficult to enforce, and the size, shape, and timing of these zones may render them inadequate as acoustic refuges for SRKW.

In addition to spatial protections, the Vancouver Fraser Port Authority implemented the Enhancing Cetacean Habitat and Observation (ECHO) voluntary vessel slowdown program to reduce underwater noise emissions and decrease acoustic disturbance to SRKW. First piloted in 2017 and fully implemented in 2018, the program encourages commercial vessels transiting Haro Strait and Boundary Pass to voluntarily reduce their speed (Joy et al. 2019; Vancouver Fraser Port Authority 2025a). As of 2024, the program reports an 86% participation rate across eligible commercial vessels (Vancouver Fraser Port Authority 2025a). However, this program only targets large commercial vessels; no speed restrictions apply to pleasure craft, ecotourism, or fishing vessels.

Although spatial restrictions and voluntary slowdowns have been implemented, comprehensive evaluations of their effectiveness in reducing underwater noise within critical SRKW habitat remain limited. Importantly, assessments of acoustic conditions must be biologically relevant. Broadband sound pressure levels (SPL) alone may not reflect the true impacts of underwater noise on SRKW. Calls used for SRKW communication typically occur between 0.5-15 kHz, while echolocation clicks used for prey detection occur between 15-100 kHz (Heise et al. 2017). Assessing noise levels within these biologically meaningful frequency bands is necessary to evaluate changes in available acoustic habitat.

1.3 Study objectives

This report assesses underwater acoustic data collected from two hydrophones deployed by partner organizations off Saturna Island (Saturna Island Marine Research and Education Society, SIMRES) and Pender Island (Raincoast Conservation Foundation) (Figure 1). These hydrophones were deployed in strategic locations to quantify the impacts of vessel noise on the underwater soundscape and evaluate implications for SRKW recovery, as both fall within designated SRKW critical habitat under the Species at Risk Act (Species at Risk Act, 2002).

The objectives of this report are to:

1. Quantify long-term vessel noise trends in Boundary Pass.
2. Evaluate recent fine-scale acoustic conditions in the Pender VRZ.
3. Quantify impacts on SRKW communication.

2. Study area

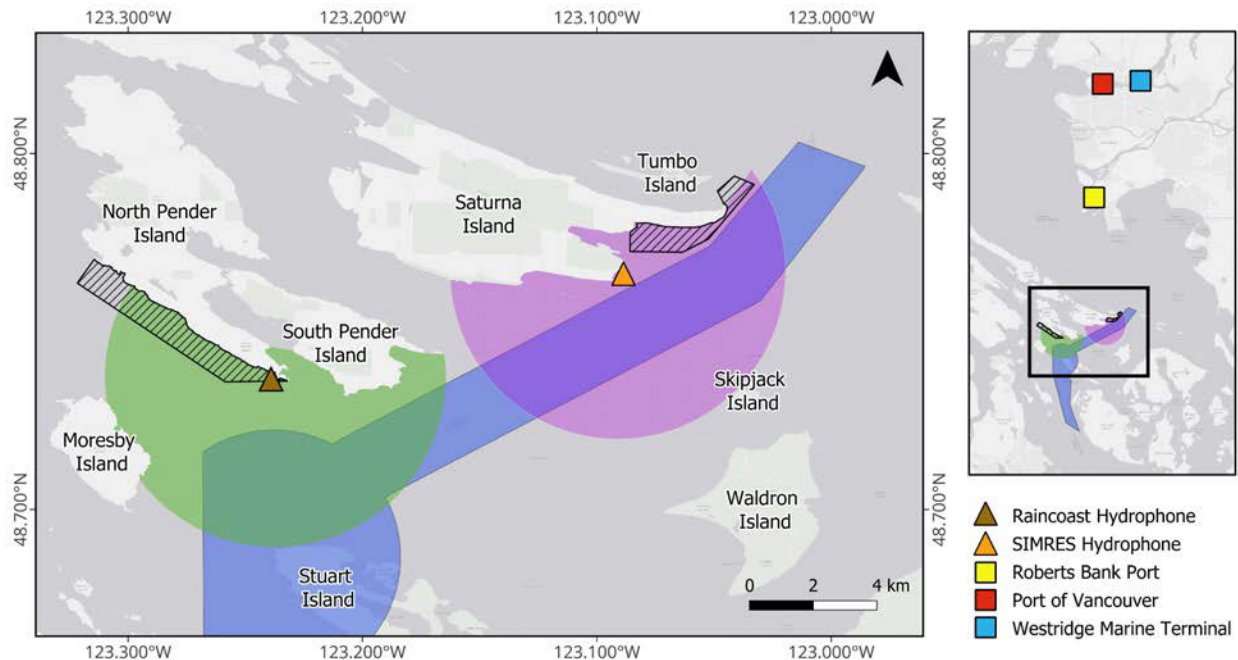
2.1 Regional setting

Boundary Pass is a major shipping corridor located within the Salish Sea, forming part of the maritime boundary between Canada and the United States (Figure 1). It serves as the primary transit route for vessels travelling to and from the Port of Vancouver (the largest port in Canada), Roberts Bank Terminal, and Westridge Marine Terminal, with vessel traffic projected to increase in the coming years. Upgrades to the Westridge Marine Terminal were completed in May 2024 as part of a larger Trans Mountain Expansion Project, resulting in a three-berth complex rather than a single-berth (Government of Canada 2025). The Roberts Bank Terminal 2 project was approved in 2023, and is currently advancing through the regulatory process (a Species at Risk Act, SARA, permit application is under review) with the potential to increase the Port of Vancouver's container capacity by 30% (Vancouver Fraser Port Authority n.d. b).

In addition to large commercial traffic, Boundary Pass experiences substantial seasonal vessel activity associated with tourism and recreation. The Southern Gulf Islands (Canada) and San Juan Islands (United States) are major summer destinations for recreational boaters and ferry passengers. Whale-watching tours and other ecotourism excursions depart from Vancouver Island, the Lower Mainland, and the San Juan Islands, contributing to concentrated small-vessel traffic during peak months.

Boundary Pass lies within designated critical habitat for SRKW and is consistently used by the whales for foraging and socializing, particularly during the summer and early fall (Olson et al. 2018). The convergence of international commercial shipping, tourism, and recreational boating makes Boundary Pass a priority location for assessing underwater noise exposure and its implications for SRKW acoustic habitat.

Figure 1. Study locations



The blue polygon represents Boundary Pass, a commercial shipping corridor within the Salish Sea that separates the Canadian Southern Gulf Islands from the American San Juan Islands. The green and purple polygons represent the 5.3 kilometre radii used to filter SRKW sightings and AIS vessel data near the Pender Island (Raincoast) and Saturna Island (SIMRES) hydrophones. The Pender and Saturna VRZs are shown as two hatched polygons. The two triangles indicate the locations of the Pender (brown) and Saturna (orange) hydrophones. On the inset map, squares mark the locations of Roberts Bank Port (yellow), the Port of Vancouver (red), and the Westridge Marine Terminal (blue).

2.2 Hydrophone locations

2.2.1 Saturna Island

The Saturna Island Marine Research and Education Society (SIMRES) has maintained a hydrophone deployment off Monarch Head (48.767, -123.091), Saturna Island, since 2014. Monarch Head is located on the southeastern side of the island, directly adjacent to the Boundary Pass shipping lane and within 700 m of the Saturna VRZ. This strategic location allows the hydrophone to record vessel noise originating from commercial traffic transiting Boundary Pass, vessels operating within the Saturna VRZ, and any cetaceans transiting through the area. The Monarch Head hydrophone was selected as the long-term monitoring site given the length and continuity of its dataset, extending back to 2017.

2.2.2 Pender Island

Raincoast Conservation Foundation (Raincoast) deployed a hydrophone off Wallace Point (48.737, -123.237) in October 2023. Wallace Point is situated at the southernmost tip of North Pender Island, at the junction of Boundary Pass, Swanson Channel, Haro Strait, and Bedwell Harbour. This location captures acoustic signatures from passing cetaceans, commercial shipping vessels transiting through Haro Strait and Boundary Pass, and substantial recreational vessel traffic travelling to and from Bedwell Harbour, including vessels visiting the Canada Border Services Agency office located at Poet's Cove Marina on South Pender Island. As this hydrophone is deployed within the Pender VRZ, analysis of the acoustic data provides an opportunity to evaluate whether the VRZ is functioning as intended by reducing underwater noise levels in this high-use habitat.



3. Methods

3.1 Acoustic data collection

The Saturna Island hydrophone is an Ocean Sonics icListen HR digital hydrophone deployed in shallow water at approximately 25 m depth. Acoustic data were collected at 24-bit resolution with a 64 kHz sampling rate before August 2017, after which the sampling rate doubled to 128 kHz. Recordings were continuous and logged in 300 s segments as .wav files. For 2023 and 2025, files were additionally converted into .flac format and archived on external hard drives using custom Java-based software. Although the Monarch Head hydrophone was initially deployed in 2014, 2017 was the first year for which a complete calendar year of consistent, calibrated acoustic data was available. Accordingly, 2017 was selected for analysis, along with 2023 and 2025, to assess temporal changes in vessel noise levels and their contribution to the regional underwater soundscape.

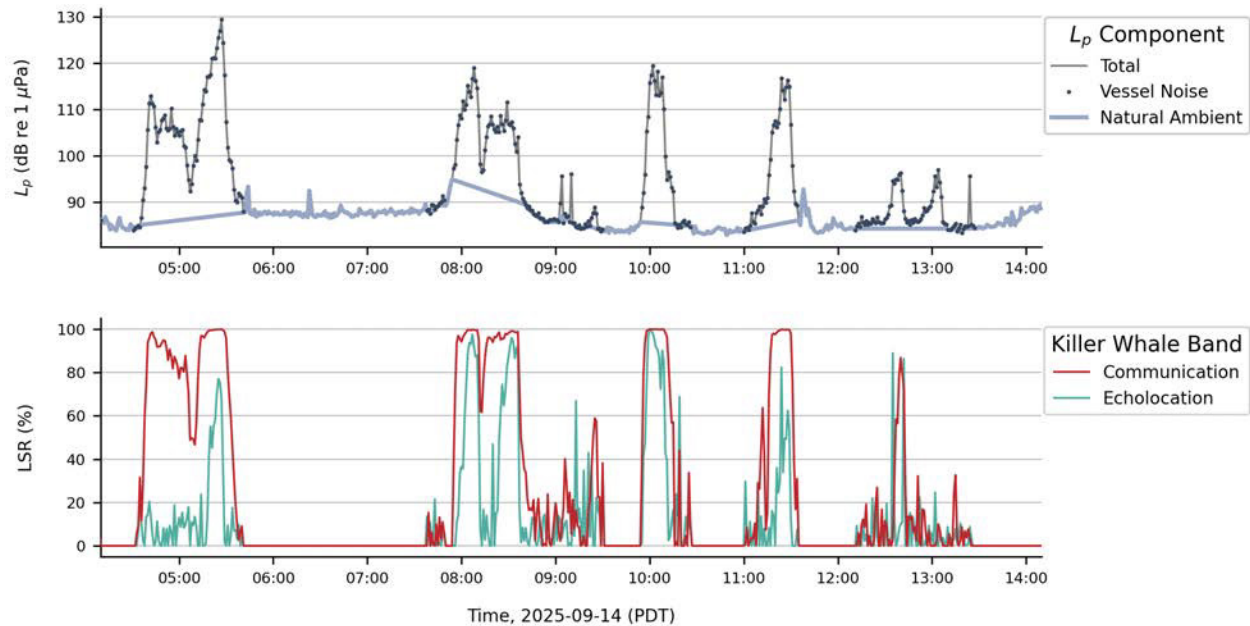
Pender Island's bottom-mounted hydrophone was deployed off Wallace Point at approximately 20 m depth from October 18, 2023, to February 1, 2025. The system consisted of a High Tec Inc. HTI-99-HF hydrophone, recording at 16-bit resolution with a 250 kHz sampling rate. Acoustic data were recorded continuously and logged in 60 s segments as .wav files. Two extended data gaps occurred during this period: mid-December 2023 to mid-January 2024, and April 2024 to July 2024 (Figure S2).

3.2 Acoustic data processing and metrics

Data processing followed the approach outlined in Hendricks et al. (2025). Vessel noise was identified by its continuous tonal noise characteristics, which distinguish it from the more stochastic signatures of natural sources such as wind, waves, and marine mammal vocalizations. The vessel noise detector distinguished between periods dominated by vessel noise and periods of natural ambient sound based on differences in the acoustic structure of the recordings. Power spectral densities (which describe how sound energy, or power, is distributed across frequencies, typically expressed per unit bandwidth such as Hz) were computed and averaged into 60-second segments, allowing segments to be classified as vessel-dominated or natural sound. Natural ambient sound levels were estimated from segments without vessel presence, with gaps up to 10 hours linearly interpolated; longer gaps were left unfilled. Excess vessel noise was calculated as the difference between total sound levels and estimated ambient levels. Acoustic habitat loss,

defined as Listening Space Reduction, was then calculated by comparing natural acoustic conditions with those elevated by Excess Noise (Figure 2).

Figure 2. Methods used to determine vessel noise impact metrics



The top panel shows 60 s average sound levels (L_p) recorded over a 12-h period in the 0.5-15 kHz SRKW communication band for the Saturna Island (SIMRES) hydrophone. Black dots indicate segments flagged as vessel noise. The thick grey line represents the resulting natural sound floor used to derive Excess Noise and LSR. Most vessel noise periods are associated with a clear increase in recorded sound levels above the natural sound floor. The bottom panel shows the resulting LSR over the same time period for two SRKW frequency bands: communication (0.5-15 kHz) and echolocation (15-100 kHz). This illustrates how vessel noise impacts the two frequency bands differently.

While data from both hydrophones were processed using the same methods, analyses differed between them (Table 1). The Saturna Island hydrophone provided a long-term dataset suitable for identifying broad trends across years, whereas the Pender Island hydrophone, with its short record, was used to evaluate fine-scale, short-term temporal trends and vessel-specific impacts.

3.2.1 Saturna Island hydrophone metrics

Metrics assessed for the Saturna Island hydrophone (SIMRES) in 2017, 2023, and 2025 included:

1. Quiet Time: the proportion of time during which no detectable vessel noise is present, expressed as a percentage of total recording time (%). Quiet Time is the inverse of Vessel Noise Presence, which is also reported.

2. **Excess Noise:** the increase in underwater sound levels attributable to vessel activity above baseline environmental noise conditions. Excess Noise is calculated by comparing periods with detected vessel noise to temporally adjacent natural conditions to estimate vessel-driven increases in sound levels. Excess Noise is expressed in decibels (dB re 1 μ Pa) above natural conditions within a defined frequency band. For this analysis, Excess Noise was calculated within the generalized SRKW communication frequency band of 0.5-15 kHz, as defined by Heise et al. (2017).
3. **Listening Space Reduction (LSR):** a measure of how much vessel noise reduces the acoustic space available to killer whales relative to baseline conditions, expressed as a percentage. LSR was calculated within the 0.5-15 kHz frequency range used by SRKWs for communication, and provides an indicator of acoustic habitat quality: the quieter the conditions, the more listening space there is.
4. **Frequency-Dependent Vessel Noise Impact:** summarizes the impact of vessel noise across the frequency spectrum, or, in other words, how vessel noise affects different frequencies. This approach breaks the spectrum into narrow, standardized frequency intervals called decidecade bands (also known as $\frac{1}{3}$ octave bands), and calculates Excess Noise and LSR for each band, revealing which frequencies are most affected by vessel activity. Results are averaged over a full calendar year and cover decidecade frequency bands between 10 Hz and 31.6 kHz (2017) or 50.1 kHz (2023, 2025), using a total of 36 and 38 bands, respectively.

3.2.2 Pender Island hydrophone metrics

Metrics assessed for the Pender Island hydrophone from October 18, 2023, to February 1, 2025, included:

1. **Spectral Probability Densities (SPD):** a tool for visualizing the full range of sound levels recorded across frequencies over time. Rather than comparing average noise level versus frequency, SPDs display how often each noise level occurs at each frequency (Merchant et al. 2013). L_{05} , L_{50} , and L_{95} represent sound levels that are surpassed 5%, 50%, and 95% of the time for each frequency, corresponding to unusually loud, typical, and unusually quiet conditions respectively, while L_{eq} represents the mean sound level for a frequency band. System noise present in the Pender Island hydrophone was identified and removed by flagging and masking affected bands.
2. **Sound Pressure Levels (SPL):** SPL was calculated for broadband, communication, and echolocation frequency bands using 60-second time segments averaged over

24-hour rolling windows. Results were summarized as daily or weekly snapshots, full deployment timelines, or seasonal averages.

3. Frequency-Dependent Vessel Noise Impact: Seasonal and annual noise levels were computed across decidecade frequency bands. With a sampling rate of 250 kHz, the Pender Island hydrophone captured a wide range of frequencies, allowing noise levels to be calculated across 41 decidecade frequency bands between 8 Hz and 100kHz.
4. Listening Space Reduction (LSR): a measure of how much vessel noise reduces the effective acoustic space available to killer whales. Calculated within the same 0.5-15 kHz SRKW communication band and reported as percent reduction relative to baseline conditions.
5. Vessel Noise Fingerprints: the acoustic signature produced by individual vessels passing near the hydrophone, including SPL, LSR, and distinctive frequency patterns.
6. Diel Noise Level Patterns: Average noise levels by hour of the day (diel refers to the full 24-hour cycle), calculated separately for summer (June to August) and winter (December to February).



Table 1. Summary table of acoustic metrics by hydrophone and their accompanying figure/table

Metric/Analysis	Saturna (SIMRES)	Pender (Raincoast)	Notes/Temporal Coverage
Quiet Time	Figure 3 Figure 4		2017, 2023, 2025
Vessel Noise Presence	Figure 5		2017, 2023, 2025
Excess Noise	Figure 6		2017, 2023, 2025
Listening Space Reduction (LSR)	Figure 7	Figure 21 Figure 22	Saturna: 2017, 2023, 2025 Pender: Jan 2025; Jan 29, 2025
Frequency-Dependent Vessel Noise Impact	Figure 8	Figure 16	Saturna: 2017, 2023, 2025 Pender: 2024
Spectral Probability Densities		Figure 12 Figure 13	July 2024 Jan 2025
SPL Timelines		Figure 14	Oct 2023 to Feb 2025
Seasonal SPL Boxplots		Figure 15	Oct 2023 to Feb 2025
Long-Term Spectral Averages and SPL		Figure 17 Figure 18 Figure 19 Figure 20	July 27 - Aug 3, 2024 July 27 - July 28, 2024 Nov 30 to Dec 6, 2024 Dec 4 to Dec 5, 2024
Vessel Noise Fingerprints		Figure 23 Figure 24 Figure 25 Figure 26 Figure 27	Jan 2, 2025 Jan 4, 2025 Jan 8, 2025 Jan 18, 2025 Jan 29, 2025
Diel Noise Patterns across all bands		Figure 28	Summer (June to Aug); Winter (Dec to Feb)
AIS Vessel Trips by Category	Table 2 Figure 9 Figure 10 Figure S3	Figure 29 Figure 30 Figure 31 Figure 32 Table 3	Saturna: 2017, 2023, 2025 Pender: 2024
SRKW Detections	Figure 11	Figure 33	Saturna: 2023, 2025 Pender: Oct 2023 to Feb 2025
Recording Effort	Figure S1	Figure S2	Saturna: 2017, 2023, 2025 Pender: Oct 2023 to Feb 2025



3.3 AIS vessel data processing

Automatic Identification Systems (AIS) allow vessels to share real-time data, such as identification, speed, or position, with other vessels and shore stations to aid navigation. AIS data can also be archived and downloaded to reconstruct historical vessel activity, allowing users to map past vessel movements and transit routes for a given area and time period. AIS vessel track data were sourced from the MarineCadastre.gov data portal (MarineCadastre 2026). Vessel data was limited to the vicinity of the study area using a 5.3 km buffer around the Saturna Island and Pender Island hydrophones (Figure 1). This radius captured commercial vessel transits through the Boundary Pass shipping lane and transits between nearby islands (Pender, Saturna, Stuart, and Skipjack). Spatial buffers were created in QGIS (v3.34.12) and exported to RStudio (v2026.01.1-403) for analysis.

AIS data are transmitted as discrete position reports at variable intervals depending on vessel type, speed, and onboard equipment settings. To standardize vessel counts and avoid overrepresenting vessels that transmit more frequently, AIS position reports were grouped into trips by their Maritime Mobile Service Identity (MMSI, a unique identification number assigned to each vessel) and time. Consecutive position reports separated by 60 minutes or less were considered part of the same trip, while gaps exceeding 60 minutes defined a new trip. This approach ensured that each vessel was counted once per transit through the survey area rather than once per AIS transmission.

AIS vessel classifications are defined by standardized numeric vessel codes describing ship and cargo type. These range from broad categories (e.g. "70-Cargo") to more specific subclasses (e.g. "73-Cargo, hazardous category C) (USCG n.d.). AIS metadata can be incomplete or inconsistently reported. Vessels lacking a valid AIS vessel code, or those classified as "0-Other," were reviewed if they completed more than ten trips through the survey area in a given year. These vessels were cross-referenced using publicly available information from MarineTraffic (MarineTraffic 2026), and an appropriate vessel category was manually assigned. In 2017, vessel types "36-Sailing" and "37-Pleasure Craft" were often jointly categorized in AIS datasets as "Pleasure Craft/Sailing," and it was not feasible to retrospectively separate them. Therefore, sailing vessels and pleasure craft were grouped into the "Pleasure Craft" vessel type for consistency across years. Following spatial filtering and manual confirmation of vessel category, the top vessel categories for each year were identified and consolidated into five general categories for analysis: Cargo, Tanker, Tug, Passenger, and Pleasure Craft.

For analysis of the Saturna Island hydrophone data, AIS records were compiled for 2017, 2023, and 2025, and vessel trips were summarized by hour and month to quantify

temporal patterns in vessel activity. The percent increase in vessel trips from 2017 to 2025 was calculated using the following formula:

$$\text{Percent Increase} = [\text{Trip Count}_{2025} - \text{Trip Count}_{2017}] / \text{Trip Count}_{2017} \times 100$$

For the Pender Island hydrophone, AIS data was analysed for 2024, and vessel trips were summarized by hour and month.

Previous studies in Boundary Pass have shown that AIS data does not accurately reflect the true number of recreational vessels on the water (O'Hara et al. 2023). To evaluate this discrepancy near the Pender VRZ, we draw on data from a land-based monitoring study we conducted in 2024 to complement the hydrophone data, in which vessels not equipped with AIS were tracked as they passed through a defined survey area within and adjacent to the Pender VRZ. Surveys were conducted over 306 hours between July 7 and October 29, 2024. Land-based observations followed established theodolite tracking protocols, using a TOPCON DT-205 theodolite paired with Mysticetus software to record vessel positions. AIS transits from 2024 were subsequently filtered to match the same spatial extent and survey hours, allowing for direct comparison between AIS-equipped and non-AIS pleasure craft.

3.4 SRKW detections

Visual SRKW sightings were reported by researchers from Raincoast, Simon Fraser University, and SIMRES, and members of the Southern Gulf Islands Whale Sighting Network (SGIWSN). Visual sightings were included in the analysis if they occurred within a 5.3 kilometre radius of either hydrophone (see Figure 1).

Acoustic events were detected using PAMGuard's Whistle and Moan Detector (PAMGuard Version 2.02.17; Gillespie et al. 2025), a software platform widely used for passive acoustic monitoring, and manually reviewed to confirm species and ecotype. SRKW sightings or vocalizations that occurred within 60 minutes of each other were grouped as a single event.

Recordings from the Pender Island hydrophone were analyzed over the full deployment period (October 18, 2023, to February 1, 2025), while Saturna Island hydrophone data were analyzed for 2023 and 2025 only. Data from 2017 were excluded due to the absence of a formally established sighting network, which limited the availability of corresponding visual sightings records to pair with the acoustic recordings.

4. Results

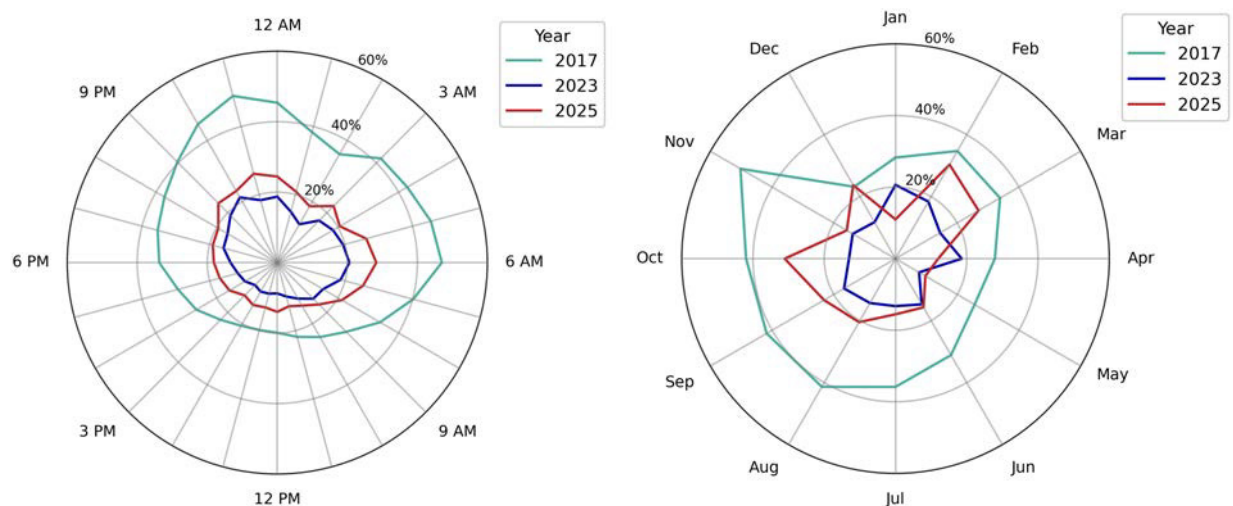
4.1 Saturna Island hydrophone

4.1.1 Quiet Time

Quiet Time near the Saturna Island hydrophone declined substantially between 2017 and 2025 (Figure 3), dropping from an average of 34.5% in 2017 to 14.8% in 2023 and 19.6% in 2025. The timing of peak Quiet Time shifted across the years, from late evening in 2017 and 2023 to early morning in 2025, while the quietest month differed across years: November in 2017, January in 2023, and October in 2025.

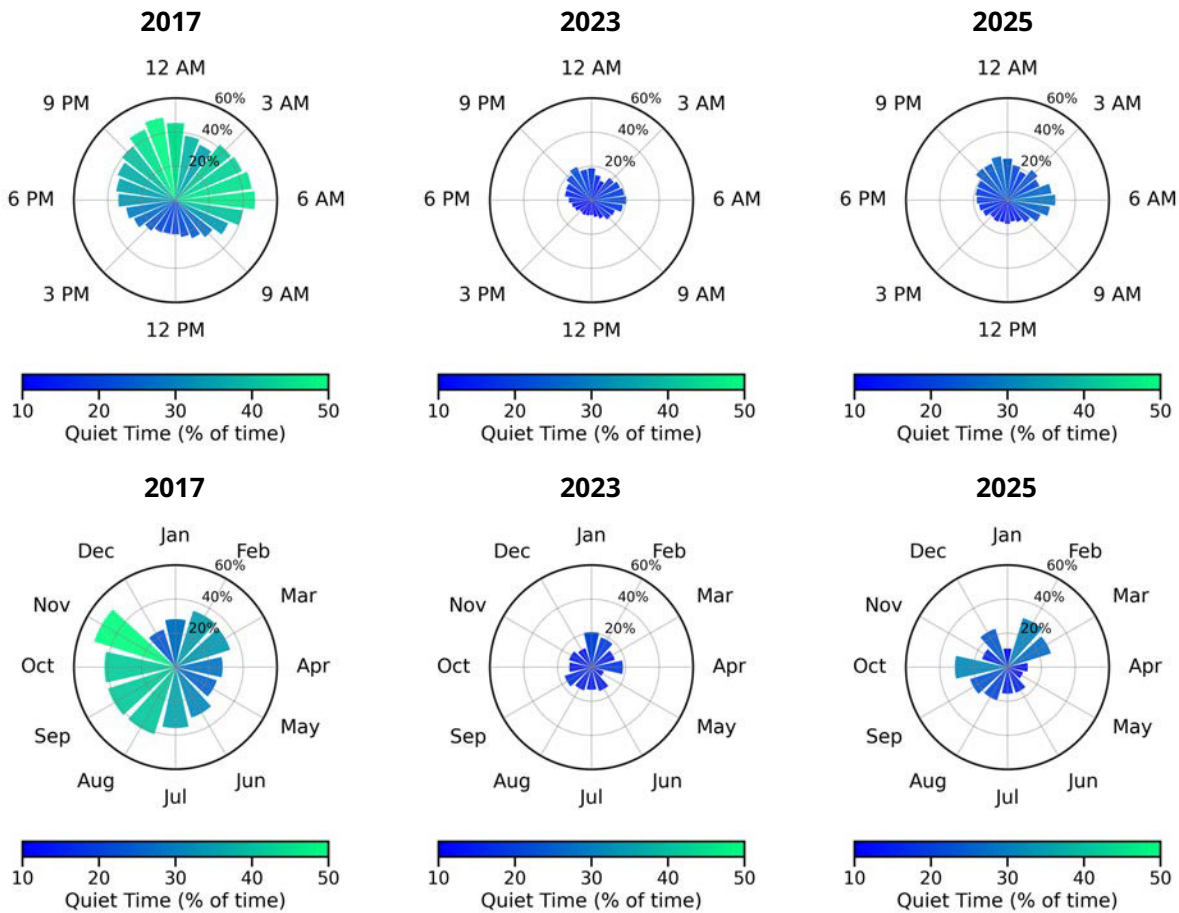
Despite these interannual changes, hourly patterns of Quiet Time were consistent (Figure 4). Quiet conditions were most common during late evening (9 PM to 12 AM) and early morning (5 AM to 7 AM), while the loudest periods consistently occurred between 11 AM and 1 PM. Monthly patterns were more variable among years. In 2017, Quiet Time increased steadily from July to November before declining sharply in December, while in 2023 and 2025 the quietest months were distributed irregularly. May was consistently ranked among the noisiest months across all years.

Figure 3. Quiet Time across years: comparison



Quiet Time (%) for each local hour-of-day (left) and calendar month (right) for the Saturna Island hydrophone in 2017 (green), 2023 (blue), and 2025 (red). This metric shows a 57.1% (2023) and 43.2% (2025) decline in Quiet Time compared to 2017. The diel pattern remained consistent across all years, while month-to-month comparisons showed variations in Quiet Time peaks. Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics.

Figure 4. Quiet Time across years: detail



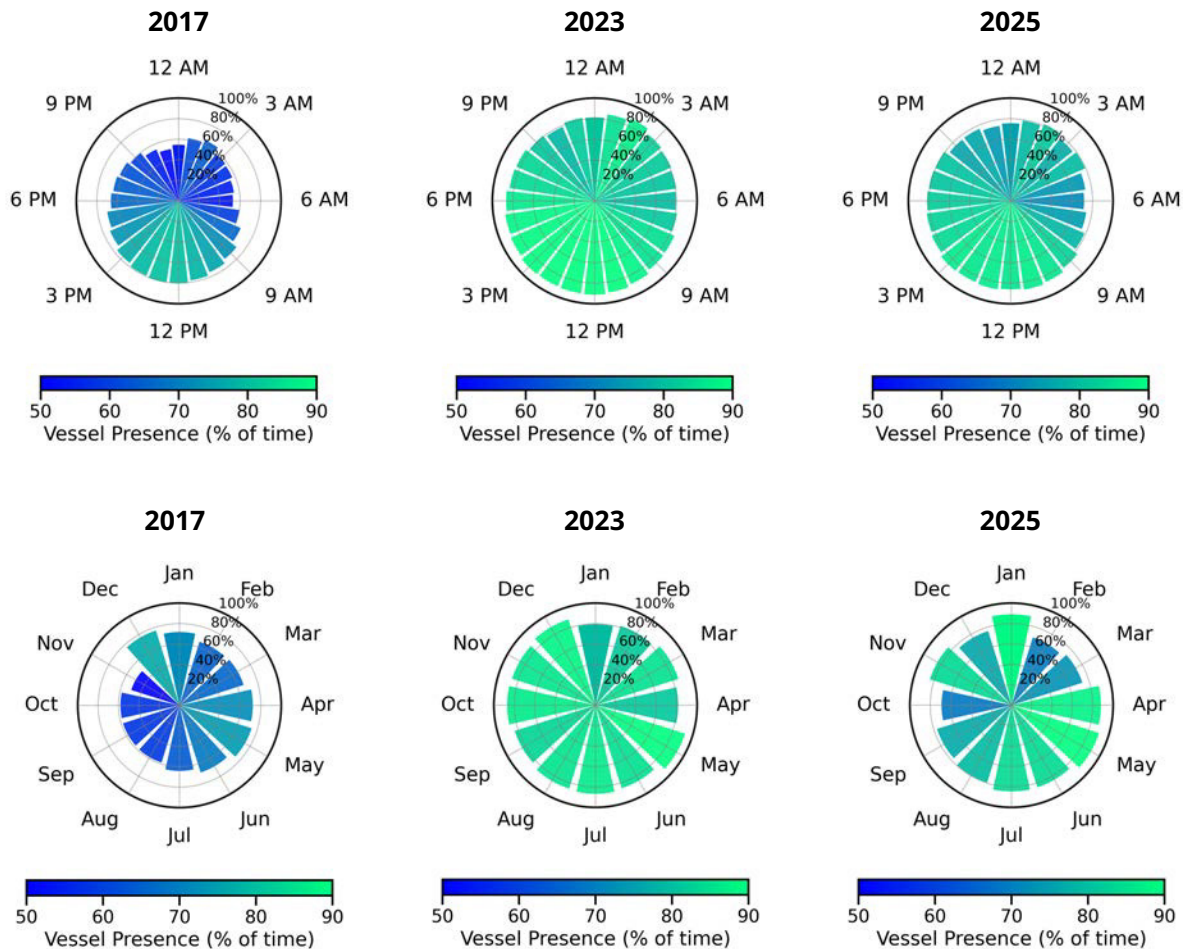
Percent (%) Quiet Time for each local hour-of-day (top) and calendar month (bottom) for the Saturna Island hydrophone in 2017, 2023, and 2025. The colouration of wedges reflects the range of values within each plot: from lowest (blue) to highest (green). Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics.

4.1.2 Vessel Noise Presence

The inverse of Quiet Time is Vessel Noise Presence, defined as the proportion of time during which vessel noise was detected. Vessel noise was present for the majority of the recording period across all years and increased substantially from 2017 to 2023 and 2025 (Figure 5). Overnight vessel activity increased, and high Vessel Noise Presence was detected consistently across all months in later years.



Figure 5. Vessel Noise Presence across years



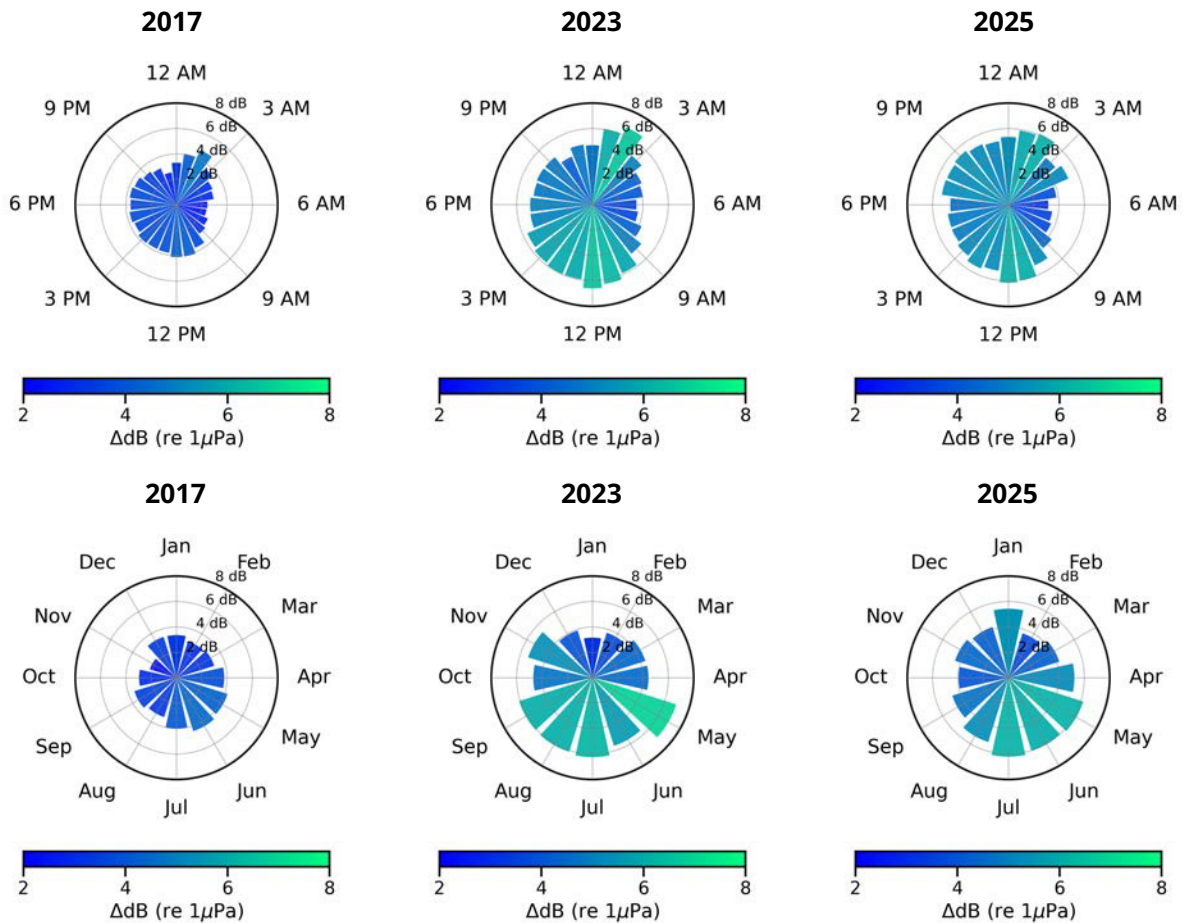
Annual Vessel Noise Presence for each local hour-of-day (top) and calendar month (bottom) for the Saturna Island hydrophone in 2017, 2023, and 2025. The colouration of wedges reflects the range of values within each plot: from lowest (blue) to highest (green). Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics.

4.1.3 Excess Noise

Excess Noise, defined on section 3.2.1, increased from 2017, with levels in 2023 and 2025 remaining substantially higher than the 2017 baseline. Annual average levels rose from 3.4 dB in 2017 to 5.1 dB in 2023 and 5.0 dB in 2025. Hourly patterns of Excess Noise were consistent across years, with two daily peaks in the early morning and midday (Figure 6). In contrast, seasonal patterns varied among years. In 2017, Excess Noise increased from spring into early summer before declining, whereas 2023 showed elevated levels of Excess Noise into the fall. In 2025, two distinct peaks of Excess Noise were observed: a broad increase from spring through fall and a second peak in January.



Figure 6. Excess Noise across years



Excess vessel noise for each hour-of-day (top) and calendar month (bottom) for the Saturna Island hydrophone in 2017, 2023, and 2025. The colouration of wedges reflects the range of values within each plot: from lowest (blue) to highest (green). Excess Noise was calculated within the generalized SRKW communication frequency band of 0.5-15 kHz. Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics.

4.1.4 Listening Space Reduction (LSR)

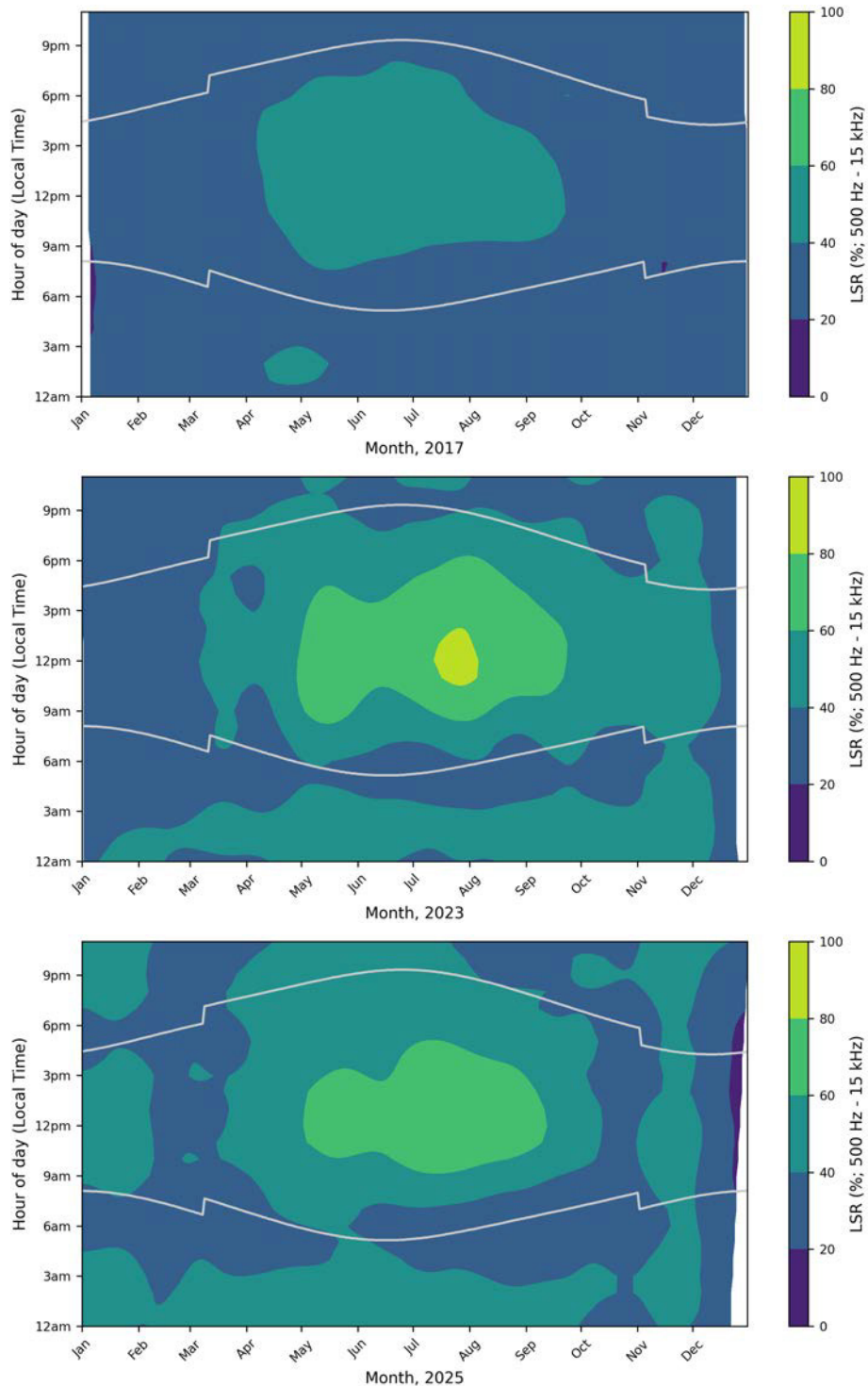
Vessel-related noise resulted in substantial acoustic habitat loss for SRKW across all years (Figure 7). LSR was generally greatest during daylight hours and was most pronounced from spring through fall.

In 2017, LSR remained relatively low outside of daytime periods, typically staying below 40% before sunrise and after sunset. In contrast, 2023 consistently exhibited elevated LSR throughout the day and across much of the year. Values frequently exceeded 40%, with sustained high levels from spring through fall and peak reductions during midsummer that surpassed 80% LSR. Seasonal impacts were also stronger in 2023, with elevated LSR persisting later in the year compared to 2017.

In 2025, LSR remained elevated across much of the year but was less concentrated in the summer months. Values generally exceeded 40%, with brief periods of lower levels (20-40% LSR) during late winter and early spring. Similar to 2023, elevated LSR persisted overnight, indicating that acoustic habitat conditions did not recover outside of peak daytime hours.



Figure 7. Seasonal-diel Listening Space Reduction (LSR)



Listening Space Reduction (LSR) for the 0.5-15 kHz killer whale communication band, shown by hour of day and month, for the Saturna Island hydrophone in 2017, 2023, and 2025. White lines indicate sunrise and sunset times. Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics.

4.1.5 Frequency-dependent vessel-noise impact

The impact of vessel noise varied across all frequencies (Figure 8), with the greatest effects occurring within mid-frequency bands (~100-1000 Hz). Within this range, both Excess Noise and LSR were substantially higher in 2023 and 2025 than in 2017. Excess Noise increased from approximately 3.5 dB in 2017 to 5.5-7.0 dB in 2023 and 2025, while LSR rose from 28-35% to 45-48%. Impacts were comparatively lower outside of this mid-frequency range.

Across most frequency bands, 2023 and 2025 exhibited consistently greater impacts than 2017. Over time, the frequencies most affected by vessel noise shifted, with the highest values occurring at relatively lower frequencies in 2023 and 2025 compared to 2017. Overall, these results indicate a shift towards lower-frequency bands experiencing the greatest vessel-noise impacts in more recent years.

4.1.6 AIS vessel data

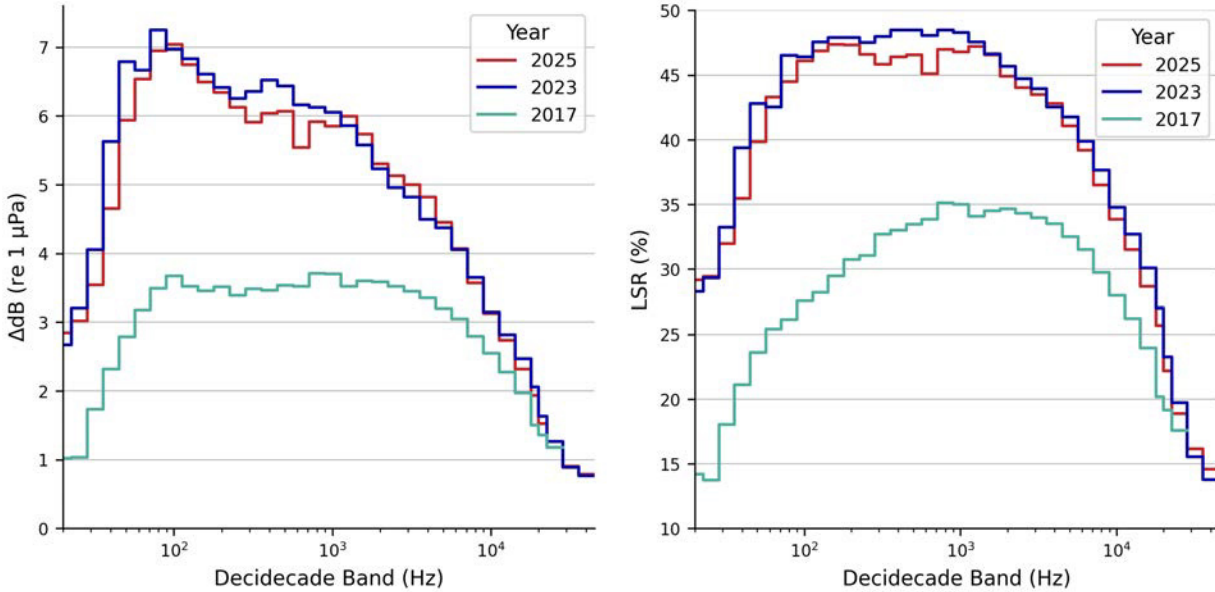
AIS-derived vessel trips increased over the study period, from 8,338 in 2017, to 10,152 in 2023 and 11,037 in 2025 (Table 2). The five most common vessel categories were cargo ships, passenger vessels, pleasure craft, tankers, and tug boats. Cargo traffic remained relatively stable, with only a modest increase (+1.9%) from 2017 to 2025, whereas all other categories showed substantial growth. Passenger vessel traffic increased sharply from 2017 to 2023 and declined slightly in 2025, but remained well above 2017 levels (+79.7%). Pleasure craft trips nearly tripled by 2023 and remained elevated in 2025 (+199.2%). Tanker traffic showed the most variable pattern, declining slightly from 2017 to 2023 before nearly tripling in 2025, for an overall increase of +145.8% across the study period. Tugboat activity increased steadily across all years, more than doubling over the study period (+105.8%).

Vessel transit patterns varied by hour of day (Figure 9) and month (Figure 10). In 2017, transits were relatively evenly distributed throughout the day, with only minor peaks observed. In contrast, 2023 and 2025 exhibited a notable shift toward increased daytime activity, with a pronounced peak in vessel transits from late morning to early afternoon. Across all years, vessel activity was consistently lowest in the early morning (around 6 AM). Although some passenger and recreational vessels transited overnight, most traffic occurred during daylight hours. The substantial increase in pleasure craft transits, in particular, likely contributed disproportionately to the observed daytime peaks. To account for this, hourly transit patterns for cargo vessels, tankers, and tug boats only are presented separately in Figure S3.

Seasonal patterns were broadly consistent across years, with higher traffic during spring and summer and lower activity in winter (Figure 10). In 2017, monthly proportions

remained relatively evenly distributed, whereas in 2023 and 2025, higher-traffic months were concentrated between late spring and early fall. Across all years, vessel transits were lowest from December through February.

Figure 8. Impact of vessel noise across the frequency spectrum



The impact of vessel noise across the frequency spectrum, expressed as Excess Noise and Listening Space Reduction (LSR), averaged across a full calendar year for the Saturna Island hydrophone. Results are presented in decidecade frequency bands between 10 Hz and 31.6 kHz (2017) or 50.1 kHz (2023, 2025) using a total of 36 and 38 bands, respectively. The largest impacts in both Excess Noise and LSR occur between 100 and 1000 Hz. Results below 100 Hz should be interpreted with caution, as shallow-water propagation loss and low-frequency sensitivity drift of the hydrophone sensor limit measurement accuracy in this frequency range. Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics.

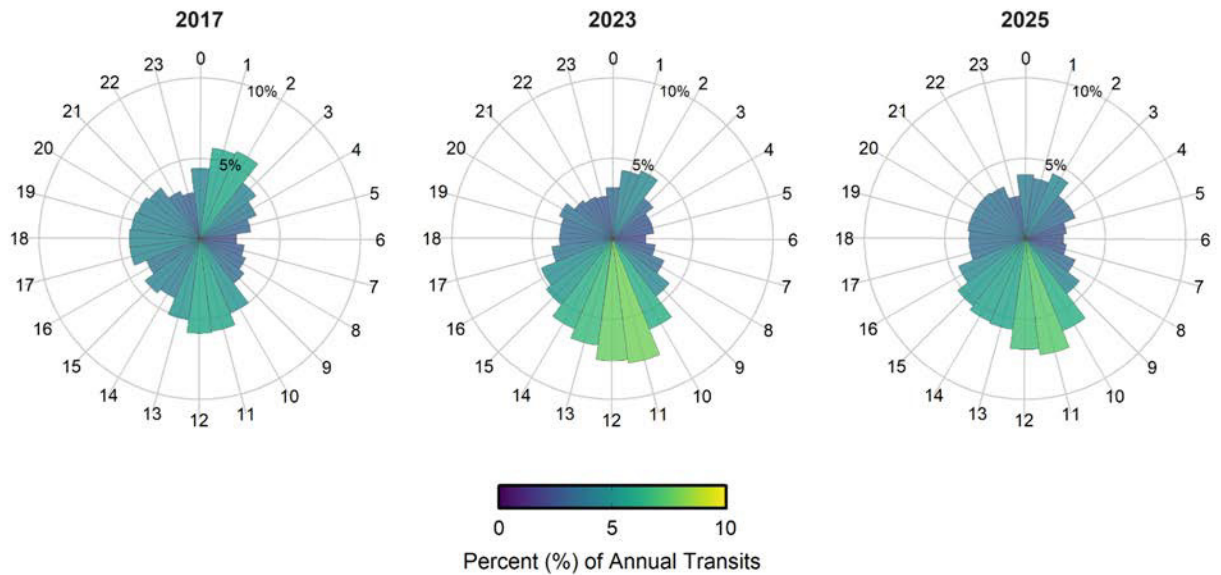
Table 2. Increase in vessel trips by Saturna Island hydrophone

Count and percent increase of AIS-equipped vessel trips within 5.3 kilometres of the Saturna Island hydrophone in 2017, 2023, and 2025. Trips were defined as sequences of AIS-transmitted positions from the same MMSI received within 60 minutes of each other. Percent increase was calculated as $[Count_{2025} - Count_{2017}] / Count_{2017} * 100$. Trip counts are presented for the five most frequent vessel types and the total count across all vessel types.

Vessel Type	Trips			% Increase from 2017 to 2025
	2017	2023	2025	
Cargo	4,953	4,838	5,048	+1.9%
Passenger	527	1,225	947	+79.7%
Pleasure Craft	646	1,950	1,933	+199.2%
Tanker	439	387	1,079	+145.8%
Tug	607	847	1,249	+105.8%
All Vessels	8,338	10,152	11,037	+32.4%

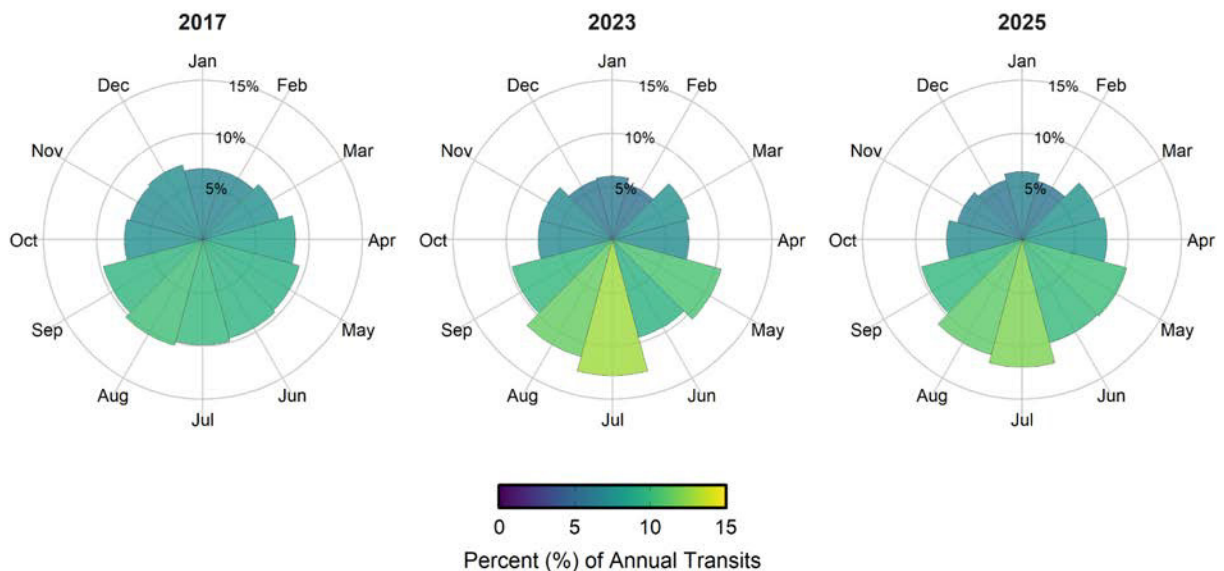


Figure 9. AIS-equipped vessel trips per hour



Proportion of AIS-equipped vessel trips within 5.3 kilometres of the Saturna Island hydrophone in 2017, 2023, and 2025, per hour. Trips were defined as consecutive AIS positions from a single MMSI (Maritime Mobile Service Identity) separated by ≤ 60 minutes. From 2017 to 2023 and 2025, we see a shift to more vessel transits during daylight hours, coinciding with the 199.2% increase in recreational vessel traffic.

Figure 10. AIS-equipped vessel trips per month



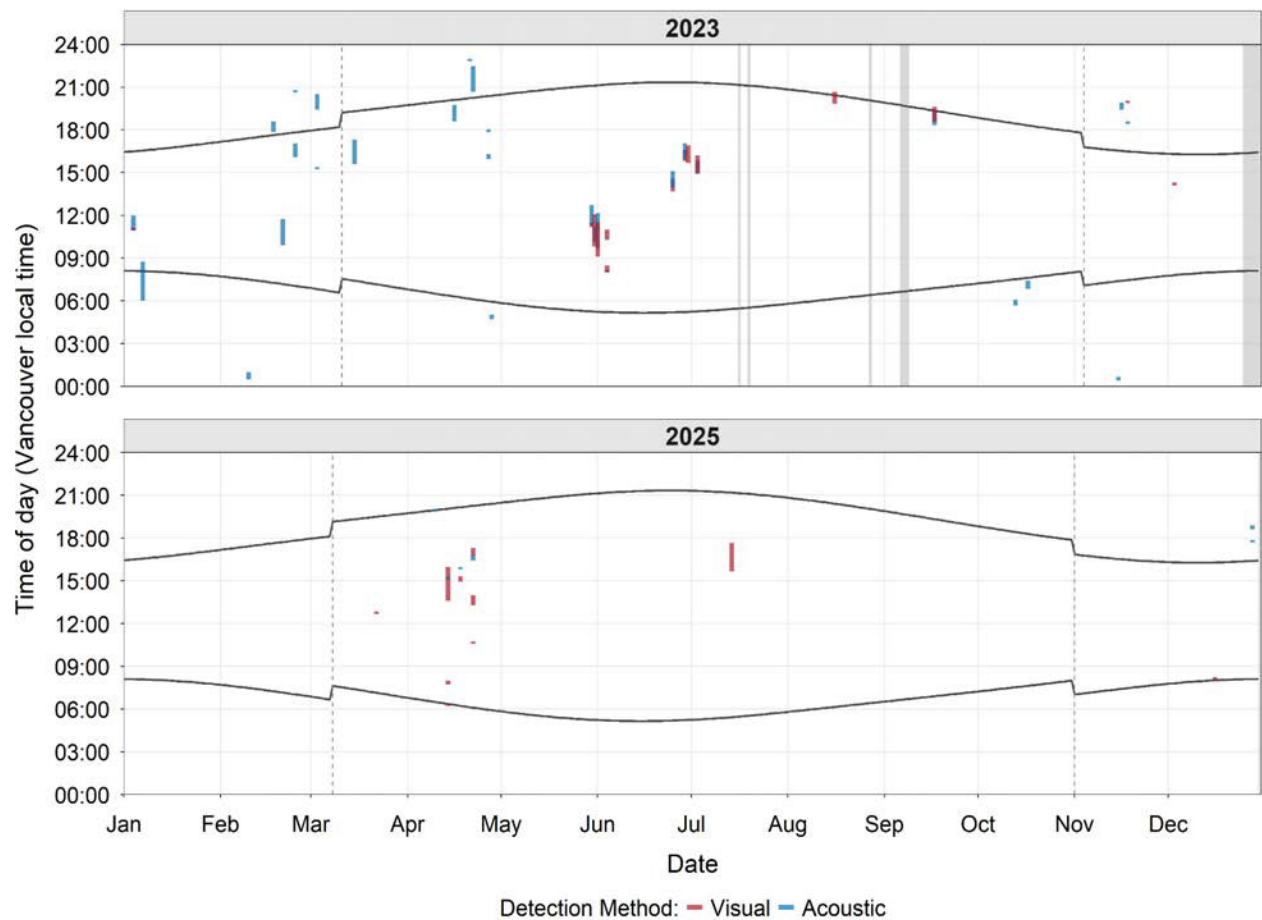
Proportion of AIS-equipped vessel trips within 5.3 kilometres of the Saturna Island hydrophone in 2017, 2023, and 2025, per month. Trips were defined as consecutive AIS positions from a single MMSI (Maritime Mobile Service Identity, a unique vessel identifier) separated by ≤ 60 minutes.

4.1.7 SRKW detections

SRKW were detected within 5.3 km of the Saturna Island hydrophone during 47 events (visual or acoustic detections occurring within 60 minutes of each other). 34 events occurred in 2023 (across 29 days) and 13 in 2025 (across 8 days). All visual sightings occurred during daylight hours, while acoustic sightings were recorded across all hours of the day. April had the highest number of days with SRKW presence in both years, with 5 days in 2023 and 4 days in 2025.

In 2023, most events were acoustic-only (n = 20), with fewer combined visual and acoustic detections (n = 10) and visual-only sightings (n = 4). 2025 had a higher number of visual-only events (n = 8), with fewer acoustic-only (n = 3) and combined detections (n = 2).

Figure 11. SRKW detections near Saturna Island



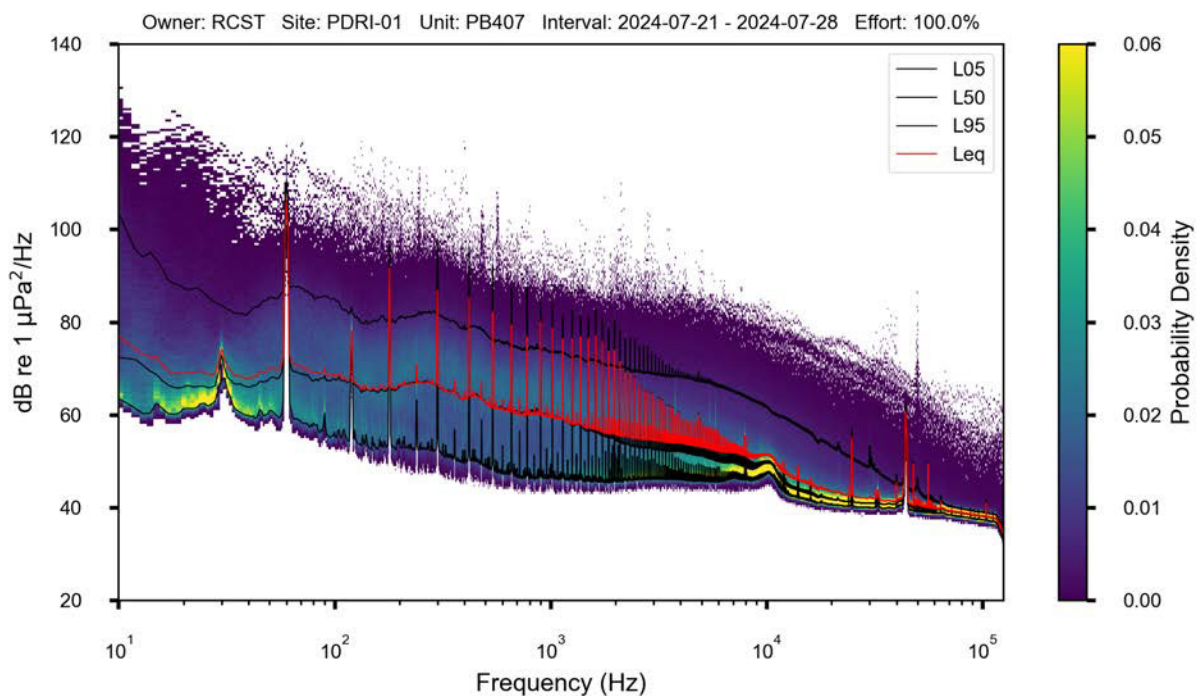
Visual and acoustic detections of SRKW within 5.3 km of the Saturna Island hydrophone in 2023 (34 events) and 2025 (13 events). Visual detections are shown in red and acoustic detections in blue. Grey shading indicates periods when the hydrophone was not operational. Dashed vertical lines mark daylight savings time changes, and the curved horizontal lines indicate sunrise and sunset times. Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics and Raincoast Conservation Foundation.

4.2 Pender Island hydrophone

4.2.1 Spectral Probability Density (SPD)

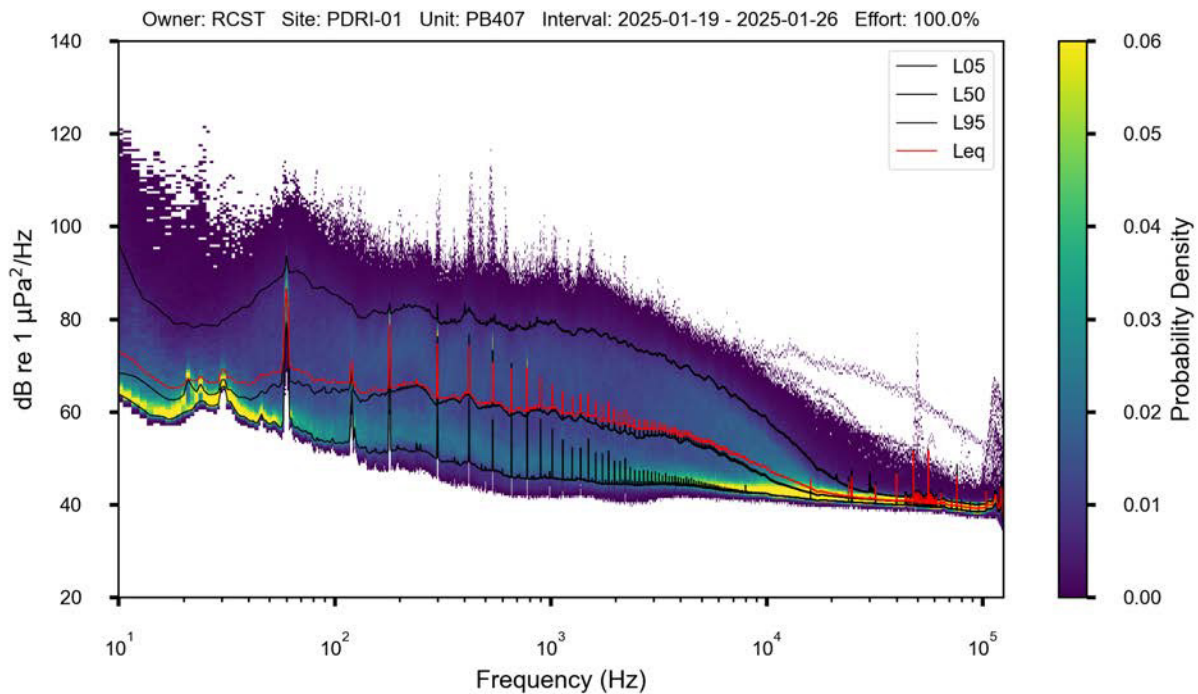
Weekly and daily SPDs were used to assess the overall data quality and long-term persistent noise patterns in the Pender Island hydrophone data. Strong system noise (interference originating from the hydrophone equipment itself rather than the surrounding environment) was present across the spectrum for almost the entire duration of the study period (Figure 12). Efforts were made to remove those noise bands from all of the noise analyses by first flagging and then masking those bands. Engineering work was undertaken on the hydrophone site in November 2024, after which system noise was greatly reduced (Figure 13).

Figure 12. Spectral Probability Density (SPD) with system noise



Spectral Probability Density (SPD) for July 21 to July 28, 2024, Pender Island hydrophone. System noise, identified by the narrow vertical spikes, is high and present across the spectrum. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 13. Spectral Probability Density (SPD) without system noise



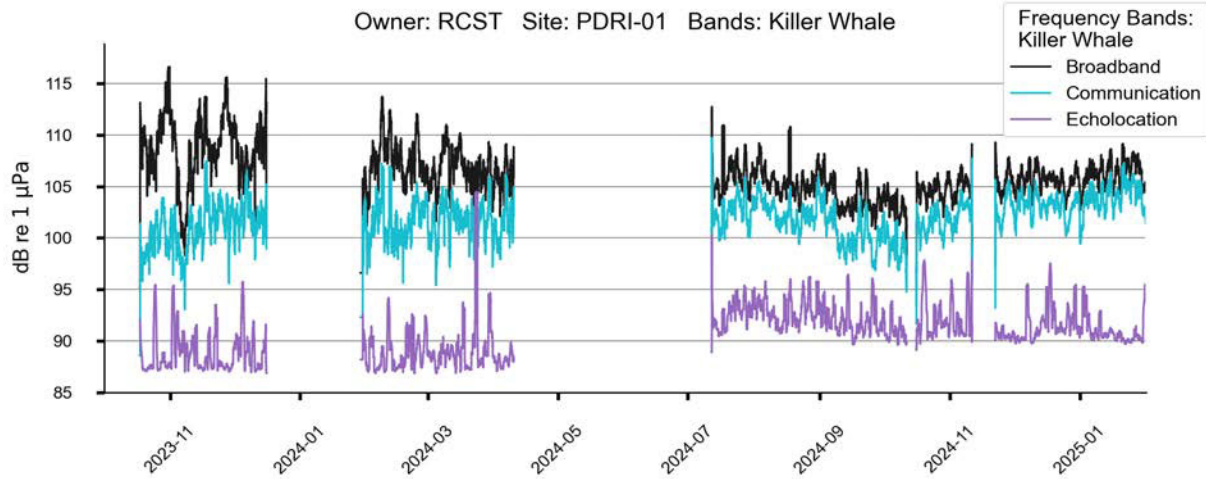
Spectral Probability Density (SPD) for January 19 to January 26, 2025, Pender Island hydrophone. System noise, identified as narrow vertical spikes across the spectrum, is substantially reduced compared to previous months (Figure 12), following work completed on the hydrophone in November 2024. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

4.2.2 Sound pressure levels (SPL)

Sound pressure levels (SPL) were measured across broadband (0.05-100 kHz), communication (0.5-15 kHz) and echolocation (15-100 kHz) frequency bands. Overall, noise levels remained relatively stable across all frequency bands throughout the year (Figure 14), based on 12-hour rolling averages derived from 60-second hydrophone recordings.

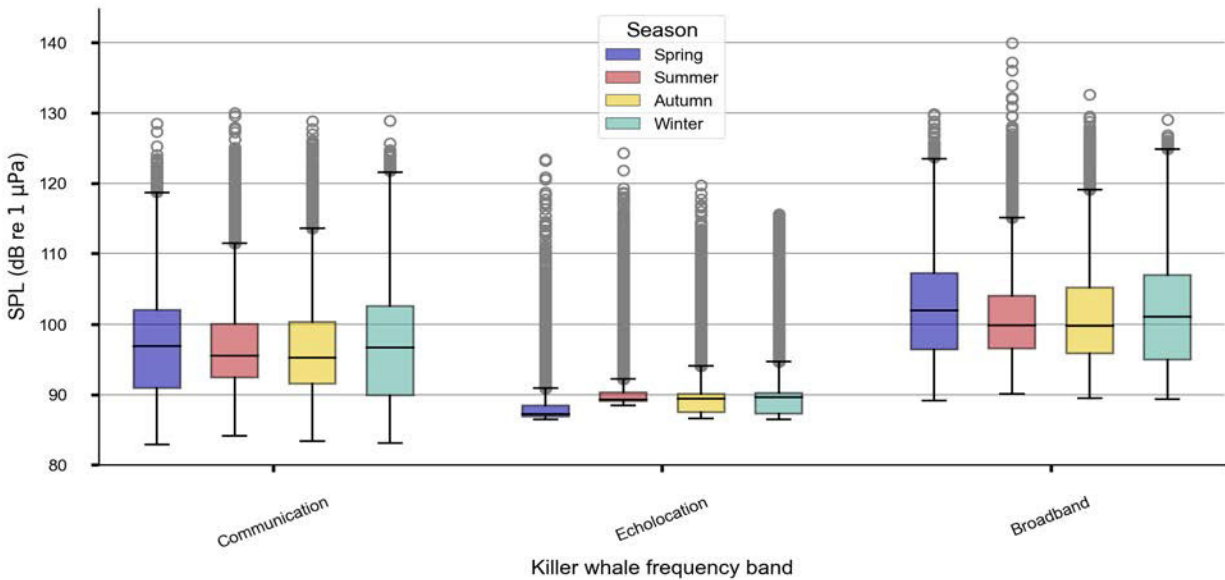
Looking at the full dataset of 60-second recording segments, median SPLs were 100.4 dB (broadband, range: 89.2-140.0 dB), 95.9 dB (communication, range: 82.9-130.0 dB), and 89.4 dB (echolocation, range: 86.5-124.3 dB). When examined by meteorological season (Figure 15), SPLs showed minimal seasonal variation across all frequency bands, with median values remaining within ± 5 dB. During winter and spring, the upper range of noise levels in the communication and broadband bands was slightly higher than in other seasons, though overall seasonal differences remained small.

Figure 14. Sound Pressure Level (SPL) timeline



Sound pressure level (SPL) timeline for the Pender Island hydrophone. A 12-hour rolling average was applied to 60-second time segments for broadband, communication, and echolocation frequency bands. Note that high and low extremes in SPL are not fully captured in this figure due to averaging. Gaps indicate periods without data. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 15. Seasonal average Sound Pressure Levels (SPL)



Seasonal average Sound Pressure Level (SPL) for communication, echolocation, and broadband frequency bands, recorded at the Pender Island hydrophone from October 2023 to February 2025. Each box shows the interquartile range (middle 50% of values), with the horizontal lines indicating the median. Whiskers extend to the 5th and 95th percentiles, and circles represent outliers beyond that range. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

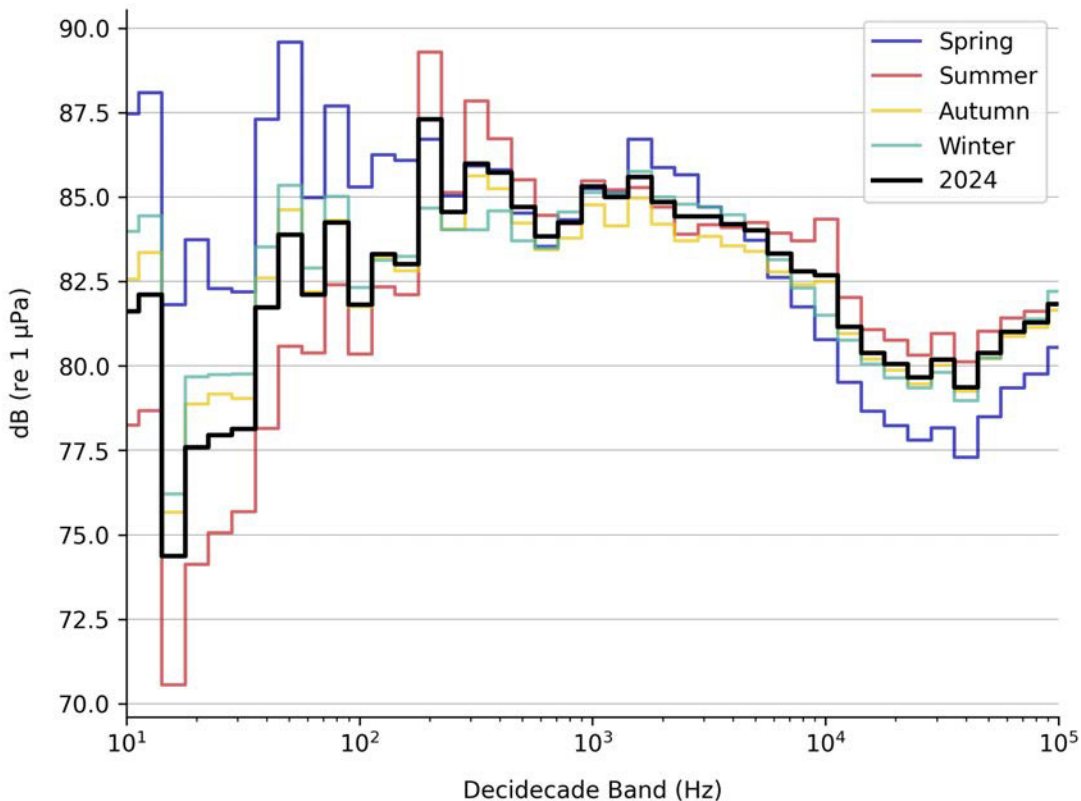
4.2.3 Frequency-dependent vessel-noise impact

The Pender Island hydrophone decade noise spectrum (Figure 16) showed clear differences in SPL across frequency bands and seasons. Overall, a broad plateau of 84-86 dB was observed in the mid-frequency range (~200-3000 Hz), with a gradual decline in SPL toward both lower and higher frequencies.

At low frequencies (<100 Hz), seasonal variation was more pronounced. Higher SPLs in winter and spring were possibly due to low-frequency noise from wind and waves. In contrast, higher frequencies (>2000 Hz) showed elevated SPL during spring and summer, potentially associated with increased recreational vessel traffic.

Spectral stability across time and across hydrophone deployments was lowest below ~100 Hz, indicating that these frequencies may be less reliably calibrated than frequencies above 100 Hz.

Figure 16. Annual and seasonal decidecade noise spectrum



Decidecade noise spectrum of the Pender Island soundscape for the full 2024 calendar year (black) and broken down by season (coloured lines). A decidecade spectrum divides the frequency range into standardized frequency bands used in acoustic analysis, allowing noise levels to be compared across frequencies. Noise level is expressed in decibels (dB re 1 μ Pa). Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

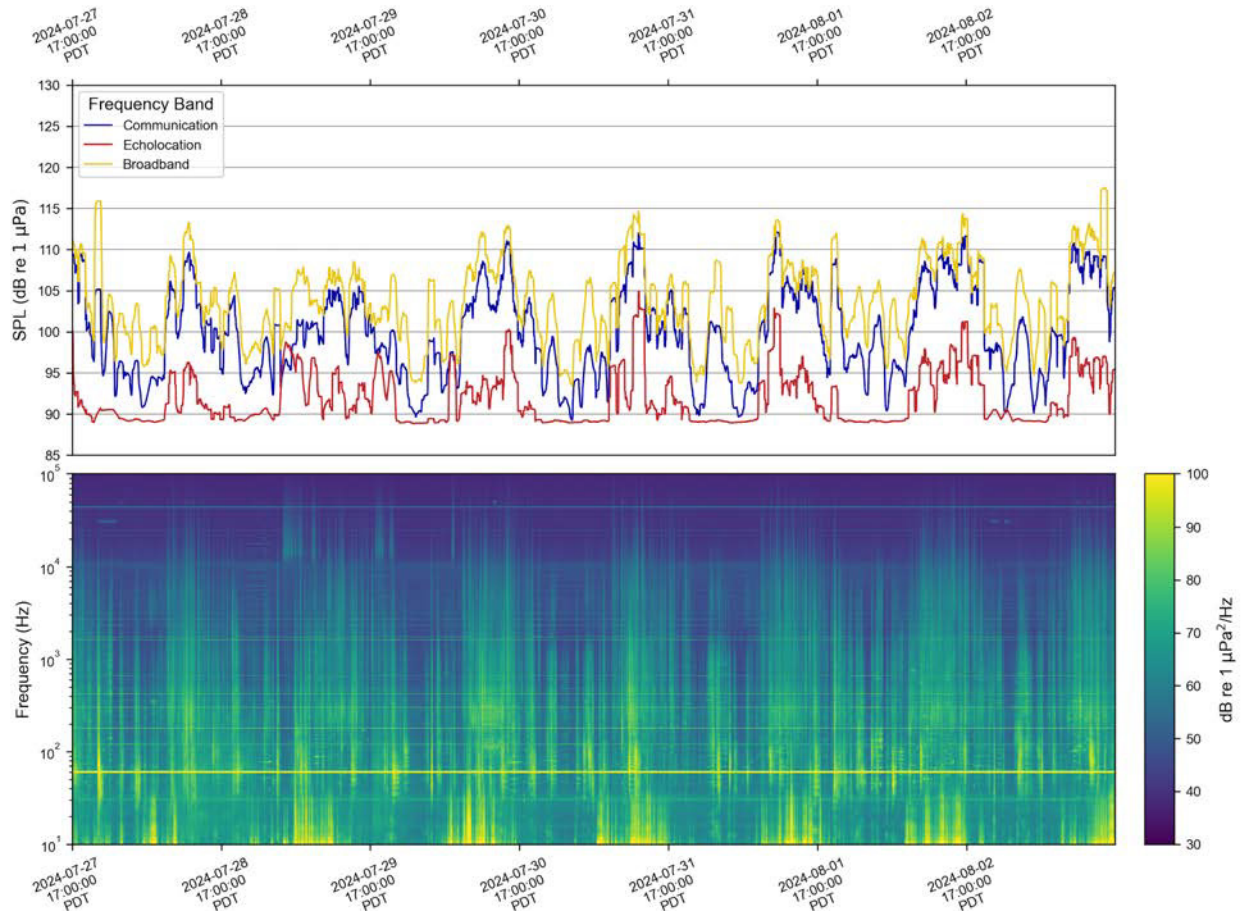
4.2.4 Long-term spectral averages and SPL

Long-term spectral averages and sound pressure levels (SPL) across the three killer whale frequency bands reveal distinct seasonal and diel patterns in the acoustic soundscape. Across seasons, the soundscape was primarily influenced by transiting vessels, including both commercial and recreational traffic, with additional contributions from wind and waves at lower frequencies due to the relatively shallow hydrophone deployment depth.

In summer, a clear diurnal pattern was evident, with elevated noise levels during daylight hours driven largely by vessel traffic (Figures 17, 18). Shorter periods of high-frequency noise in the echolocation band were associated with daytime recreational vessel use, while large commercial vessel transits contributed to elevated broadband and communication band SPL throughout the day. In contrast, winter recordings showed no clear diel pattern

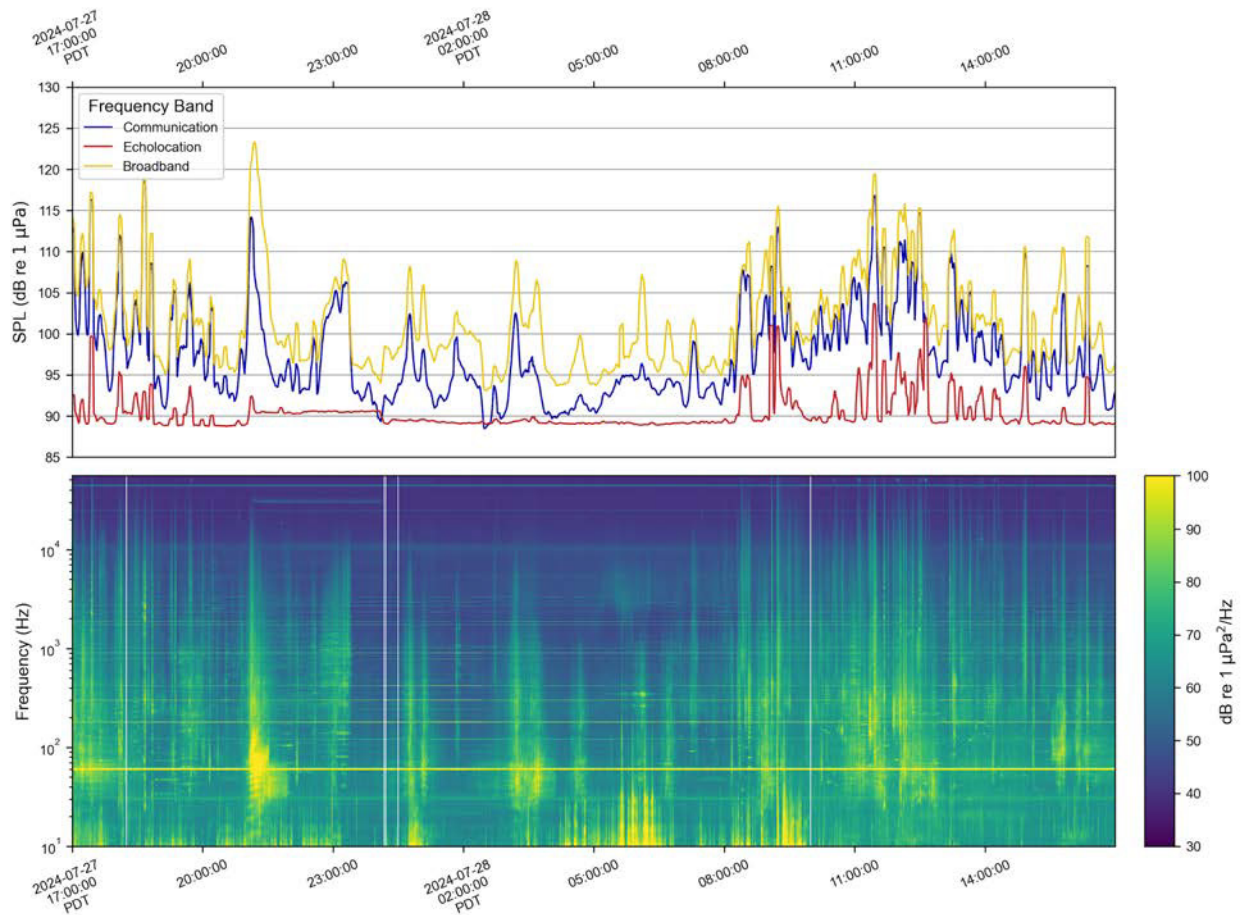
(Figures 19, 20). Long periods of elevated noise in the echolocation band were consistent with rainfall events rather than vessel activity.

Figure 17. SPL and frequency: summer week (Jul/Aug 2024)



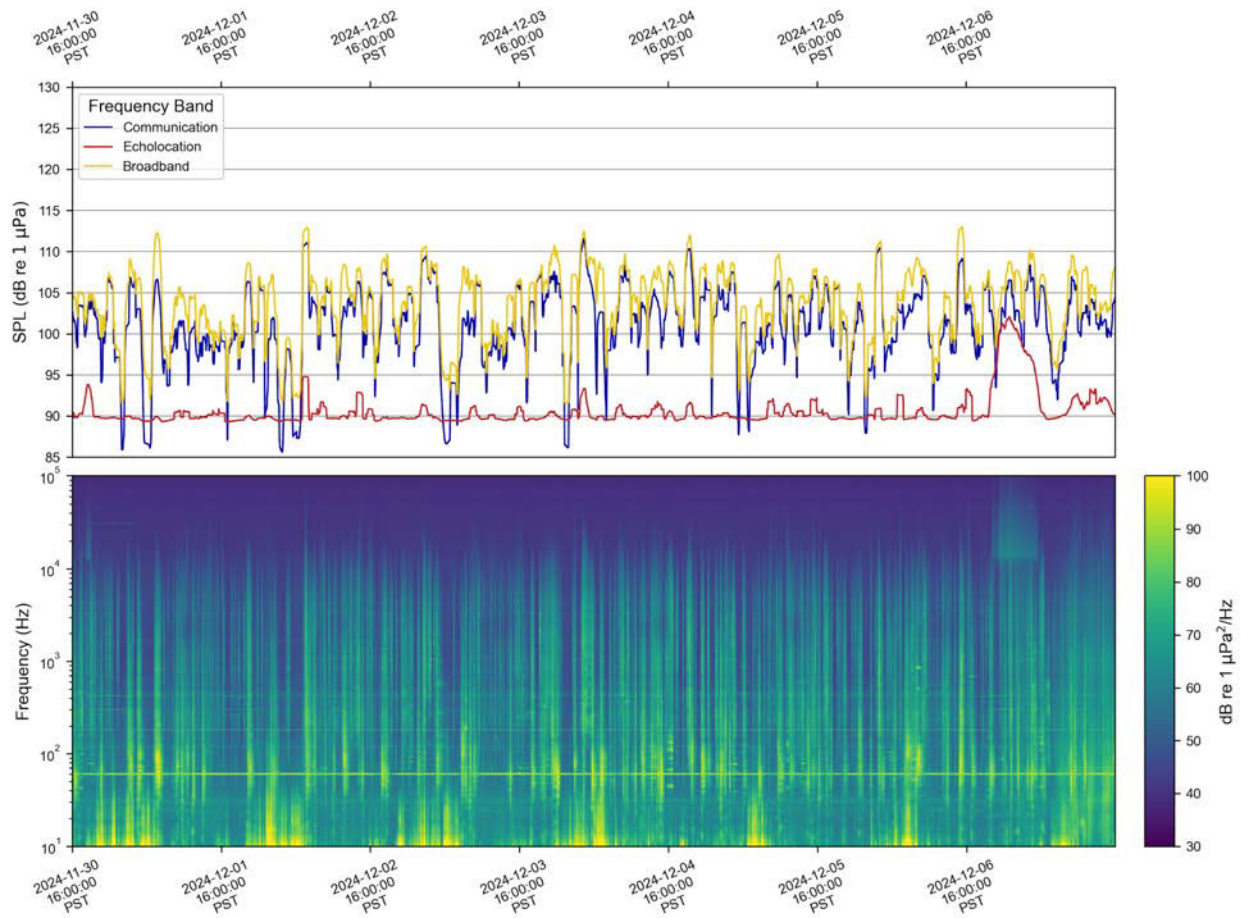
Sound Pressure Level (SPL) timeline (top) and spectrogram (bottom) for July 27 to August 3, 2024, at the Pender Island hydrophone, showing three frequency bands relevant to killer whales: communication (blue, 0.5-15 kHz), echolocation (red, 15-100 kHz), and broadband (yellow, 0.05-100 kHz). The spectrogram shows noise intensity across all frequencies over time, with brighter colours indicating higher noise levels. A clear diel pattern is evident across all frequency bands, with noise rising as recreational vessel traffic builds during the day and subsiding overnight. Elevated noise levels in the high-frequency echolocation band (15-100 kHz) reflect increased recreational vessel traffic during daytime hours, while large commercial vessels primarily affect the broadband and communication frequency bands. At night, the echolocation band returns close to its natural baseline, while communication and broadband levels remain somewhat elevated, reflecting continued commercial vessel traffic. Southern Resident killer whales were acoustically detected on July 27, 2024 (16:06-19:26) and on July 28, 2024 (21:45-22:36). Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 18. SPL and frequency: summer day (July 2024)



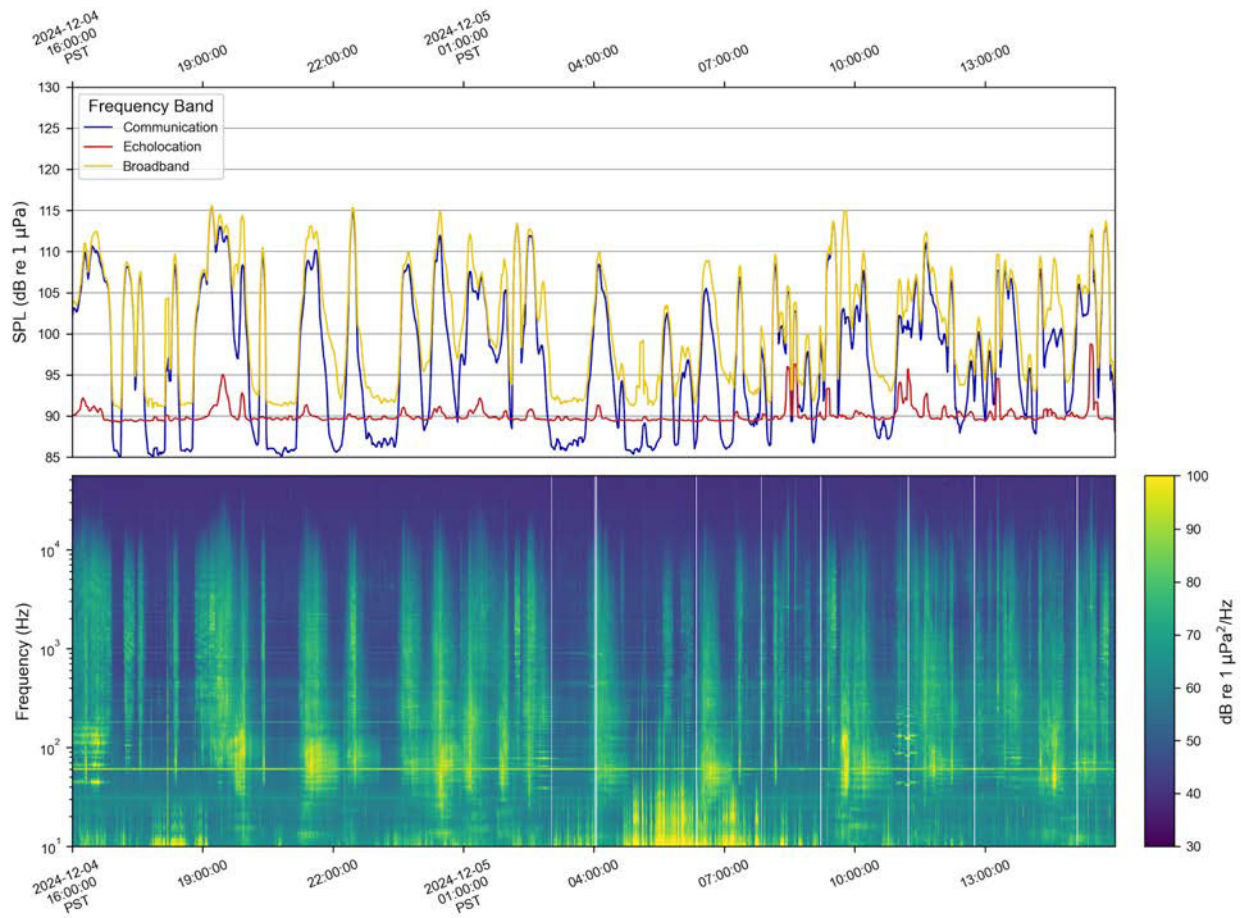
Sound Pressure Level (SPL) timeline (top) and spectrogram (bottom) for a 24-hour period from July 27 to July 28, 2024, at the Pender Island hydrophone, showing three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The spectrogram shows noise intensity across all frequencies over time, with brighter colours indicating louder sound. A typical diel pattern is evident, with SPL increasing in the early morning hours, peaking around midday, and declining again in the evening. No significant peaks in the echolocation band occurred overnight, as recreational vessel traffic had largely ceased. Periodic peaks in the lower frequency bands represent large commercial vessels transiting by the hydrophone approximately once per hour. Southern Resident killer whales were acoustically detected on July 27, 2024 (16:06-19:26). Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 19. SPL and frequency: winter week (Dec 2024)



Sound Pressure Level (SPL) timeline (top) and spectrogram (bottom) for November 30 to December 6, 2024, at the Pender Island hydrophone, showing three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The spectrogram shows noise intensity across all frequencies over time, with brighter colours indicating louder sound. Winter noise levels show no clear diel pattern, in contrast to summer conditions. Recreational vessel traffic decreases substantially during winter, resulting in few vessels affecting the echolocation frequency band (15-100 kHz). Minor increases in this band are primarily associated with rainfall. Southern Resident killer whales were acoustically detected on December 5, 2024 (1:04-2:07). Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 20. SPL and frequency: winter day (Dec 2024)



Sound Pressure Level (SPL) timeline (top) and spectrogram (bottom) for a 24-hour winter period from December 4 to December 5, 2024, at the Pender Island hydrophone, showing three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The spectrogram shows noise intensity across all frequencies over time, with brighter colours indicating louder sound. No clear diel pattern in SPL is present across any frequency band. Increases in the communication and broadband frequency bands correspond to large commercial vessel transits, while extended periods of elevated noise in the echolocation frequency band are associated with rainfall. Southern Resident killer whales were acoustically detected on December 5, 2024 (1:04–2:07). Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

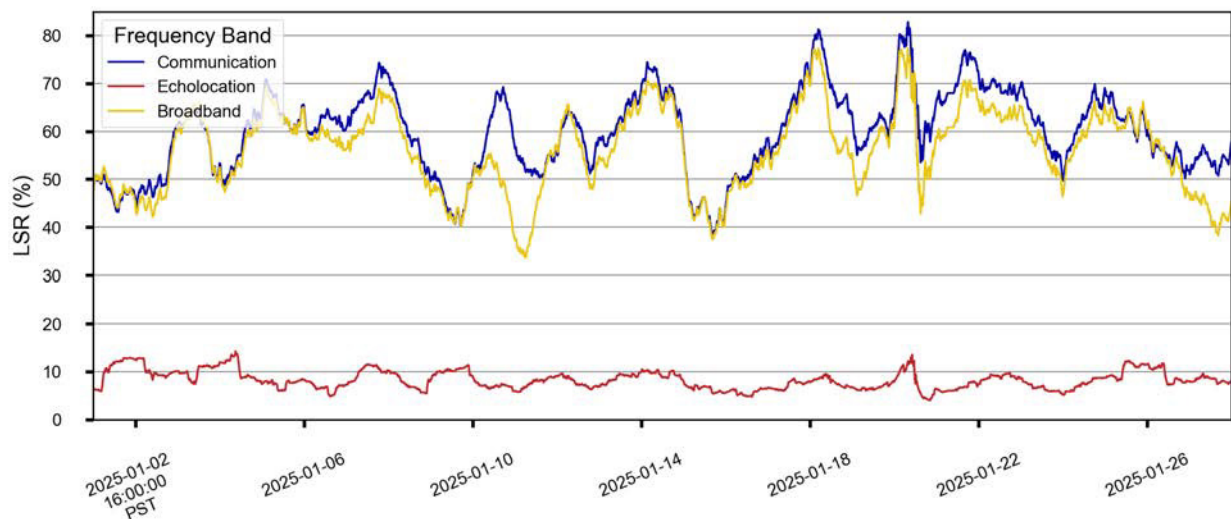
4.2.5 Listening Space Reduction (LSR)

LSR, defined in section 3.2.1, was calculated for January 2025 (Figure 21) and for a period with confirmed killer whale presence on January 29, 2025 (Figure 22). Over January, LSR in the broadband and communication bands was elevated, generally ranging between

40-80%, whereas LSR in the echolocation band remained substantially lower (approximately 5-15%).

SRKW were not detected in January 2025 (see Section 4.2.9); therefore, an acoustic detection of Bigg's (transient) killer whales on January 29 was used to illustrate short-term variability in LSR while cetaceans are present. During this detection period (14:45 to 17:54), LSR in the broadband and communication bands frequently reached high levels approaching 100% reduction, while echolocation-band LSR remained comparatively lower (peaking around 60% LSR).

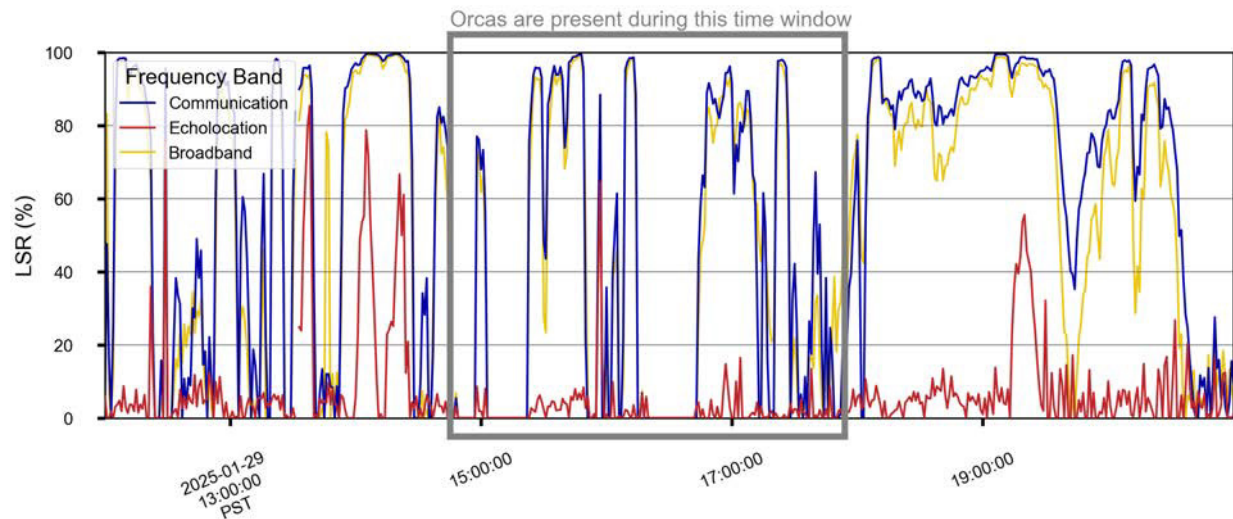
Figure 21. Listening Space Reduction (LSR): January 2025



Listening Space Reduction (LSR) is a measure of soundscape quality tailored for a specific species and its acoustic needs. It is shown here for the communication (0.5-15 kHz) and echolocation (15-100 kHz) frequency bands of killer whales, as well as a broadband (0.05-100 kHz) assessment, at the Pender island Hydrophone. Data were smoothed using a 24h rolling average applied to 60s original resolution data. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.



Figure 22. Listening Space Reduction (LSR): January 29, 2025



Listening Space Reduction (LSR) at the Pender Island hydrophone is shown here for the communication and echolocation frequency bands of killer whales, as well as a broadband assessment, during a confirmed killer whale presence close to the hydrophone (grey box). Their vocal activity falls within a time window that includes favourable acoustic conditions (i.e. periods of low LSR), and vocalizations cease when conditions worsen with constant high levels of LSR in the communication frequency band. Data are shown at 60s resolution. Bigg's killer whales were detected from 14:45 to 17:54. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

4.2.6 Vessel-specific impacts

When individual vessel transits are examined in isolation, their noise contributions or acoustic signatures become visible in Spectrograms (visual representations of sound across frequencies over time). These “fingerprints” illustrate how different vessel types influence overall noise levels and availability of acoustic habitat for killer whales (Figures 23-27).

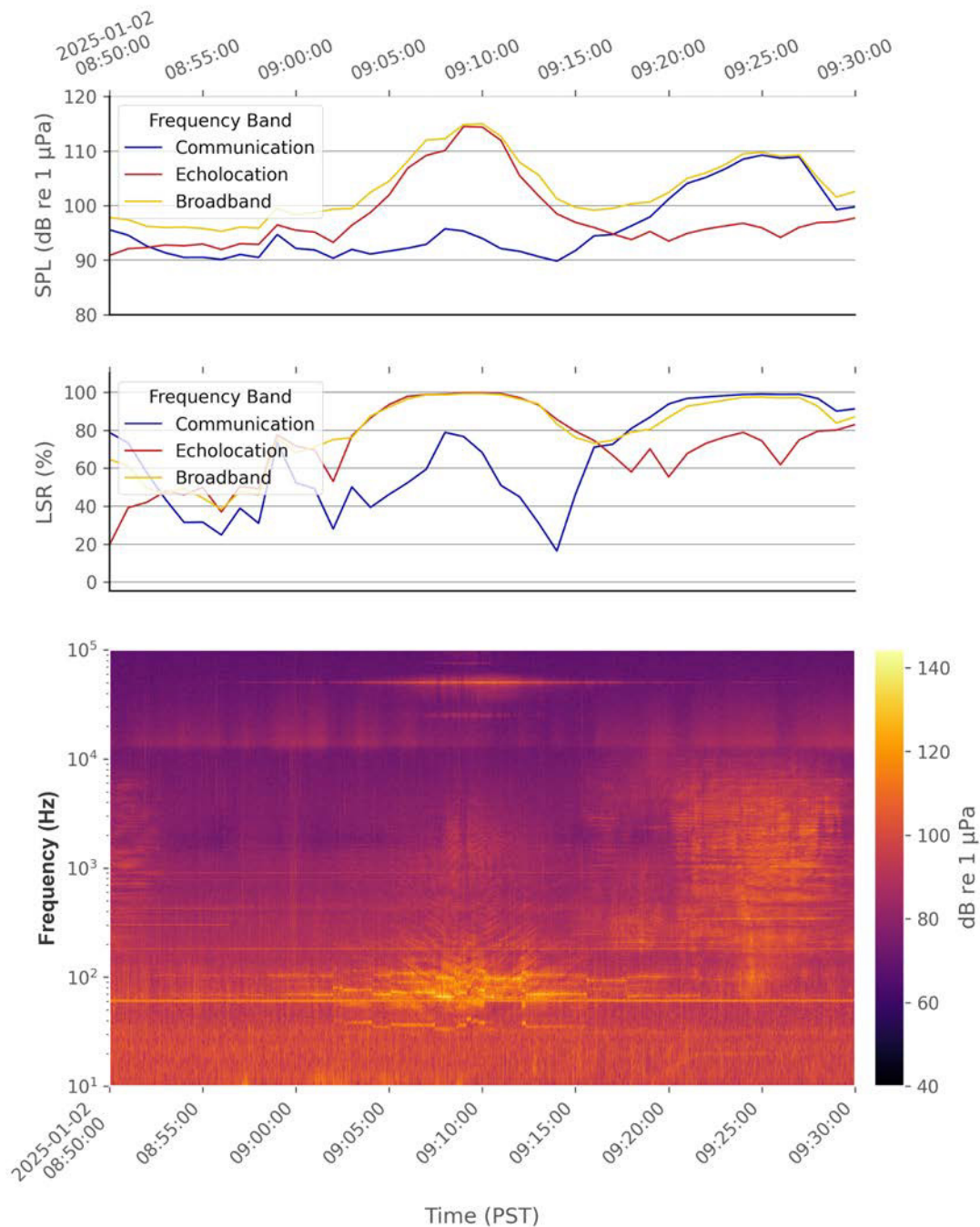
Across all cases, vessel transits produced distinct increases in broadband and communication band SPLs. Impacts to the echolocation band were comparatively lower, except when high-frequency sonar signals were present. Recreational and commercial vessels both contributed to elevated SPL and increased LSR, with the magnitude and duration of impact depending on vessel size, speed, and activity.

Recreational vessels exhibited variable signatures, including slow repeated passes (Figure 23), high-speed transits (Figure 24), and some vessels showing high-frequency tonal signals consistent with fish-finding sonar (Figures 23, 25). In these instances, echolocation band LSR was temporarily elevated when vessels and sonar sources were closest to the hydrophone.

Larger commercial vessels produced longer-duration and more sustained acoustic impact, with near-continuous reductions in broadband and communication band listening space during transits.

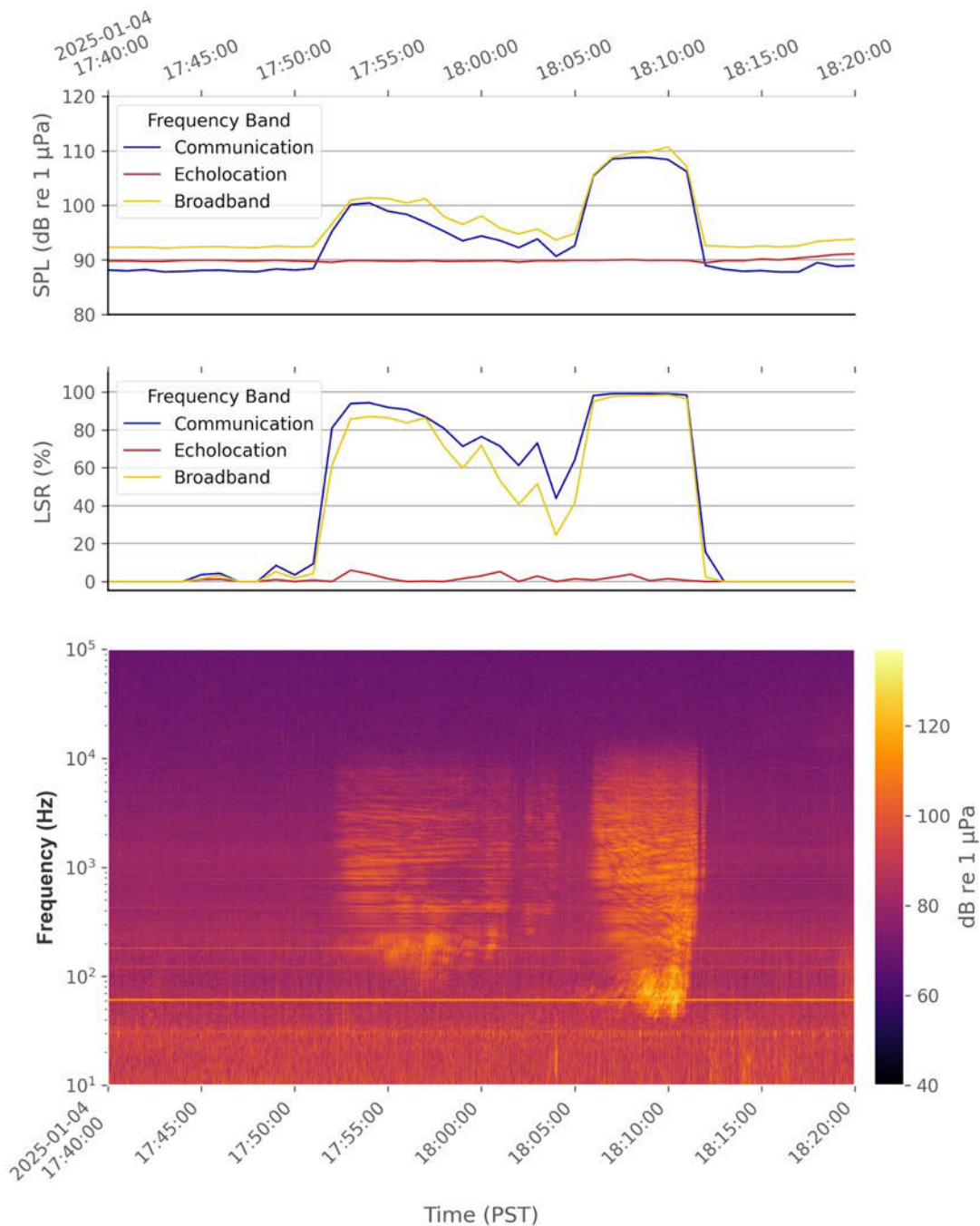
During a confirmed Bigg's killer whale encounter, vessel passage coincided with a temporary reduction in detected vocalizations, followed by a resumption of calls after vessel noise decreased (Figure 27), illustrating the potential for masking during periods of elevated vessel noise.

Figure 23. SPL, LSR, vessel fingerprint: recreational vessel with sonar



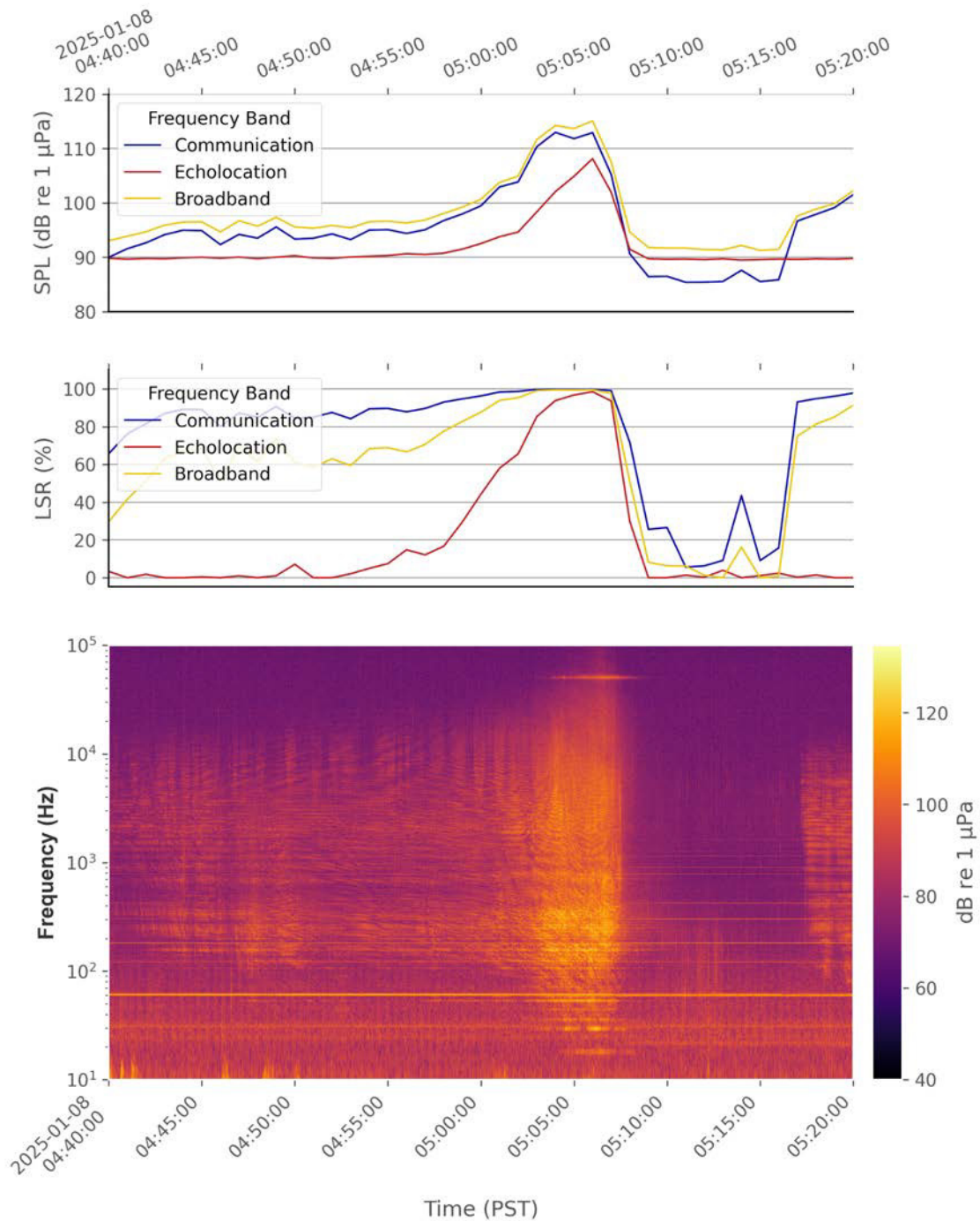
Sound Pressure Level (SPL), Listening Space Reduction (LSR), and vessel fingerprint of a recreational vessel making slow, repeated passes by the Pender Island hydrophone on January 2, 2025. The top panel shows SPL across three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The middle panel shows LSR across the same bands. The bottom panel shows the spectrogram, with brighter colours indicating louder sound. Active sonar use is indicated by a narrowband tonal feature (~40 kHz), consistent with fish-finding equipment. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 24. SPL, LSR, vessel fingerprint: recreational vessel



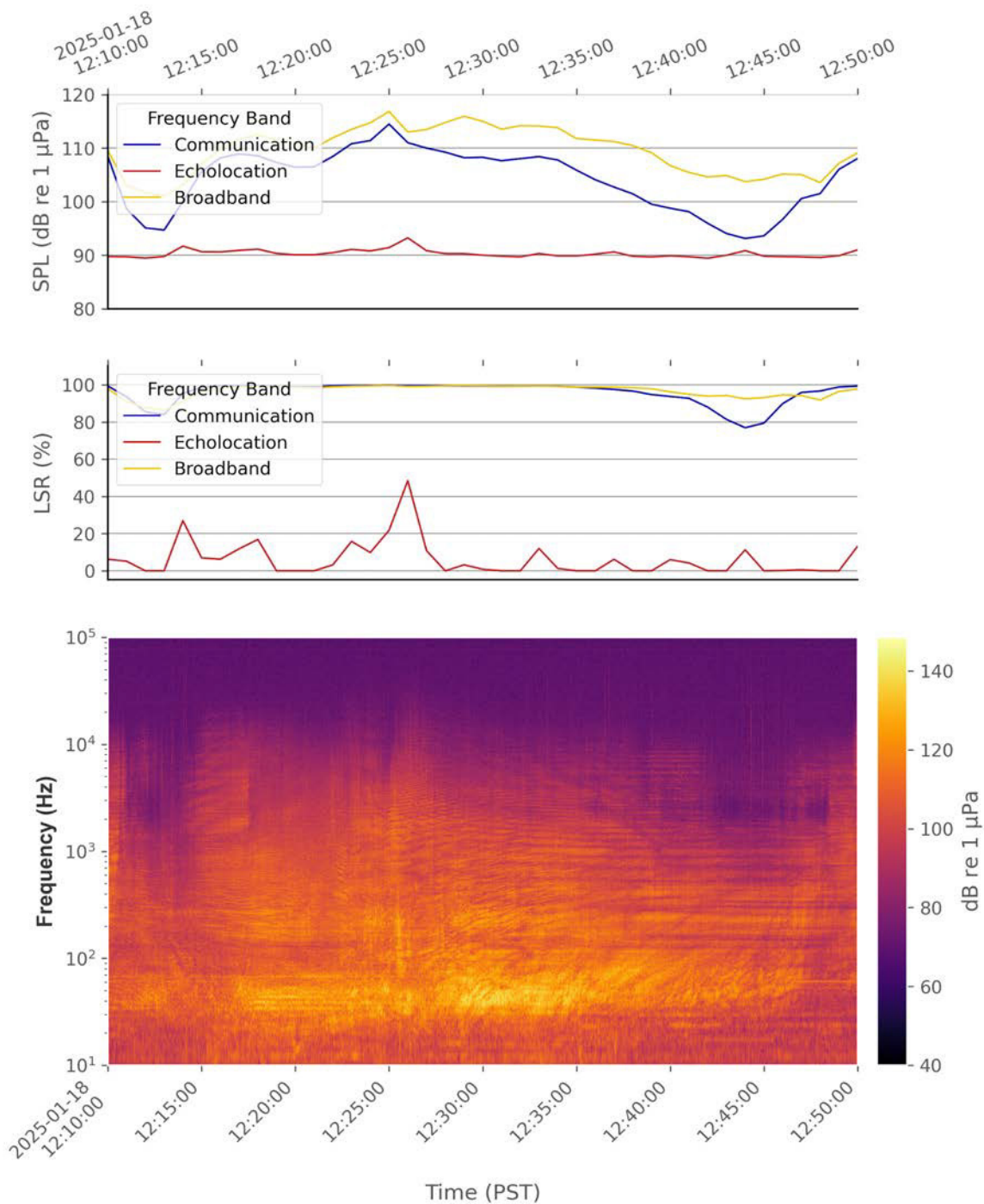
Sound Pressure Level (SPL), Listening Space Reduction (LSR), and vessel fingerprint of a recreational vessel transiting at speed near the Pender Island hydrophone on January 4, 2025. The top panel shows SPL across three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The middle panel shows LSR across the same bands. The bottom panel shows the spectrogram, with brighter colours indicating louder sound. Increased noise is primarily observed in the broadband and communication frequency bands, while the echolocation band remains comparatively unaffected. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 25. SPL, LSR, and vessel fingerprint: recreational vessel with sonar



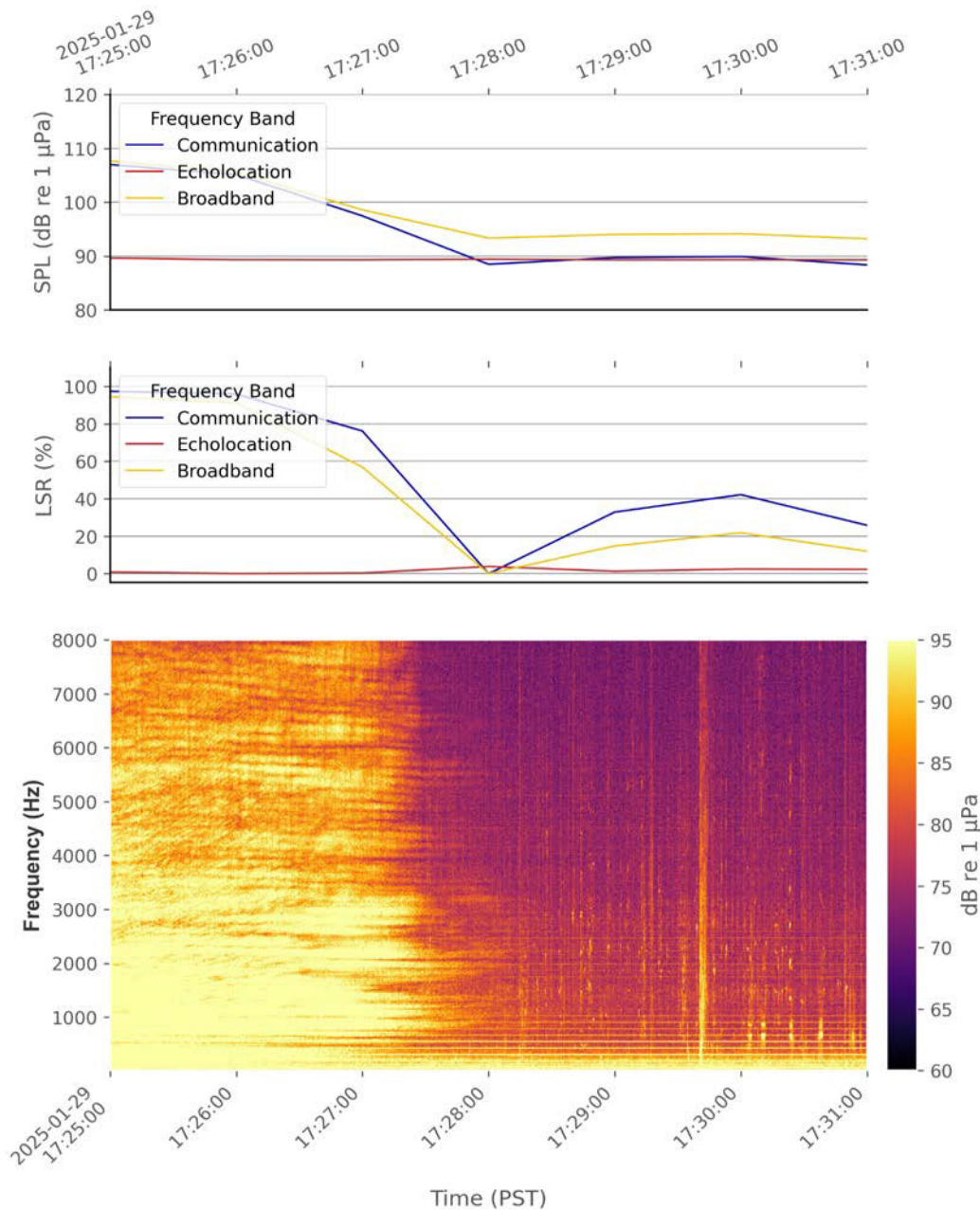
Sound Pressure level (SPL), Listening Space Reduction (LSR), and vessel fingerprint of a recreational vessel travelling at speed before stopping, near the Pender Island hydrophone on January 8, 2025. The top panel shows SPL across three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The middle panel shows LSR across the same bands. The bottom panel shows the spectrogram, with brighter colours indicating louder sound. High-frequency sonar signals (~40 kHz) are visible in the spectrogram while the vessel is in transit. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 26. SPL, LSR, and vessel fingerprint: commercial vessel transit



Sound Pressure Level (SPL), Listening Space Reduction (LSR), and vessel fingerprint of a commercial vessel transit near the Pender Island hydrophone on January 18, 2025. The top panel shows SPL across three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The middle panel shows LSR across the same bands. The bottom panel shows the spectrogram, with brighter colours indicating louder sound. Elevated noise levels are sustained throughout the passage, particularly in the broadband and communication bands. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

Figure 27. SPL, LSR, and vessel fingerprint: masking killer whale vocalizations

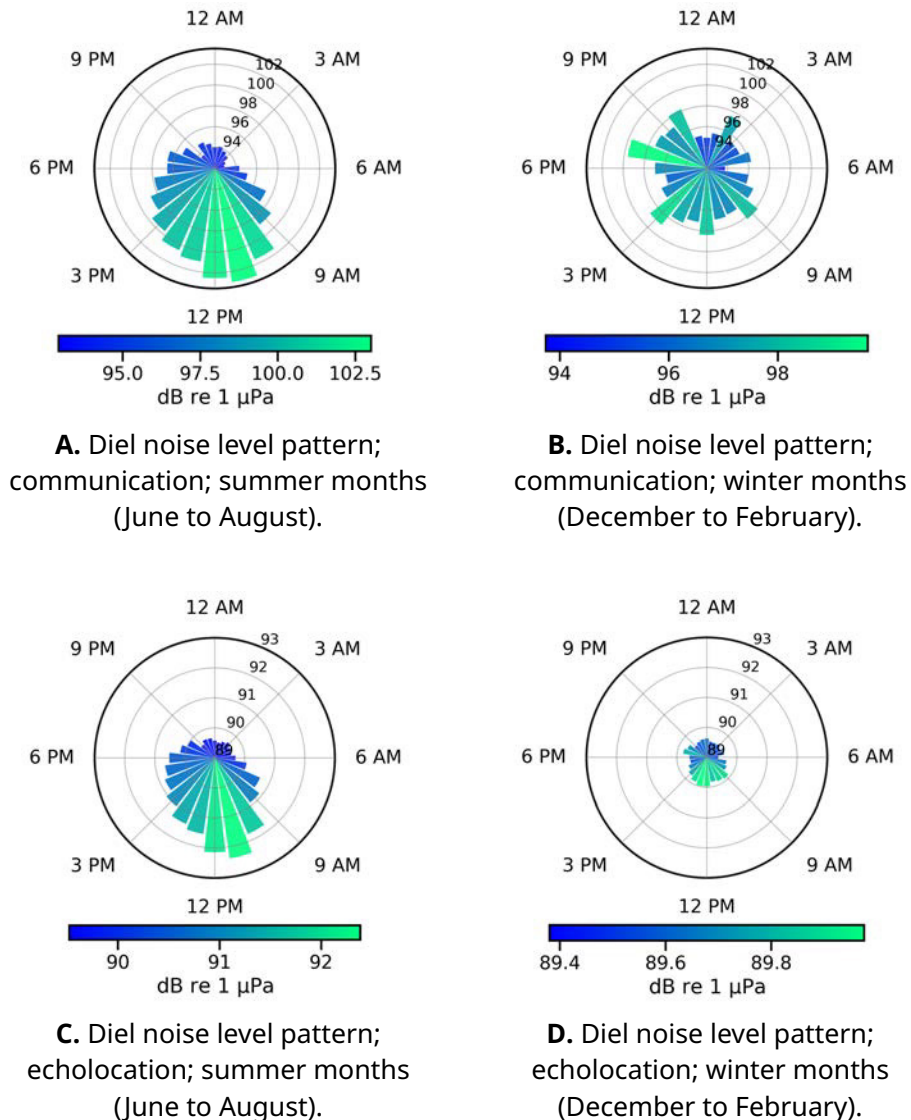


Sound Pressure Level (SPL), Listening Space Reduction (LSR), and vessel fingerprint of a commercial vessel in transit, recorded at the Pender Island hydrophone on January 29, 2025. The top panel shows SPL across three frequency bands relevant to killer whales: communication (blue, 0.5–15 kHz), echolocation (red, 15–100 kHz), and broadband (yellow, 0.05–100 kHz). The middle panel shows LSR across the same bands. The bottom panel shows the spectrogram for the killer whale communication frequency range (0–8 kHz), with brighter colours indicating louder sound. Bigg's killer whale vocalizations were detected from 14:45 to 17:54; this panel shows 17:25–17:31. During the vessel transit, LSR was at or near 100% in the communication and broadband frequencies, and no killer whale calls were detected, indicating potential interruption or masking of acoustic signals. Killer whale calls resumed after the reduction in vessel noise. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

4.2.7 Diel noise patterns

Noise levels were compared across hours of the day for the communication and echolocation frequency bands (Figure 28). In both bands, clear diurnal patterns were observed during summer months, with elevated noise levels during daylight hours and reduced levels overnight (Figures 28A, 28C). Winter showed no consistent pattern in either frequency band, with noise levels fluctuating across all hours of the day (Figures 28B, 28D).

Figure 28. Vessel noise by hour: summer versus winter



Diel noise level patterns for the killer whale communication band (0.5-15 kHz; A, B) and echolocation band (15-100 kHz; C, D) at the Pender Island hydrophone, comparing summer (A, C) and winter (B, D) months. Noise levels showed a stronger diel pattern in the summer months, with elevated vessel noise during daytime hours. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.

4.2.8 AIS vessel data

A total of 23,144 vessel trips were recorded within 5.3 kilometres of the Pender Island hydrophone in 2024. Vessel trips were defined as AIS transmissions from the same MMSI occurring within 60 minutes of one another. The five most common vessel categories were pleasure craft (8,511 trips), cargo (5,106 trips), passenger (1,903 trips), tug boats (1,774 trips), and tankers (768 trips), indicating that pleasure craft dominated overall traffic.

Clear differences in hourly transit patterns were observed among vessel types (Figure 29). Pleasure craft showed the strongest diurnal structure, with transits largely confined to daylight hours and peak activity occurring in late morning. Passenger vessels also displayed structured daytime patterns, consistent with ferry and ecotourism operations (Table 3). In contrast, cargo vessels, tankers, and tug boats showed relatively uniform activity across all hours.

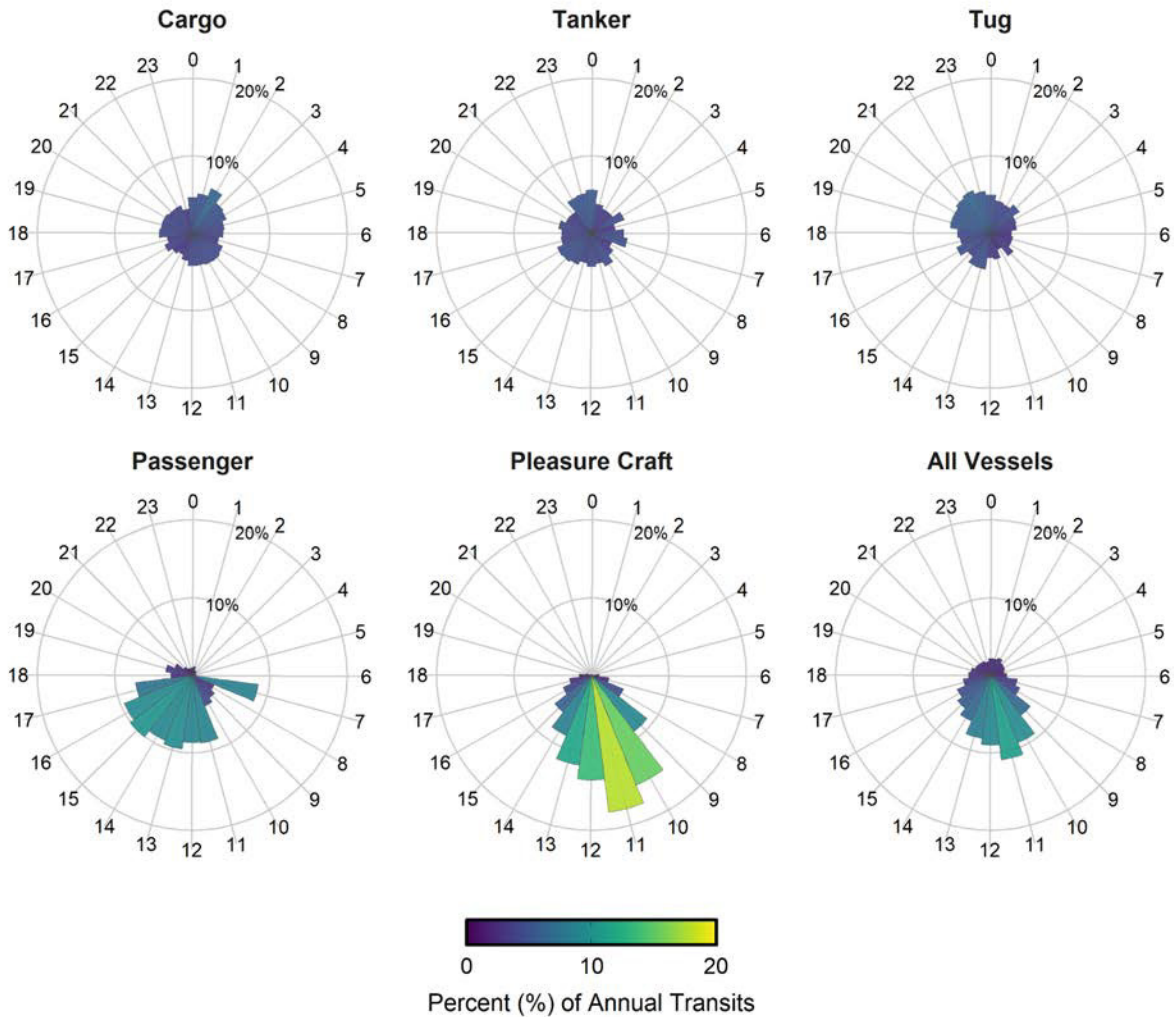
A small number of exceptions to these patterns were observed. A localized peak in passenger vessel activity at 7 AM was associated with a water taxi service in Bedwell Harbour, and an additional winter peak reflected temporary re-routing of a BC Ferries vessel (Coastal Inspiration) through the study area on a two-hour schedule (Chan, 2024; Figure S4).

Seasonal patterns further differentiated vessel types. Pleasure craft and passenger vessel traffic increased substantially from May to September and remained low during winter months (Figure 30). Tanker traffic increased following the opening of the Westridge Marine Terminal in May 2024, which expanded capacity from 5 to 34 tankers per month (Trans Mountain n.d.). Tug activity showed a modest increase in vessel transits from May to October, with slightly higher activity during evening and early morning hours, likely reflecting port-related operations.

To address limitations in AIS coverage, Raincoast-led land-based monitoring surveys were used to quantify non-AIS vessel transits through the Pender survey area. A total of 2,574 non-AIS vessels were recorded during survey hours, of which 2,445 were pleasure craft (Figure 32). During the same survey hours, 1,028 AIS-equipped pleasure craft transits were recorded within the survey area.

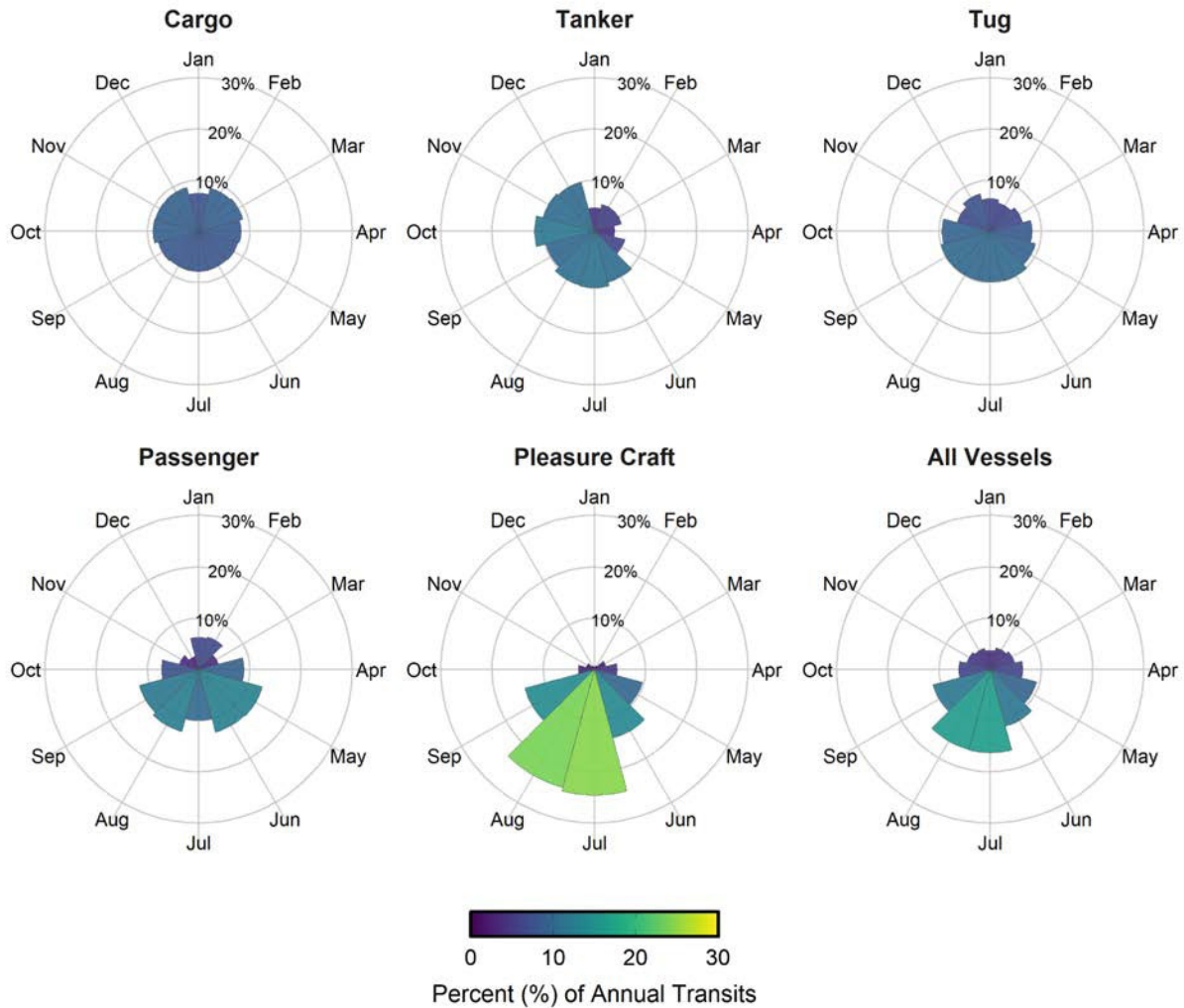
Overall, 3,602 pleasure craft transited through the study area, with 71.5% not equipped with AIS. This finding is consistent with O'Hara et al. (2023), who reported that 72% of vessel transits through Boundary Pass were non-AIS vessels, the majority of which were also pleasure craft.

Figure 29. AIS-equipped vessel trips per hour



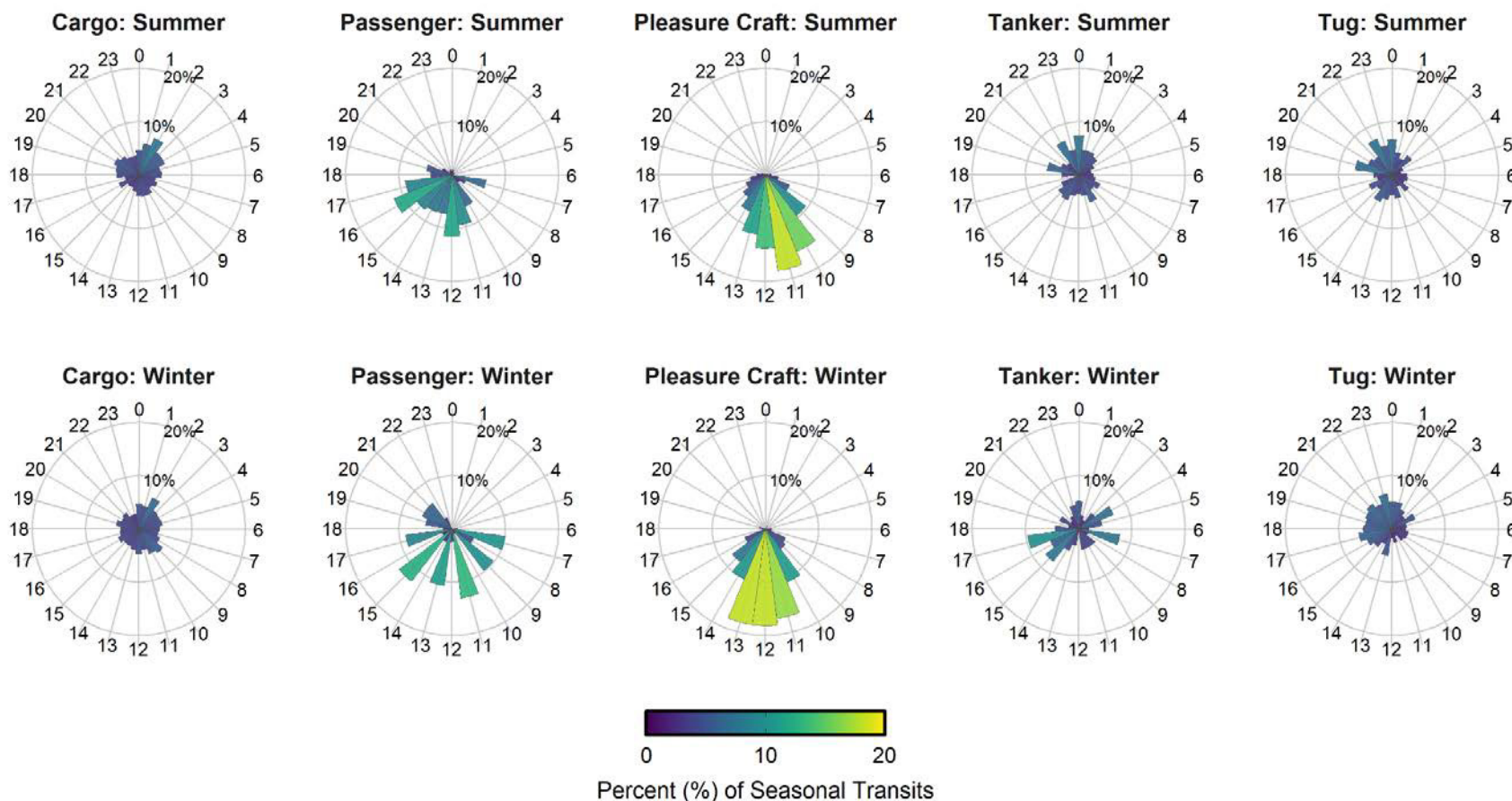
Proportion of AIS-equipped vessel trips within 5.3 kilometres of the Pender Island hydrophone in 2024, by hour and vessel category. The colour of each wedge indicates the percentage of annual transits occurring in that hour, from lowest (dark blue) to highest (yellow). Trips were defined as consecutive AIS (Automatic Identification System) positions from a single MMSI (Maritime Mobile Service Identity, a unique vessel identifier) separated by ≤ 60 minutes.

Figure 30. AIS-equipped vessel trips per month



Proportion of AIS-equipped vessel trips within 5.3 kilometres of the Pender Island hydrophone in 2024, by month and vessel category. The colour of each wedge indicates the percentage of annual transits occurring in that month, from lowest (dark blue) to highest (yellow-green). Trips were defined as consecutive AIS (Automatic Identification System) positions from a single MMSI (Maritime Mobile Service Identity, a unique vessel identifier) separated by ≤ 60 minutes.

Figure 31. AIS-equipped vessel trips per hour: summer versus winter



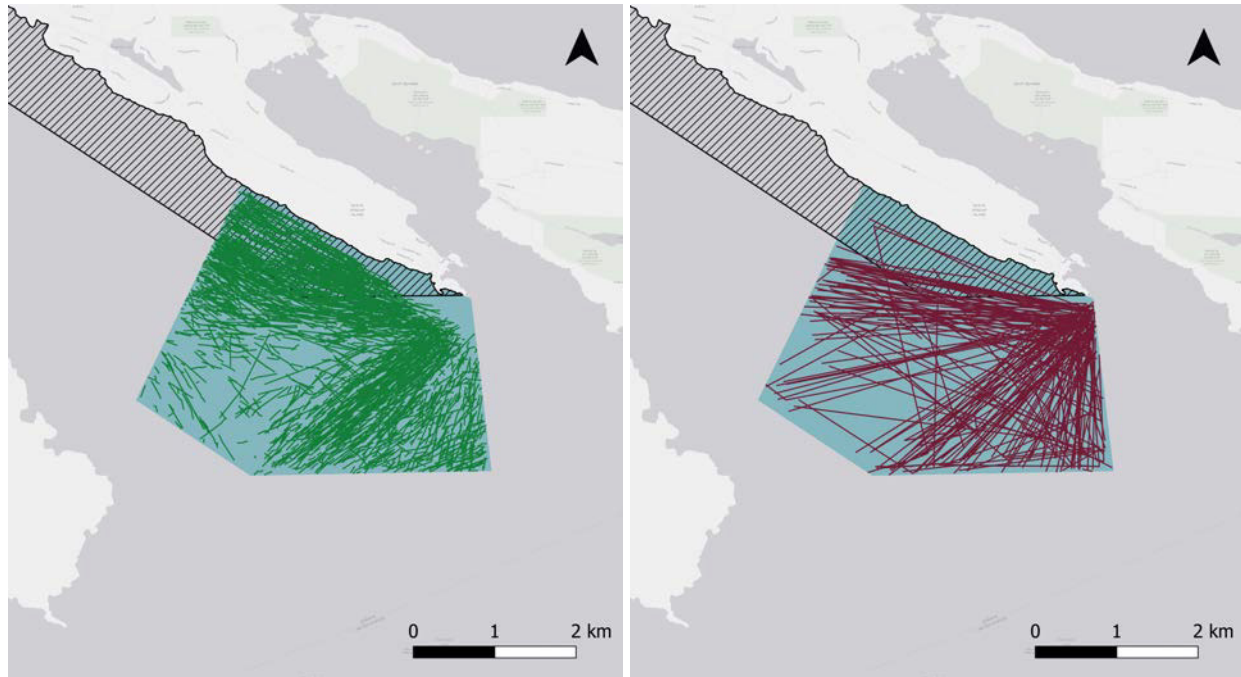
Proportion of AIS-equipped vessel transits near the Pender Island hydrophone by hour of day and vessel category in the summer (June to August) and winter (December to February) of 2024. Trips were defined as consecutive AIS (Automatic Identification System) positions from a single MMSI (Maritime Mobile Service Identity, a unique vessel identifier) separated by ≤ 60 minutes. The colour of each wedge indicates the percentage of seasonal transits occurring in that hour, from lowest (dark blue) to highest (yellow-green).

Table 3. Number of whale-watching / ecotourism vessels, 2024

The number of unique whale-watching / ecotourism vessels and the number of trips they took through the study area in 2024. Unique vessels were determined from their MMSI (Maritime Mobile Service Identity, a unique vessel identifier) number in the AIS (Automatic Identification System) data. Trips were defined as AIS positions that were logged ≥ 60 minutes apart.

Season	Ecotourism Vessels	Trips
Spring (March-April)	39	267
Summer (June to August)	43	433
Fall (September to November)	35	183
Winter (December to February)	5	15

Figure 32. Vessel tracks near Pender Island



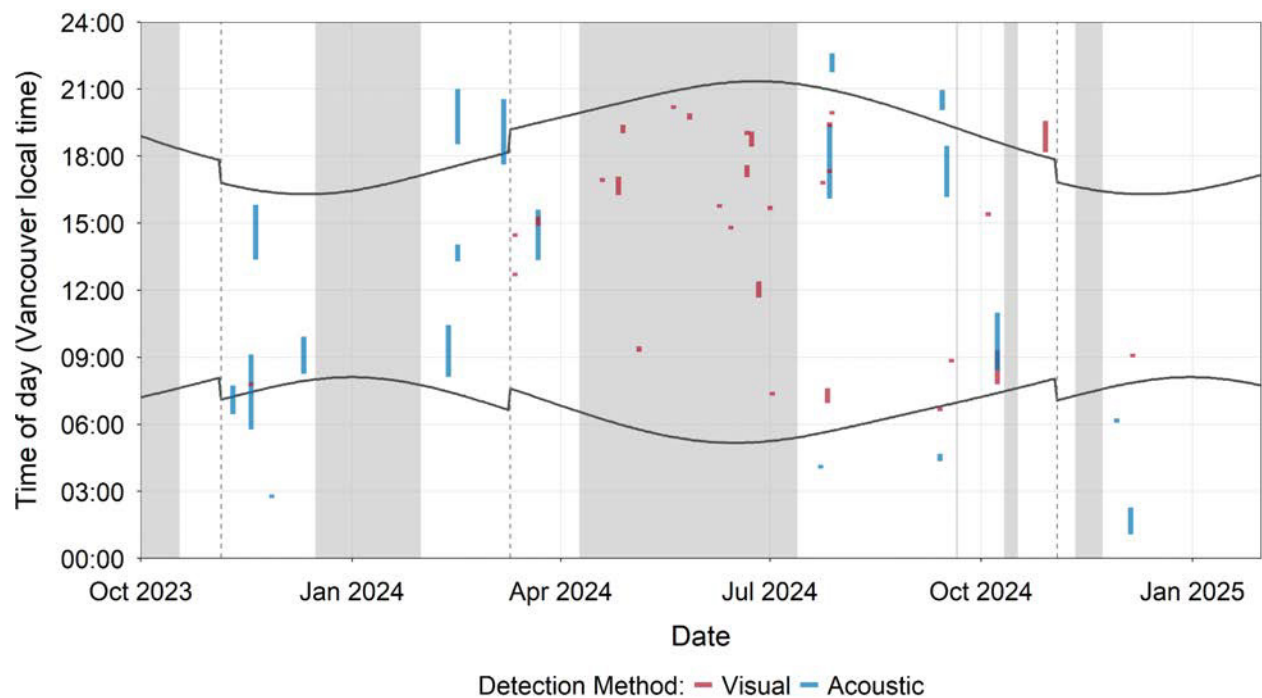
Vessel tracks near the Pender Island hydrophone, showing 2445 non-AIS equipped vessels (left) and 1028 AIS-equipped vessels (right). AIS tracks were compiled from the existing dataset and filtered to match the spatial and temporal extent of land based surveys conducted within and adjacent to the Pender Vessel Restricted Zone (VRZ) in 2024.

4.2.9 SRKW detections

From October 18, 2023, to February 1, 2025, there were 43 SRKW events (visual or acoustic detections that occurred within 60 minutes of each other) within 5.3 kilometres of the Pender Island hydrophone, spanning 38 days. SRKW were most frequently observed in July, with detections on 10 separate days. Several days included multiple detections, indicating extended SRKW presence within the study area. Acoustic detections occurred across all hours of the day, whereas visual sightings were limited to daylight hours or twilight.

Over half of all detections were visual-only (n = 24), with fewer acoustic-only (n = 15) and combined detections (n = 4). The relatively low number of acoustic and combined detections may reflect intermittent recording coverage from the Pender Island hydrophone during the study period.

Figure 33. SRKW detections near Pender Island



Visual and acoustic detections of Southern Resident killer whales within 5.3 km of the Pender Island hydrophone from October 18, 2023, to February 1, 2025. Visual detections are shown in red and acoustic detections in blue. Grey shading indicates periods when the hydrophone was not operational. Dashed vertical lines mark daylight savings time changes, and the curved horizontal lines indicate sunrise and sunset times. Acoustic data collected and analyzed by Raincoast Conservation Foundation.

5. Discussion

5.1 Vessel impacts on acoustic habitat loss

Analysis of the Saturna Island hydrophone data (SIMRES) indicates a sustained degradation of the underwater acoustic environment in Boundary Pass from 2017 to 2025. All metrics (Quiet Time, Vessel Noise Presence, Excess Noise, and LSR, defined in section 3.2.1), results indicate reduced availability of functional acoustic environment for SRKW. Rather than isolated seasonal or diel reductions in Quiet Time observed in 2017, acoustic conditions in 2023 and 2025 were consistently degraded across both daily and seasonal time scales.

This shift reflects a transition from intermittent to chronic acoustic disturbance to SRKW, driven by increased Vessel Noise Presence and prolonged noise exposure within their habitat. Elevated noise levels occurring within the 100-1000 Hz range were consistent with large vessel source frequencies (Veirs et al. 2016) and overlapped with the lower portion of the SRKW communication band (0.5-15 kHz). Rather than discrete noise events associated with individual transits, the acoustic environment increasingly reflects sustained elevated background noise, with reduced recovery time between vessels.

Changes in vessel traffic composition, operational behaviour, and seasonal patterns provide context for these trends. Cargo ship transits remained relatively consistent over the study period, but vessel dwell time has increased due to prolonged wait times at the Port of Vancouver, resulting in more ships running their engines while at anchorage and contributing to increased ambient noise levels (World Bank 2025; Vancouver Fraser Port Authority 2026b; Vancouver Fraser Port Authority n.d. c). Tanker traffic increased dramatically in 2024 with the expansion of the Westridge Marine Terminal (Environmental Assessment Office n.d.). Each laden tanker must be accompanied by an escort tug while transiting Haro Strait and Boundary Pass, increasing underwater noise levels (Pacific Pilotage Authority 2019). Other factors, such as daylight-only departures and slack tide requirements in Burrard Inlet, further concentrate tanker traffic and amplify vessel noise (Vancouver Fraser Port Authority 2025b).

Tourism-related vessels, including whale-watching operations, add additional variability to the soundscape, especially in the summer months. Although regulatory changes have shifted operator focus towards non-SRKW cetaceans (Government of Canada 2019), they do not fully mitigate the broader acoustic impacts associated with whale-watching operations. Their persistent presence and frequent high-speed transits between sightings contribute to underwater noise levels within the Salish Sea (Houghton et al. 2015).

Recreational vessel traffic represents an increasingly important component of local vessel activity, with substantially higher densities observed near the Saturna Island hydrophone in 2025 (1,933 transits) relative to 2017 (646 transits). This 199.2% increase was likely influenced by the COVID-19 pandemic: recreational boat sales increased by 12% from 2019 to 2020 in the United States, with wake boat sales rising by up to 20% (National Marine Manufacturers Association 2021). These vessels operate across a wider spatial range than commercial vessels and are typically not subject to speed restrictions, which may increase local noise contributions relative to their size (Houghton et al. 2015).

However, AIS data alone underestimates total recreational vessel presence in the region. Land-based surveys conducted by Raincoast in 2024 found that 71.5% of pleasure craft transiting in or near the Pender VRZ were not equipped with AIS. This suggests that the observed increase in AIS-equipped recreational vessels near the Saturna Island hydrophone likely represents only a portion of total traffic. Improvements in AIS affordability and accessibility may increase updates among recreational boaters over time, leading to more accurate estimates of overall vessel activity.

5.2 SRKW presence

SRKW detections at the Saturna Island hydrophone in 2023 and at the Pender Island hydrophone in 2024 followed similar seasonal patterns, with the highest concentration of whale events occurring during the spring and summer months. Acoustic detections occurred across all hours of the day throughout the study period (notwithstanding periods of hydrophone downtime). These trends were consistent with long-term observations of SRKW habitat use in the Salish Sea, where presence is elevated between May and September but occurs year-round (Olson et al. 2018).

In contrast, detections at the Saturna Island hydrophone in 2025 showed a marked reduction in SRKW presence across the study area. The summer of 2025 recorded one of the lowest observed levels of SRKW presence in the Salish Sea in recent decades (Orca Behavior Institute 2025), representing a significant departure from historical patterns of habitat use. While our results indicate that underwater noise levels in Boundary Pass have increased over the past decade, the 2025 decline in SRKW detections is unlikely to reflect acoustic disturbance alone, and may reflect multiple interacting factors.

SRKW in the Salish Sea are exposed to vessel noise year-round, with persistent low-frequency inputs from commercial shipping and seasonally elevated contributions from recreational and tourism vessels. These overlapping sources create a continuously variable acoustic environment across frequency bands that reduces available acoustic

space. Chronic noise exposure and the masking of echolocation and other vocalizations may impact SRKW communication, foraging efficiency, and social behaviour, depending on received sound levels and other ecological factors.

5.3 Implications for management measures

Despite implementation of the ECHO Program's voluntary vessel slowdown and the Pender and Saturna VRZs, noise levels in critical SRKW habitat have continued to increase.

Although vessel slowdowns reduce source levels, particularly at lower frequencies, received sound levels are strongly influenced by vessel density, proximity, and duration of exposure (Burnham et al. 2021). While reductions in individual vessel speed do reduce noise emissions, these gains can be offset by increases in overall vessel traffic, such that ambient noise levels may not decrease, or may even rise, despite individual vessels travelling more slowly. Indeed, Excess Noise increased by up to 3.4 dB at 100 Hz between 2017, the pilot season of the voluntary slowdown, and 2025, suggesting that the benefits of speed reductions have been offset by increases in overall vessel activity.

Both the Pender Island and Saturna Island hydrophones capture conditions representative of SRKW habitat within and adjacent to the VRZs. Results at both sites indicate persistently elevated noise levels throughout most hours of the day and across seasons, regardless of whether the VRZ is in effect. These results suggest limited effectiveness in maintaining consistently reduced acoustic conditions within the zones. Several factors likely limit VRZ benefits. Seasonal implementation (June to November) leaves substantial portions of the year unprotected. Non-compliance during active months may reduce overall effectiveness. In addition, the fixed spatial boundaries of the VRZs may not align with SRKW movements during all whale transits, and vessels operating outside the zone boundaries can still contribute to received noise levels within them. This is particularly relevant in narrow areas such as East Point, Saturna Island, where the VRZ boundary is in close proximity to the Boundary Pass shipping lane.

Unlike the Robson Bight (Michael Bigg) Ecological Reserve, where Northern Resident killer whales spend extended periods of time in a concentrated area (Bouvier 2022), SRKW typically transit through the Pender and Saturna VRZ rather than remain within them. This limits opportunities for the VRZs to offer sustained acoustic refuge to the whales while in the Salish Sea.

The vessel acoustic fingerprints illustrated in Figures 23-27 indicate that individual transits can result in complete or near-complete masking of the SRKW communication band frequencies (LSR approaching 100%), highlighting the potential for acute acoustic

disruption even during short exposure periods. Previous studies have demonstrated that SRKW foraging behaviour is inversely related to vessel proximity, with increased foraging time observed under low vessel presence (Lusseau et al. 2009; Holt et al. 2021b). These studies suggest that both chronic and acute noise exposure negatively impact SRKW foraging efficiency.

5.4 Limitations

While acoustic measurements were thorough, attributing noise to specific vessel sources remained challenging. In the absence of continuous visual monitoring of the study area, vessel presence was inferred primarily from AIS data, which does not capture all vessel activity. Hydrophone placement in relatively shallow, nearshore environments may have also influenced source detection. Smaller vessels operating closer to the hydrophones may be overrepresented, while larger vessels that must remain in the shipping lanes may be underrepresented. The noise levels reported here reflect conditions at the hydrophone locations and may not fully represent the acoustic environment experienced by SRKW across the study area.

Many of our analyses separated sound pressure levels into three frequency bands for broadband (0.05-100 kHz), communication (0.5-15 kHz) and echolocation (15-100 kHz). These ranges were selected based on values reported in the literature, but they may not fully capture the true extent of frequencies used by SRKW. In particular, the lower bound of the echolocation band (15 kHz) is likely conservative, and it may extend into the upper range of the communication band. As a result, vessel noise occurring at these overlapping frequencies may impact SRKW echolocation to a greater extent than is reflected in our analysis. This may explain why echolocation appeared less affected by vessel noise than SRKW communication.

The Pender Island hydrophone was operational for only 64% of the study period (Figure S2). Self-noise was also present in the recordings early in the deployment. These limitations may have influenced seasonal comparisons of acoustic conditions in the Pender VRZ, despite efforts to minimize their impact.

Detecting SRKW presence through visual and acoustic monitoring both have inherent limitations. Visual sightings were limited by observer effort, daylight, and weather conditions. Acoustic monitoring enabled detection across all hours of the study period, but was affected by intermittent recording gaps. Therefore, the SRKW detections reported in Figures 11 and 33 are likely conservative estimates of SRKW occurrence.

Overall, these limitations suggest that vessel presence and associated noise exposure experienced by SRKW may be underestimated. Future work integrating hydrophone data with precise SRKW movement data, along with expanded visual and acoustic monitoring beyond current temporal and spatial management measures, would improve estimates of noise exposure within and outside of these measures.

6. Conclusions

This report demonstrates a clear and consistent increase in underwater noise in Boundary Pass from 2017 to 2025. Across all evaluated metrics, results indicate a measurable degradation of available acoustic habitat for SRKW.

This trend reflects the cumulative impacts of vessel activity in the region. While mitigation measures such as the ECHO Program's voluntary slowdown reduce per-vessel noise levels, these benefits are offset by increasing vessel traffic, the presence of vessels not subject to mitigation, and prolonged exposure within critical habitat. Similarly, while the Pender and Saturna VRZs provide localized reductions in vessel disturbance, their effectiveness is limited by seasonal implementation, limited geographic coverage, and variable compliance.

SRKW detections in 2023 and 2024 remained consistent with long-term seasonal patterns in the Salish Sea. Notably, SRKW were detected under a wide range of acoustic conditions, including periods of elevated noise, indicating that their presence does not infer improved acoustic conditions. Further monitoring will be needed to determine whether the prolonged SRKW absence in 2025 was an outlier or an emerging shift in habitat use.

Overall, the findings suggest that current management measures are insufficient to reduce underwater noise levels in critical SRKW habitat. More effective strategies will require enforceable, species-specific noise reduction targets that account for vessel type, speed, and proximity to SRKW, while addressing the cumulative and prolonged nature of noise exposure across the Salish Sea.

The long-term recovery of SRKW will depend on integrated conservation actions that address multiple threats to their population. Reducing underwater noise may improve SRKW foraging efficiency, but without sufficient prey availability and reduced contaminant exposure, these benefits are unlikely to support population recovery.

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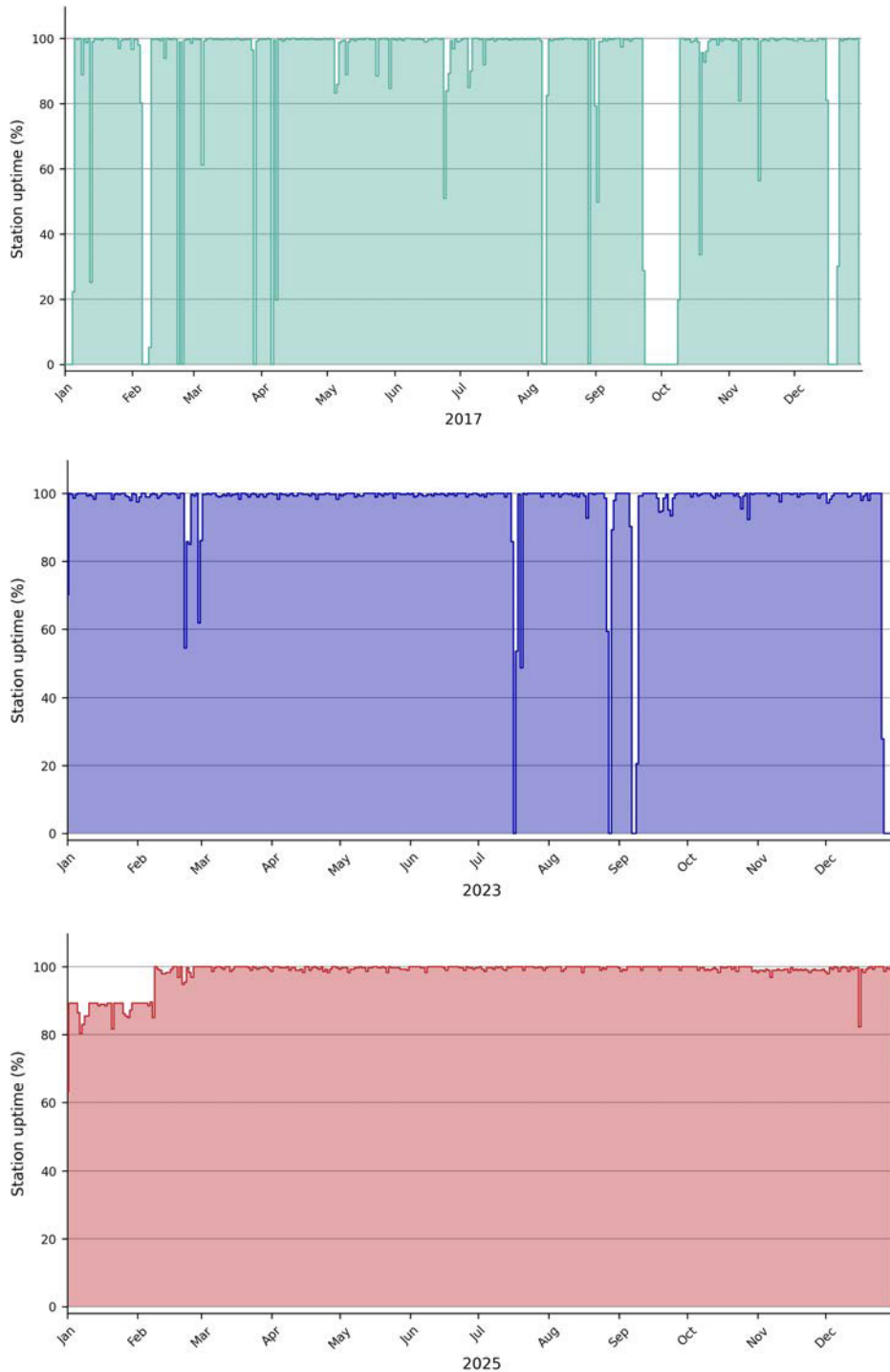
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<https://doi.org/10.1017/S0952836902000298>.

World Bank. 2025. The Container Port Performance Index 2020 to 2024: Trends and Lessons Learned, Washington DC: World Bank, License: Creative Commons Attribution Non-commercial CC BY-NC 3.0 IGO.

Supplementary figures

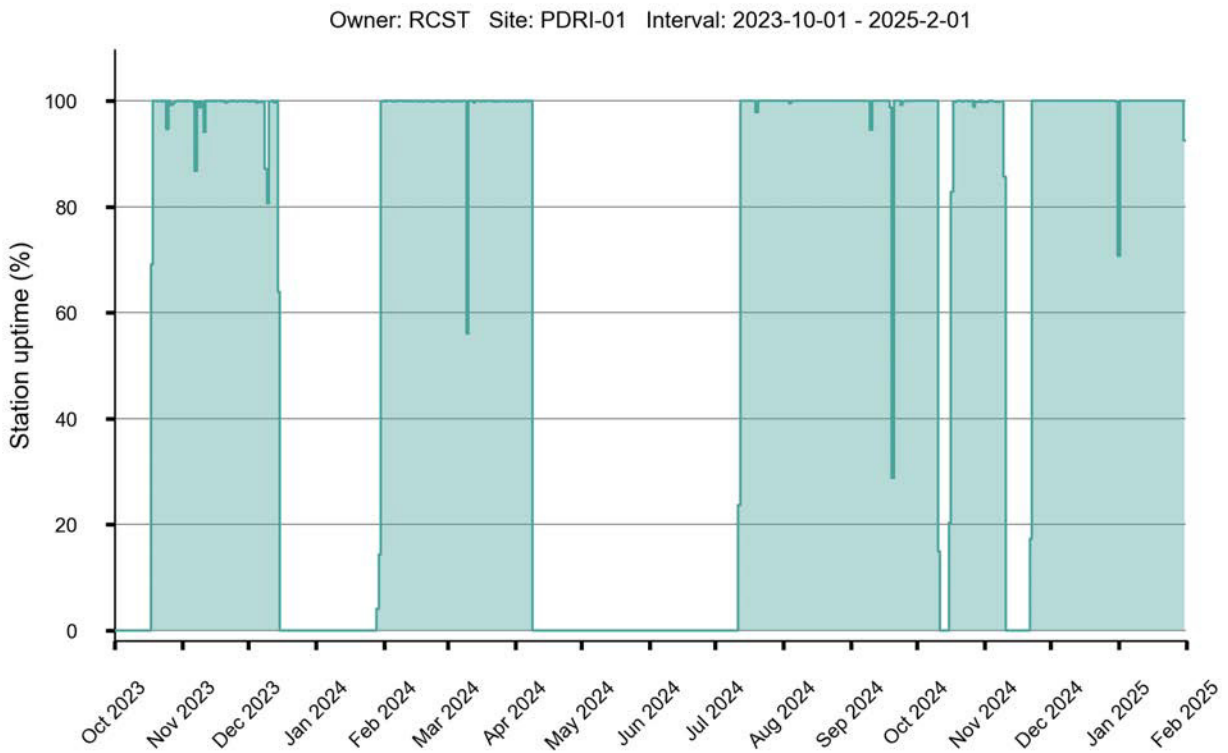
Figure S1. Hydrophone uptime, Saturna Island



Saturna Island hydrophone daily recording effort for 2017, 2023, and 2025. Station uptime is the % of time for which hydrophone data was available each day. Calendar months were considered statistically meaningful if data was recorded least 50% of the time. Acoustic data collected by SIMRES and analyzed by SoundSpace Analytics.



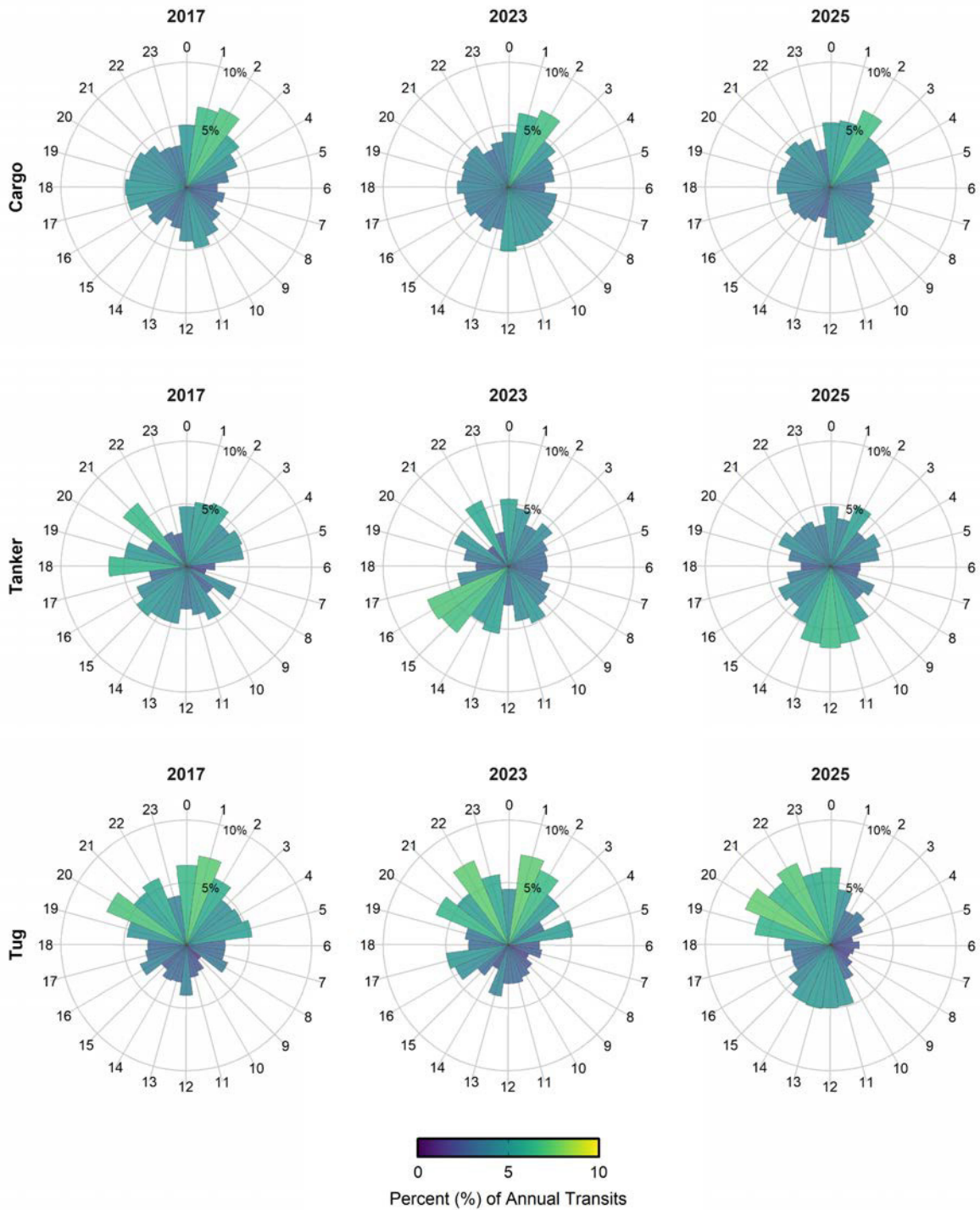
Figure S2. Hydrophone uptime, Pender Island



Pender Island hydrophone daily recording effort for October 18, 2023, to February 1, 2025. 2017, 2023, and 2025. Station uptime is the % of time for which hydrophone data was available each day. Recording effort was inconsistent at this site, with two large data gaps and shorter system outages, resulting in no hydrophone data for 35% of the study period. Calendar months were considered statistically meaningful if data was recorded least 50% of the time. Acoustic data collected by Raincoast Conservation Foundation and analyzed by SoundSpace Analytics.



Figure S3. Hourly AIS-equipped commercial vessel trips near Saturna Island



Hourly AIS-equipped vessel trips within 5.3 kilometres of the Saturna Island hydrophone in 2017, 2023, and 2025 for cargo ships, tankers, and tug boats. Unlike pleasure craft and passenger vessels, these vessel categories are likely to transit through Boundary Pass at all hours of the day.

Glossary

Acoustic habitat: the sound environment that surrounds marine animals, characterized by typical noise levels and patterns.

Auditory masking: when a loud or overlapping sound makes it harder for an animal to detect or recognize another important sound. This happens because the interfering sound raises the level at which the quieter sound can be heard, or the “threshold” at which the second sound becomes noticeable, a process known as masking. For marine mammals, this can interfere with their ability to communicate, find food, or detect danger, for example, masking a call from a calf, an echolocation click or the sound of approaching prey

Broadband sounds: sounds that contain energy across a wide range of frequencies simultaneously. Examples include whale songs, breaking waves, or ship noise. Broadband noise can mask multiple types of marine mammal sounds because it overlaps with many frequency bands.

Decibels: a unit for measuring sound intensity on a logarithmic scale, where small increases in dB represent large increases in actual sound energy. Underwater acoustic uses a different reference pressure than airborne acoustics (1 μ Pa versus 20 μ Pa respectively), meaning decibel values for underwater sounds are not directly comparable to those reported for sounds measured in air.

Decidecade band: A standardized frequency interval used in underwater acoustics to measure and compare sound levels. The full range of audible frequencies can be divided into broad intervals called decades (each spanning a tenfold increase in frequency, e.g., 100 to 1,000 Hz). A decidecade is one-tenth of such an interval, providing a finer-resolution slice of the frequency spectrum. Decidecade bands allow consistent, detailed comparisons of noise levels across studies and are commonly used to characterize underwater noise across biologically relevant frequency ranges..

Echolocation: the natural sonar system used by dolphins, whales, and other marine animals to navigate and hunt by producing sounds and interpreting the echoes.

Excess Noise: the increase in underwater sound levels attributable to vessel activity above baseline environmental noise conditions. Excess Noise is calculated by comparing periods with detected vessel noise to temporally adjacent natural conditions to estimate vessel-driven increases in sound levels.

Frequency: the number of sound wave cycles that pass a given point per second, measured in Hertz (Hz). Low frequencies (few cycles per second) produce low-pitched sounds; high frequencies (many cycles per second) produce high-pitched sounds. In underwater acoustics, frequency is biologically relevant because different marine animals produce and hear sounds within specific frequency ranges. For example, Southern Resident killer whales use frequencies roughly between 0.5 and 100 kHz for communication and echolocation. One kilohertz (kHz) equals 1,000 Hz.

Listening Space Reduction (LSR): a measure of how much vessel noise reduces the acoustic space available to killer whales relative to baseline conditions, expressed as a percentage. LSR was calculated within the 0.5-15 kHz SRKW communication band.

Quiet Time: the proportion of time during which no detectable vessel noise is present, expressed as a percentage of total recording time (%).

Sound Pressure Level (SPL): a standardized physical measure of the pressure fluctuations caused by a sound wave, expressed in decibels (dB). SPL allows consistent comparison of sound intensity across different environments and studies.

Spectral Probability Density (SPD): A method for summarizing the statistical distribution of underwater sound levels across frequencies over a given time period. Rather than reporting a single average, SPDs show how frequently each combination of frequency and sound level occurs, providing a more complete picture of the acoustic environment. Percentile levels, such as L05, L50, and L95, describe the sound levels exceeded 5%, 50%, and 95% of the time, respectively, representing unusually loud, typical, and unusually quiet conditions. The mean sound level within a frequency band is expressed as Leq.

Spectrogram: a visual representation of sound showing frequency (Hz) over time, with intensity typically represented by colour or brightness.

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Tracking vessel noise and its implications for Southern Resident
killer whales in the Salish Sea. Raincoast Conservation
Foundation. [DOI: 10.70766/8.76355](https://doi.org/10.70766/8.76355)

