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Characterisation of the underwater soundscape at Norwegian salmon farms

Luke T. Barrett [a], Frode Oppedal [b,*]

[a] Sustainable Aquaculture Laboratory – Temperate and Tropical (SALTT), Queenscliff Marine Science Centre, Deakin University, Victoria 3225, Australia
[b] Animal Welfare Research Group, Institute of Marine Research, Matre, 5984 Matredal, Norway

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ABSTRACT

The average fish farm has become larger and more mechanised over recent decades, employing an array of machines (workboats, wellboats, pumps, compressors) that generate noise, potentially reducing the health, welfare and productivity of cultured fish or wild animals in the vicinity of the farm. We measured underwater sound pressure levels (SPLs) at 10 Atlantic salmon (*Salmo salar*) aquaculture sites in Norway, including 4 open sea-cage sites, 2 closed sea-cage sites, and 4 onshore sites. The soundscape (amplitude, frequency and variability of sound pressure waves) varied considerably, not only between sites, but also over time and space within sites, and generally peaked at frequencies within the sensitive range of salmonids (~20–500 Hz). Continuous root-mean-square SPLs under typical farming conditions were higher within tanks and closed sea-cages than open sea cages, especially at low frequencies (mean 1-s SPL: 112–129 vs. 98–105 dB re 1 μPa over 20–100 Hz), but were relatively predictable compared to open sea-cages, where diurnal patterns and visits by workboats and wellboats exposed fish to fluctuating sound levels (range 1-s SPL: 83–157 dB re 1 μPa over 20–100 Hz). SPLs >140–150 dB re 1 μPa over 20–1000 Hz were rare at all sites, although impulsive SPLs with >173 dB re 1 μPa were observed on two occasions. More work is needed to understand long-term effects of ambient noise levels and the predictability of sounds on health and welfare outcomes for farmed fish.

1. Introduction

Aquatic animals use bioacoustics to navigate aquatic environments and find, avoid or communicate with other animals over long distances (Montgomery and Radford, 2017). However, various human activities generate noise pollution that can mask acoustic signals and disturb, deter, injure, or in extreme cases even kill animals that are sensitive to underwater sound (Slabbekoorn et al., 2010). There is now substantial evidence that noise pollution has measurable impacts on ecosystems (de Jong et al., 2020; Popper and Hawkins, 2019; Risch et al., 2021; Slabbekoorn et al., 2010; Solan et al., 2016).

Aquaculture sites can be particularly noisy places, whether situated in natural waterways or onshore facilities. Sea-cage or net-pen farms in coastal waters are regularly exposed to external noise pollution from motorised vessels (Farcas et al., 2020; Hermannsen et al., 2019), and depending on the location, pile driving, seismic surveys, and naval sonar (Andrew et al., 2002; Slabbekoorn et al., 2010). Sea-cage aquaculture also generates its own noise pollution, predominantly via the fleet of vessels that service farms (Radford and Slater, 2018). In the Los Lagos region of Chile, an area of intense salmon and mussel farming, movements of the aquaculture fleet were identified as the main cause of disturbance for blue whales using the Sea of Chiloé (Bedriñana-Romano et al., 2021). In Norway, it is common for sea-cage salmonid farms to have multiple workboats on-site simultaneously, in addition to less frequent visits from large vessels used to deliver feed or transfer, harvest, or treat fish (BarentsWatch, 2023). In comparison, onshore farms are less likely to propagate noise pollution beyond the confines of the facility, as there is a greater reliance on land-based transport. However, the large pumps used to cycle water through flowthrough or recirculating aquaculture systems can transmit high sound levels into growing tanks (Bart et al., 2001; Craven et al., 2009; Radford and Slater, 2018), while additional sounds across relevant frequency spectra are generated by drum filters, aerators, on-demand oxygen injection and other equipment employed within modern aquaculture systems.

Aquaculture soundscapes have not been well-researched in terms of the composition of the soundscape or effects on the health, welfare and production of cultured animals. The few studies conducted at fish farms to date (Bart et al., 2001; Craven et al., 2009; Radford and Slater, 2018) have documented long-term sound pressure levels (SPLs) ranging from ~75–160 dB re 1 μPa within the typical hearing range of fishes

* Corresponding author.
E-mail address: frodeo@hi.no (F. Oppedal).

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(∼10–1000 Hz: Popper and Hawkins, 2019). Additional data are needed to understand how sound levels vary within and between farms sites, and whether large modern farms produce louder environments than those documented in the aforementioned studies.

Here, we characterise the frequency and amplitude of sounds present within Norwegian Atlantic salmon (*Salmo salar*) aquaculture today. The Norwegian salmon industry is in many ways the most modernised and mechanised aquaculture industry in the world, with >1.5 million t of annual production (Directorate of Fisheries, 2022) supported by large onshore smolt production facilities and routine use of vessels >80–90 m in length (BarentsWatch, 2023). We aimed to survey a wide range of sites holding Atlantic salmon (*Salmo salar*), including sea sites operating open and closed sea-cages, and onshore sites with flowthrough, hybrid and recirculating aquaculture systems. Targeted sampling efforts at sea sites also allowed us to quantify the range of sound levels within those sites, from 'baseline' ambient conditions to periods of high activity, including delousing operations using large wellboats.

2. Methods

2.1. Sampling design and deployment protocol

We sampled the soundscape at 10 different salmon farming sites in Norway, including 4 open sea-cage sites, 2 closed sea-cage sites, and 4 onshore sites (Table 1). We visited some sites on more than one occasion and/or deployed hydrophones in multiple positions to represent the range of acoustic conditions, for instance, with and without wellboats on site, or in positions closer or farther from noise sources (Table 1). Deployment durations ranged from 2 to 290 h.

The acoustic environment was sampled using SoundTrap ST300 or ST400 hydrophones (Ocean Instruments, New Zealand), which save data to device memory in wav format with a nominal accuracy of ±3 dB re 1 μPa over a frequency band from 20 to 60,000 Hz. Factory end-to-end system sensitivity values were used for calibration.

We deployed the hydrophones with a 48 kHz sampling rate and high pre-amp gain. The hydrophones were then attached to the end of a 10 mm diameter rope using large cable ties and suspended in the water from the perimeter of sea-cages or suitable over-water structures at onshore or closed containment sites. To reduce the potential for flow noise ('pseudosound') caused by turbulent water flow across the hydrophone surface, we avoided suspending the hydrophone from any structures with machinery attached, and wrapped electrical tape over the cable ties to reduce turbulence and prevent the rope from rubbing against the housing (the tape also protected fish from the cut ends of the cable ties). After positioning the hydrophone in the water, we observed the position of the hydrophone and the rope to ensure that both were hanging freely in midwater and that there was no visible cable strum (vibration). It was sometimes necessary to reposition the hydrophone to achieve this. In high density stocking environments, we were forced to position the hydrophone near the surface to reduce incidences of fish bumping the rope.

To maintain biosecurity, we used new ropes and cable ties for each deployment, and thoroughly disinfected the hydrophone housings before and after each deployment using 70 % ethanol or Virkon (Lanxess, Germany).

2.2. Acoustic data processing

Sound files were initially inspected using playback and visualization tools within Audacity software (Audacity Team, 2023), and timestamps corresponding to out-of-water periods or specific events of interest were noted. All further acoustic data processing was done using custom scripts in the Python programming language (version 3.10), including use of data handling functions from the *numpy* and *pandas* libraries (Harris et al., 2020; McKinney, 2010).

The sound files were read individually into Python as floating point data at the native sampling rate using the *librosa* module (McFee et al., 2015), which normalises the signal within the range [−1,1]. Files were trimmed at this stage if necessary to omit out-of-water periods or other events.

At one smolt facility (Gjæravågen), high stocking densities resulted in fish frequently bumping the rope or the hydrophone housing, producing a spike in amplitude that clearly exceeded the loudest acoustic signals. These bumps were removed by detecting cases where samples exceeded the highest amplitudes associated with true acoustic signals, and deleting a 0.05-s segment centred on that sample. Hydrophones or ropes were occasionally bumped at other sites, but not often enough to significantly affect the soundscape metrics used within this analysis.

Next, the signal amplitude was calibrated using the end-to-end system sensitivity value corresponding to the hydrophone serial number and gain setting:

$$y_c = y \bullet 10^{S/20}$$

where y is the uncalibrated amplitude and S is the system sensitivity).

Band-pass filters were applied to calibrated signals according to the focal bandwidth in each instance (detailed in the following subsection).

Table 1
Key characteristics of each deployment. Abbreviations: R&D = research and/or product development with commercial fish production. Hydrophones were also placed outside the cage wall at Gjermundnes and Oslandsurda, but are not included in the main analysis (see Appendix A).

Locality	Environment	Infrastructure	Dimensions	Hydrophone position	Purpose	Sampling effort
Hjartholm	Sea-cage (open)	HDPE 'polar circle' surface ring with net pen	160 m circumference, ∼32 m deep	1 m outside wall, 12 m deep	Food fish	147 h × 1 position
Indre Oppedal	Sea-cage (open)	HDPE 'polar circle' surface ring with net pen	160 m circumference, ∼32 m deep	1 m outside wall, 15 m deep	Food fish	290 h × 1 position
Tveit	Sea-cage (open)	HDPE 'polar circle' surface ring with net pen	160 m circumference, ∼32 m deep	1 m outside wall. 16 m deep	Food fish	93 h × 1 position
Smørdalen	Sea-cage (open)	Steel surface structure with plastic flotation and net pen	12 × 12 m, 12 m deep	1 m outside wall, 5 m and 15 m deep	R&D	124 h (sum of 2 positions)
Oslandsurda	Sea-cage (closed)	Aluminium surface structure with flexible tarpaulin/fabric outer pen and internal net pens (Ecomerden)	32 × 32 m structure containing four 15 × 15 m pens, ∼30 m deep	1 m inside and 1 m outside wall, 5 m and 15 m deep	Broodstock	2 h (sum of multiple positions)
Gjermundnes	Sea-cage (closed)	Egg-shaped rigid composite shell (Ovum)	15 m diameter, ∼18 m deep	2 m and 6 m inside wall, 5 m and 15 m deep	R&D	12 h (sum of multiple positions)
Matredal	Onshore	Flowthrough, glass-reinforced plastic tank, outdoor	5 m diameter, 1.2 m deep	1 m inside wall, 0.6 m deep	Broodstock	24 h × 1 position
Gjæravågen	Onshore	Flowthrough, concrete tank, indoor Flowthrough, glass-reinforced plastic tank	5 m diameter, 0.8 m deep 12 m diameter, ∼3 m deep	0.5 m inside wall, 0.3 m deep 4 m inside wall, 1 m deep	R&D Smolts	48 h × 2 positions 23 h × 2 positions
Indre Harøya	Onshore	Hybrid flowthrough, concrete tank	28 m diameter, 8 m deep	2 m and 10 m inside wall, 4 m deep	Food fish	5.5 h × 2 positions
Trovåg	Onshore	Recirculating, glass-reinforced plastic tank	15 m diameter, ∼4 m deep	4 m inside wall, 1 m deep	Smolts	22 h × 2 positions

Signals below 20 Hz or above 1000 Hz were not analysed, as the ST300/400 hydrophones have a nominal lower limit of 20 Hz, while salmon are thought to have limited hearing capacity above 500–1000 Hz, with peak sensitivity to sound pressure waves around 200 Hz (Fig. 1) (Harding et al., 2016; Hawkins and Johnstone, 1978; Knudsen et al., 1992). All band-pass filtering was done using low-pass and then high-pass Butterworth filters (5th order), applied forward and backward using the *butter* and *filtfilt* functions from the *scipy.signal* module (Virtanen et al., 2020).

The continuous root-mean-square sound pressure level (dB re 1 μPa) was calculated from calibrated and filtered signals using the formula:

$$SPL_{RMS} = 10 \bullet log_{10}\left(\frac{\Sigma {y_c}^2}{n}\right)$$

where n is the number of samples. We also calculated percentile SPLs for comparison to SPL_{RMS} using the following method:

$$SPL_{P_k} = 10 \bullet log_{10}\left({P_k}^2\right)$$

where P_k is the kth (e.g., 99th) percentile sample among all samples from the clip of interest. Where applicable, we calculated the cumulative sound exposure level (SEL) over a specified frequency band and duration as follows:

$$SEL = SPL_{RMS} + 10 \bullet log_{10}(T)$$

where T is the duration of the clip in seconds. We inspected the frequency content of the same clips using spectrogram and power spectral density (PSD) plots. Spectrograms were produced by applying consecutive fast Fourier transforms over time increments using the *spectrogram* function from *scipy.signal*. PSDs were produced using the *welch* function from *scipy.signal* with a Hanning window and 4096 samples per segment. Both plot types were then plotted using the *matplotlib* module (Hunter, 2007).

Further manipulation and plotting of aggregated data was performed using the R programming language (R Core Team, 2023), including use of the *readr*, *purrr*, *tidyr*, *dplyr*, and *ggplot2* packages from the *tidyverse* metapackage (Wickham et al., 2019).

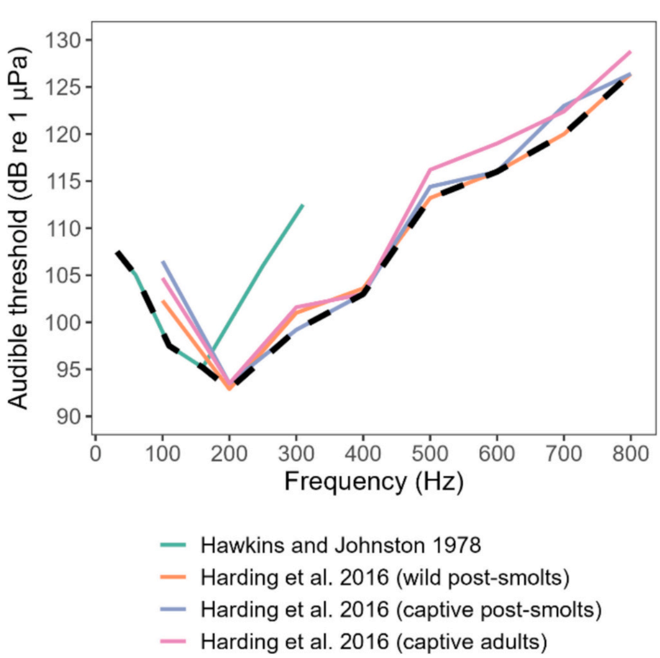

Fig. 1. Audiogram for Atlantic salmon (*Salmo salar*) based on published values. The dashed line indicates the minimum audible threshold among available data.

2.3. Focal sounds

Two main analyses were conducted. First, sound levels were characterised over full deployments spanning hours to days, by calculating the root-mean-square, median and 95th percentile SPL at 1-s intervals (zero overlap). Second, we analysed shorter clips that were representative of specific acoustic conditions, namely the baseline (most silent) ambient soundscape (60-s clips), the elevated ambient soundscape (60-s clips), and a selection of impulsive or relatively rare continuous sounds with a high intensity within the hearing range of salmon (1-s or 60-s clips as appropriate for the duration of the event). The baseline ambient conditions at each site were quantified by viewing waveform and spectrogram plots from several randomly selected *wav* files from each deployment, and noting timestamps that exemplified the most silent conditions during normal operation. In tanks or closed sea-cages, these times occurred when the main pumps were running but sources of intermittent noise (e.g., on-demand injection of oxygenated water or cleaning ROVs) were not. In open sea-cages, these were moments without any vessels on-site or passing close by, and without feeding lines or other machinery operating. At the same farms, we also noted timestamps at which common but intermittent noise sources were present, such as oxygenation or feeding lines. This is termed the 'elevated ambient' condition, although these were relatively low amplitude sounds that were primarily above the sensitive hearing range of salmon. Impulsive or other particularly intense sounds included blasting, loud noises from doors or hatches, and workboats or wellboats operating within close range of the sea-cage holding the hydrophone.

At all sites, the SPL_{RMS} was influenced by the highest sound levels, yielding SPL_{RMS} values that were substantially higher than the median SPL but lower than the 95th percentile SPL. Some authors have recommended against using SPL_{RMS} for recordings containing intermittent high amplitude events such as pile driving (Merchant et al., 2015). We opted to report SPL_{RMS} values to aid comparisons to previous work on this topic (Bart et al., 2001; Craven et al., 2009; Radford and Slater, 2018), and because the aquaculture soundscape tends to be dominated by relatively continuous sounds.

3. Results

Sound levels varied considerably between sites, over time within sites, and between environments (Fig. 2). Open sea-cage farms tended to be quieter than closed sea-cage or onshore farms on a typical day at relevant frequencies for fish hearing (Fig. 2; Table 2). However, sound levels were also more variable at the open sea-cage farms (higher kurtosis and positive skewness: Table 3), and there was a notable diurnal pattern at open sea-cage sites that was less evident at onshore sites (Fig. 2). The soundscape in all environments was characterised by continuous sound sources, meaning that the continuous SPL_{RMS} was a reasonable measure of central tendency (~3–4 dB re 1 μPa higher than the median SPL: Fig. 3).

At the open sea-cage farms sampled, mean 1-s SPL_{RMS} values ranged from 91 to 105 dB re 1 μPa within audible frequency bands for Atlantic salmon (20–100, 100–500, and 500–1000 Hz: Table 2). These mean SPL_{RMS} values correspond to cumulative 60-min sound exposure levels (SELs) of 127–141 dB re 1 $\mu Pa^2 s$ over the same frequency bands (Table 2). Sound levels at sea-cages were often highest at low frequencies, usually within the 20–100 Hz band (Table 2; Figs. 2–4). SPL_{RMS} values below ~90 dB re 1 μPa within the same frequency bands occurred on occasions when there were no vessels nearby, with the lowest SPL_{RMS} tending to occur during the night and into early morning (Fig. 3; Fig. 5A). The proximity of vessels to the hydrophone had a dramatic effect on measured sound levels, with the highest levels recorded when workboats or wellboats were alongside the sea-cage containing the hydrophone. These occasional loud events contributed to higher kurtosis and a positively skewed distribution of SPL values from open sea-cage deployments (Table 3). Cage-side visits by

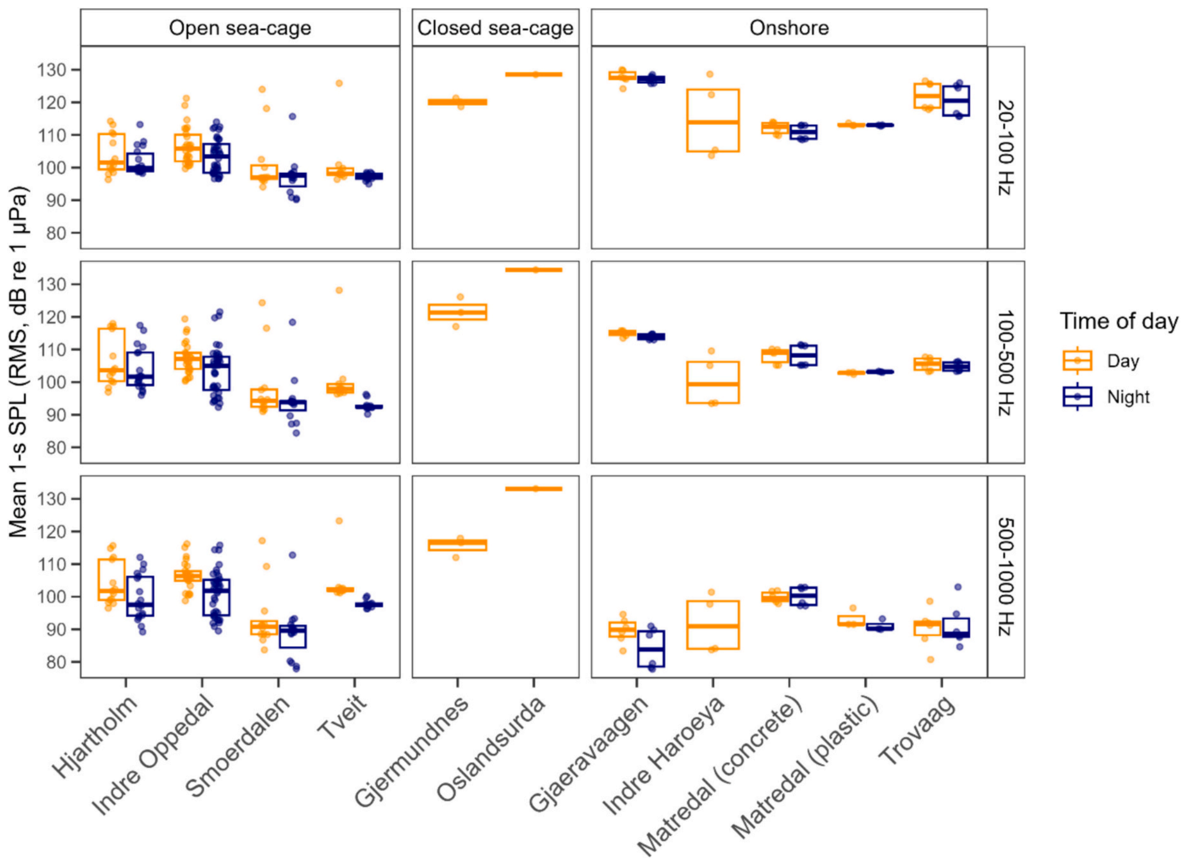

Fig. 2. Continuous root-mean-square sound pressure level (SPL) over 20–100, 100–500 and 500–1000 Hz frequency bands during hydrophone deployments at 10 commercial salmon farming sites. Each point represents the arithmetic mean of numerous 1-s SPL values within 1-h time-of-day bins (colour-coded by day/night, where day is 06:00–18:00). Boxes indicate the 25th, median, and 75th percentile levels among the mean SPLs.

workboats generally occurred during daylight hours unless delousing was in progress, in which case the wellboat and associated machinery were run around the clock, producing SPL_{RMS} values between ~130–140 dB re 1 μPa at the hydrophone for minutes to hours (Fig. 2; Fig. 6; Fig. 5B). The acoustic signature of delousing operations is dominated by constant-frequency signals (presumably produced by engines, pumps and compressors running at constant speed), overlaid by broadband signals that we believe result from reverberations through the structure of the vessel. The highest sustained sound levels (seconds to minutes) at relevant frequencies were associated with propellor/impeller cavitation while the vessels were manoeuvring alongside the cage (Fig. 5C), generating 1-s SPL_{RMS} values of up to 157 dB re 1 μPa at the hydrophone (Table 2). It is likely that the salmon will be exposed to similar sound levels during cage-side visits, especially while being crowded alongside the vessel. We did not measure sound levels experienced by fish while being treated or moved on or off the wellboats.

The 2 closed containment sites were the loudest sites overall (Fig. 2; Fig. 3). The tarpaulin pens at Oslandsurda had 1-s SPL_{RMS} values ranging from 113 to 143 dB re 1 μPa over 20–100, 100–500, and 500–1000 Hz (Table 2; Fig. 2). The SPL_{RMS} was relatively constant over time at a given hydrophone position, but varied with proximity to the main pumps (5–15 m). The mean SPL_{RMS} over the deployment produced a cumulative 60-min SEL of 165–169 dB re 1 $\mu Pa^2 s$ within relevant frequency ranges (Table 2). We only measured sound for a total of 90 min at this site, but the sound produced by the system is not believed to vary greatly through the day, as the soundscape is dominated by pumps that operate at a constant speed, rather than outside vessel traffic. At Gjermundnes, we measured sound levels within a prototype rigid composite pen termed the 'Ovum'. A range of conditions were encountered during the half-day sampling visit, namely the sound of the main pumps with and without the additional sounds of a workboat idling outside, a wall-cleaning ROV, oxygen injection, mort collection, and a large underwater hatch opening and closing. Baseline ambient sound levels within the structure (i.e., essential continuous pumping only) produced 1-s SPL_{RMS} values as low as 99–108 dB re 1 μPa over the 20–100, 100–500, and 500–1000 Hz bands (Table 2). The addition of intermittent sounds from oxygen injection, a cleaning ROV and dead fish lift-up pump elevated the ambient SPL_{RMS} to ~120–138 dB re 1 μPa over the same frequency bands, depending on the precise position of the hydrophone relative to noise sources. The elevated ambient soundscape peaked within the 100–500 Hz band with a 95th percentile 1-s SPL_{RMS} value over the deployment of 132 dB re 1 μPa. Notably, the sound pulses generated by closing the hatch momentarily exceeded the dynamic range of the hydrophone at ~2 m distance (>173 dB re 1 μPa), although in the middle of the enclosure, ~6 m from the hatch, the maximum continuous SPL (SPL_{Max}) was reduced to ~165 dB re 1 μPa over the dominant frequency band of 100–500 Hz. We observed the behaviour of the fish while the hatch was closed 3 times in succession. A subgroup of 5–10 fish swimming near the hatch startled each time it was closed, but did not leave the vicinity of the hatch.

The typical soundscape at onshore farms was louder on average than the open sea-cage sites, but quieter than the closed sea-cage sites visited, with mean 1-s SPL_{RMS} values ranging from 87 to 127 dB re 1 μPa over 20–100, 100–500, and 500–1000 Hz (Table 2). The onshore soundscape was also more predictable (less variable) than at open sea-cage sites, particularly over a timescale of minutes, hours or days, indicated by lower kurtosis (tailedness) of the frequency distribution of 1-s SPL_{RMS} values from onshore sites than open sea-cage sites (Table 3), as well as the more pronounced diurnal pattern in SPL within open sea-cages (Fig. 2). Peak energy generally occurred within the 20–100 Hz

Table 2
Range of 1-s continuous sound pressure levels (SPL, dB re 1 μPa) recorded at each of the 10 sites sampled. Values are reported for the mean and range of 1-s root-mean-square SPL (SPL_{RMS}, dB re 1 μPa), representing the average, quietest and loudest periods lasting at least 1 s. The cumulative 60-min sound exposure level (SEL, dB re 1 $\mu Pa^2 s$) is also calculated based on the mean 1-s SPL_{RMS}.

Environment	Site	Band (Hz)	Mean 1-s SPL_{RMS}	Range 1-s SPL_{RMS}	60-min SEL
Open sea-cage	Hjartholm*	20–100	104	89–157	140
		100–500	105	81–143	141
		500–1000	102	76–140	138
	Indre Oppedal*	20–100	105	90–147	141
		100–500	105	82–148	141
		500–1000	103	76–143	139
	Smørdalen*	20–100	99	83–142	135
		100–500	97	78–145	133
		500–1000	91	72–138	127
	Tveit	20–100	98	90–147	134
		100–500	95	86–138	131
		500–1000	100	92–134	136
Closed sea-cage	Gjermundnes*	20–100	120	108–149	156
		100–500	123	111–154	159
		500–1000	116	99–149	152
	Oslandsurda*	20–100	129	113–139	165
		100–500	134	123–143	170
		500–1000	133	121–140	169
Onshore	Gjæravågen*	20–100	127	121–133	163
		100–500	114	108–128	150
		500–1000	87	70–116	123
	Indre Harøya*	20–100	122	92–135	158
		100–500	105	77–123	141
		500–1000	97	68–120	133
	Matredal (concrete)	20–100	112	104–129	129
		100–500	108	100–126	126
		500–1000	100	88–118	118
	Matredal (plastic)	20–100	113	109–131	131
		100–500	103	96–121	121
		500–1000	92	80–121	109
	Trovåg*	20–100	121	110–135	157
		100–500	105	94–121	141
		500–1000	91	70–125	127

* Range spans multiple deployments or positions within the site.

frequency band at all 4 onshore sites (Table 2; Fig. 4), despite a variety of infrastructure in use across the sites (e.g., flowthrough and RAS systems, indoor and outdoor, plastic and concrete tanks of varying sizes). At Matredal, we compared two tank constructions of similar size (plastic tanks holding broodstock outdoors, vs. concrete tanks holding smolts indoors). The resulting soundscapes were similar, with a low frequency peak in each, although the 500–1000 Hz band was higher in the concrete than the plastic tanks (mean 100 and 92 dB re 1 μPa, respectively: Table 2). The low frequency peak was more pronounced at onshore sites than at open or closed sea-cage sites (Fig. 4; Fig. 5D). In additional to typical operating sounds, the recirculating smolt facility at Trovåg experienced a single blast from a neighbouring construction site during our hydrophone deployment. This signal was omitted from the main analysis and is not represented in Table 2, but the sound level emanating from the blast briefly exceeded the dynamic range of both hydrophones (~173 dB dB re 1 μPa). The blasts had been occurring infrequently for several months, and farm personnel reported severe startle responses leading to a spike in oxygen demand within the RAS facility following each blast, but no evidence of severe acoustic injuries.

Appendix A presents broadband sound pressure levels over 20–5000 Hz from hydrophone deployments immediately outside open and closed sea-cages at Hjartholm, Indre Oppedal, Tveit, Gjermundnes and Oslandsurda (i.e., positions and frequencies relevant to farm-associated wild fishes).

Table 3
Variability of aquaculture soundscapes quantified by skewness and kurtosis of root-mean-square sound pressure levels (SPL_{RMS}) within 3 frequency bands audible to Atlantic salmon. Skewness and kurtosis were originally calculated for each farm site based on all 1-s SPL_{RMS} values from that site. The values reported here are the grand mean (± SD) of those site-specific values.

Environment	Band (Hz)	Skewness	Kurtosis
Open sea-cage	20–100	1.8 ± 1.3	9.2 ± 9.6
	100–500	1.3 ± 1.1	6.1 ± 4.7
	500–1000	1.1 ± 1.1	6.4 ± 5.9
Closed sea-cage	20–100	−0.4 ± 0.4	3.5 ± 3.3
	100–500	0.1 ± 0.5	2.1 ± 1.3
	500–1000	0 ± 0.1	2.3 ± 1.7
Onshore	20–100	−0.3 ± 0.8	3.1 ± 1.2
	100–500	0 ± 1.2	4.3 ± 1.6
	500–1000	−0.2 ± 1	3.1 ± 1.2

4. Discussion

This study focused on the most common types of salmon farming facilities in use today, from flowthrough and recirculating onshore sites with tanks holding broodstock, parr or smolts, to grow-out sites holding production fish in open sea-cages. We also documented the soundscape produced by more developmental or futuristic farming systems that may become more common as farming companies seek to limit environmental interactions within coastal seas, namely a very large flowthrough system with concrete tanks used to grow production fish to harvest size (Indre Harøya), and two semi-closed containment sea-cage systems with differing construction methods (tarpaulin net-pen at Oslandsurda and a rigid composite structure at Gjermundnes). Together, this study provides the most comprehensive overview of sound levels within salmonid aquaculture today.

Measured underwater sound levels varied considerably, both between and within farms, ranging from ambient broadband sound levels that are close to typical levels in the marine environment and are likely barely audible to salmon (SPL_{RMS} < 100 dB re 1 μPa over 20–1000 Hz, cf. salmon audiogram: Fig. 1), to continuous and impulsive sounds that

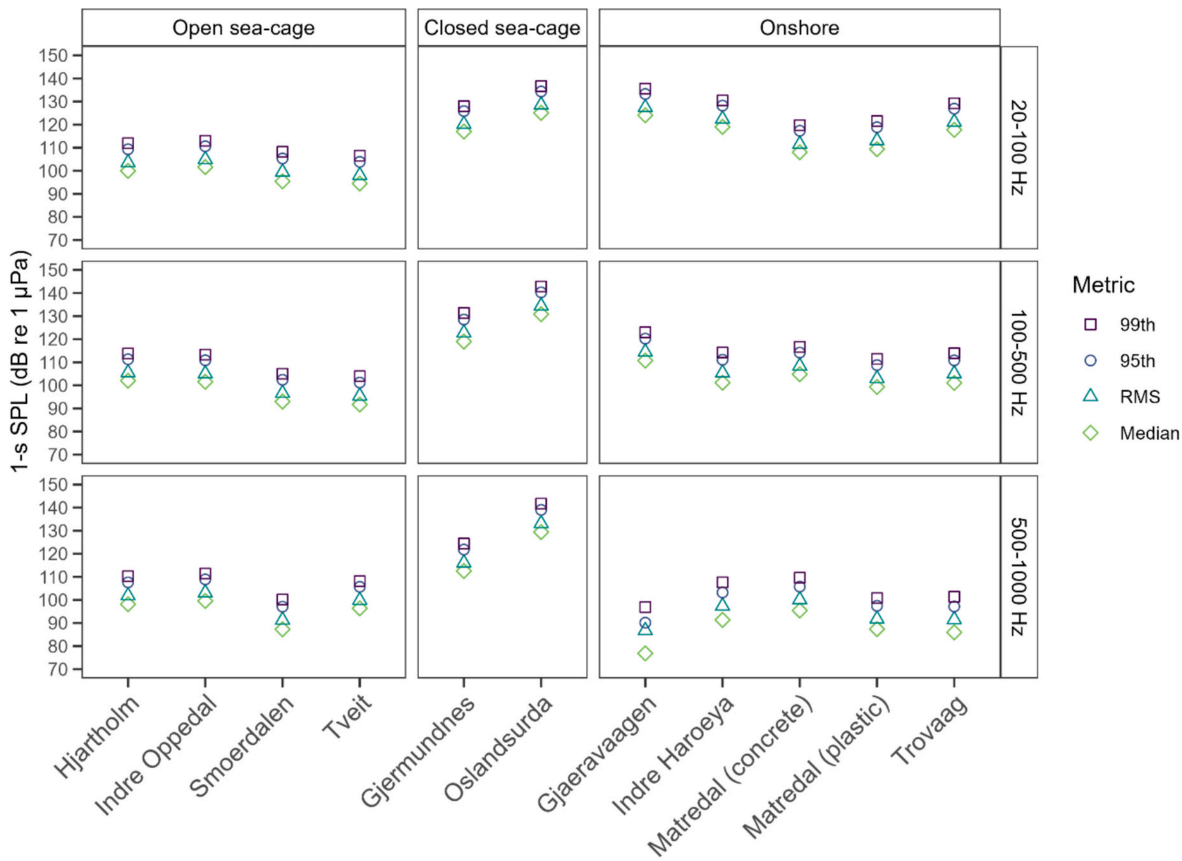

Fig. 3. Comparison of sound pressure levels (SPLs) at 10 salmon aquaculture sites in Norway based on either root-mean-square (RMS) or percentile metrics (median, 95th, and 99th percentiles). Each point depicts the arithmetic mean of all 1-s SPL values corresponding to each site.

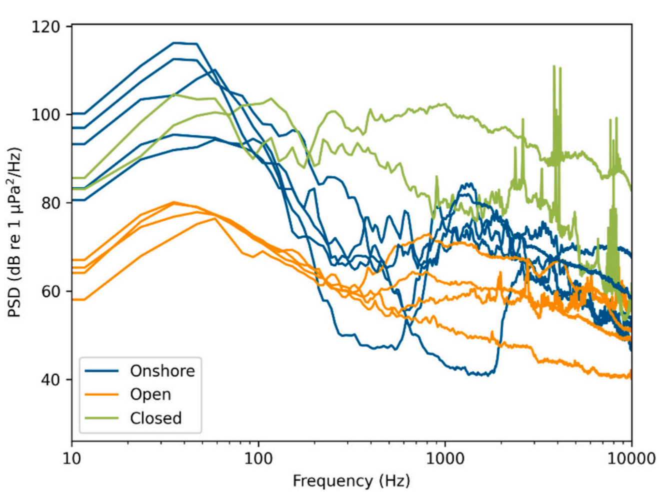

Fig. 4. Power spectral densities (PSDs) of 60-s audio clips representing baseline sound levels (i.e. most silent typical ambient conditions) at 4 onshore, 4 open sea-cage, and 2 closed sea-cage salmon farms in Norway. Clips were high-pass filtered with a 20-Hz cutoff to de-emphasise signals outside the optimal frequency response of the hydrophone. The PSD calculations used a Hanning window with 4096 samples per segment, 50 % segment overlap, and a fast Fourier transform length of 4096 samples.

are much louder than a typical marine soundscape (Table 2). In general, the soundscape reflected the infrastructure and equipment in use at commercial sites, such as constant noise from large pumps and filters used in onshore and closed containment systems, and variable noise from vessels that visit open sea-cages. Accordingly, the open sea-cage farms had lower minimum and mean sound levels than onshore or closed containment farms, but generally had higher maximum levels than onshore farms due to vessel visits (Table 2; Fig. 2). This was most evident when comparing sound levels at sea-cages during the day and night (Fig. 2; Fig. 5A), and with and without wellboats present (e.g., Hjartholm: Fig. 4 cf. Fig. 6). At Hjartholm, the quietest periods (minimum 81 dB re 1 μPa over 100–500 Hz: Table 2) were likely below the hearing threshold of salmon, while vessel activity (maximum 143 dB re 1 μPa over 100–500 Hz: Table 2) elevated the sound level far above the hearing threshold (Fig. 1), although not to a level that is expected to cause hearing loss or other injuries (Popper and Hawkins, 2019). Frequencies below 500 Hz appear to be most relevant, as only the two closed containment sites had mean sound levels within the 500–1000 Hz band that are expected to be audible to salmon (Table 2 cf. Fig. 1), while the 500–1000 Hz band was also the least affected by noisy events (Table 2).

External sound sources appear to be a factor at open sea-cage facilities, where baseline sound levels may be more dependent on exposure to non-aquaculture vessel traffic or natural sound sources than on any sound sources related to the farm. For example, the baseline SPL at Smørdalen was 7–9 dB lower over 20–1000 Hz than at the other open sea-cage sites sampled (Fig. 2), likely because Smørdalen is located within a sheltered inner fjord (Masfjorden), while the remaining three sites (Hjartholm, Indre Oppedal, Tveit) are situated in more exposed positions in Sognefjord, a very large fjord with frequent large vessel traffic (https://nais.kystverket.no/).

4.1. *Comparison to previous studies of fish farming soundscapes*

The sound levels documented within this study are broadly comparable to those documented by the few previous studies of fish farming

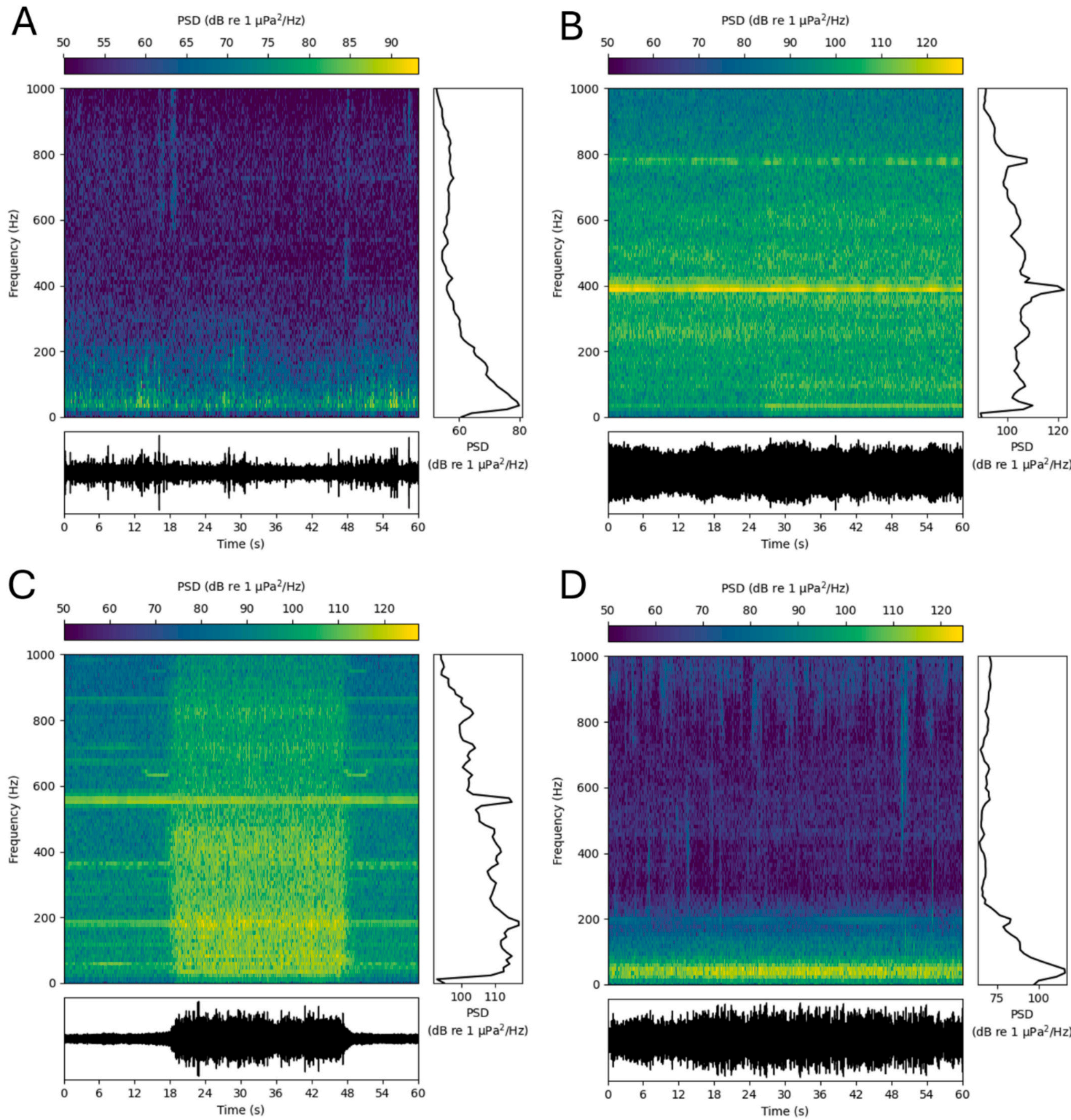

Fig. 5. Spectrograms (main panels), power spectral density (PSD, right panels) and waveform (lower panels) of farm soundscapes. Signal were bandpass filtered to 20–1000 Hz to de-emphasise sounds below optimal frequency response range of the hydrophone or above the nominal hearing range of salmon (Butterworth filter applied forward and backward). (A) Ambient (baseline) conditions at Hjartholm, with a root-mean-square sound pressure level (SPL_{RMS}) of 97 dB re 1 μPa over 20–1000 Hz, and a 60-min cumulative sound exposure level (SEL) of 133 dB re 1 $\mu Pa^2 s$. (B) Hjartholm during a visit by the wellboat Ronja Måløy with thermal delousing equipment. The soundscape is dominated by constant-frequency signals generated by various motors, pumps and compressors on board the vessel. SPL_{RMS} = 138 dB re 1 μPa over 20–1000 Hz, 60-min SEL = 174 dB re 1 $\mu Pa^2 s$. (C) Smørdalen during a visit by the wellboat Ronja Strand. The wellboat's drivetrain was engaged between 18 and 48 s, in addition to the constant frequency signals produced by the various motors, pumps and compressors on board the vessel. SPL_{RMS} = 139 dB re 1 μPa over 20–1000 Hz, 60-min SEL = 175 dB re 1 $\mu Pa^2 s$. (D) Typical daytime soundscape at Indre Harøya (Salmon Evolution), highlighting the peak power at low frequencies. SPL_{RMS} = 131 dB re 1 μPa over 20–1000 Hz, 60-min SEL = 167 dB re 1 $\mu Pa^2 s$.

systems. Early work by Bart et al. (2001) characterised the soundscape within recirculating aquaculture systems (RAS) and earthen ponds holding striped bass, tilapia and Atlantic salmon, and reported SPLs of up to 140–160 dB re 1 μPa, with primary peaks between 25 and 250 and 630–2000 Hz. Similarly, Craven et al. (2009) recorded a maximum SPL of 124 dB re 1 μPa within a recirculating aquaculture system (RAS) holding broodstock, with the soundscape dominated by a 187.5 Hz frequency component linked to the main pump at the facility. Later, in

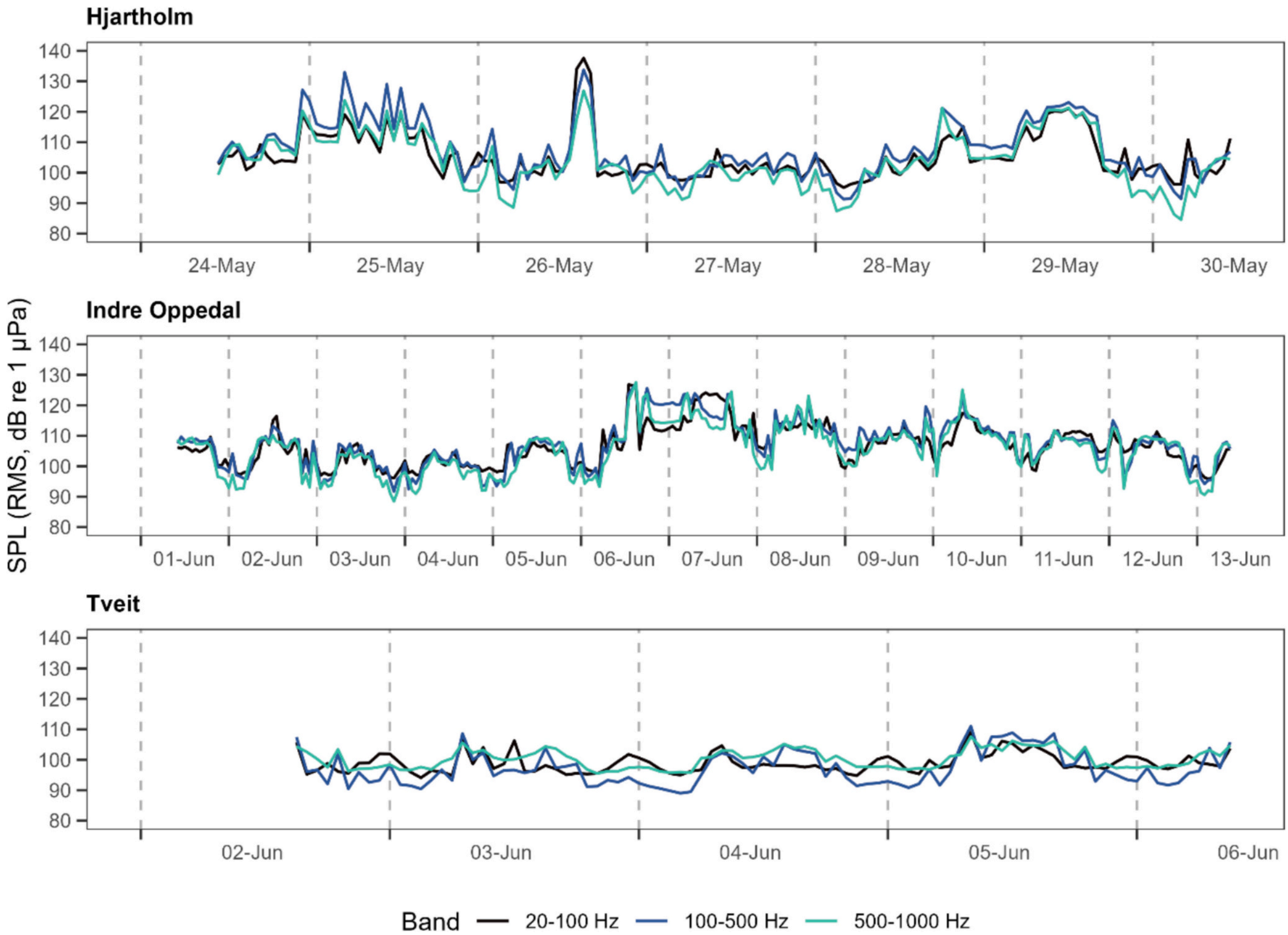

Fig. 6. Temporal patterns in the root-mean-square sound pressure level (SPL_{RMS}) at 3 sea-cage salmon farms in Sognefjord, Norway. Sound levels were calculated at hourly intervals over 3 frequency bands. Delousing wellboats visited Hjartholm (24–26 May and 28–29 May) and Indre Oppedal (6–12 June). Tveit was only visited by workboats conducting routine activities.

the most comprehensive study to date and the only one involving sea-cages, Radford and Slater (2018) surveyed sound levels at a sea-cage salmonid farm in New Zealand, an onshore RAS facility in Germany, and a pond-based aquaculture farm in Indonesia. Overall, they found that low frequency sounds (<500 Hz) were dominant within the systems sampled. The sea-cage farm had sound levels ranging from 107 to 112 dB re 1 μPa SPL, which was elevated in comparison to nearby control sites (98–107 dB re 1 μPa). The additional sound at farms was primarily attributed to vessels visiting or passing near the farm, and was most evident at frequencies below 1000 Hz. Sound levels in the RAS facility were lower, ranging from 96 to 103 dB re 1 μPa depending on the position and construction of the tank. Earthen ponds in Indonesia were quieter still, at 75 dB re 1 μPa (Radford and Slater, 2018). Taken together, SPL values within our study generally fell within the known range for aquaculture, although we have added detail regarding the variability of sound levels, particularly relating to new farming systems, procedures, diurnal patterns and rare acute events.

4.2. Potential effects of sound on farmed salmonids

Salmonids appear to be relatively resilient to the range of sound levels observed in the present study. For instance, Solé et al. (2021) found no effects on the sensory epithelia or other internal organs after repeatedly exposing Atlantic salmon to 350 and 500 Hz for 2–4 h (SPL: ~152–155 dB re 1 μPa; SEL: 195 dB re 1 $\mu Pa^2 s$, 2 h). Other studies have found that hearing sensitivity, feeding, growth and survival did not differ between groups of rainbow trout reared at different ambient sound levels, including 8 months at 115, 130 or 150 dB re 1 μPa RMS (Wysocki et al., 2007), 5 months at 117 or 149 dB re 1 μPa RMS (Davidson et al., 2009), and 8 weeks at 127 dB re 1 μPa (Slater et al., 2020). These studies concluded that typical sound levels in commercial aquaculture were unlikely to be a limiting factor for salmonid production (but see Terhune et al., 1990). However, all tested for effects of elevated sound levels compared to a baseline of ≥115 dB re 1 μPa SPL, which is higher than the ambient sound level in many busy coastal waterways (Andrew et al., 2002; Bardyshev, 2007; Dinh et al., 2018; Halliday et al., 2021; Merchant et al., 2016). Accordingly, we cannot discount a negative effect of sound that applies equally across the range of typical sound levels in salmonid aquaculture. Alternatively, it may be the case that salmonids acclimate quickly to a predictable soundscape. Rainbow trout exhibited a behavioural stress response when exposed to a 149 dB re 1 μPa treatment, but acclimated relatively quickly to the predictable soundscape and resumed normal behaviour (Davidson et al., 2009). It may be more difficult to acclimate to intermittent or unpredictable sounds: Bui et al. (2013) exposed salmon to intermittent sounds from a fish scaring device and surface slaps, which caused the salmon to dive to the bottom of the cage and not resume normal behaviour until after the sound exposure protocol had ceased. Tank-reared salmon showed some evidence of behavioural acclimation following regular exposures to a fish-scaring device over 42 days (136–146 dB re 1 μPa), although neurobiological traits indicated that chronic stress continued (Oppedal et al., 2024). More work is needed to understand the significance of constant/predictable and sudden/unpredictable sounds within aquaculture settings. Doing so will also require an improved understanding of the sensitivity of salmonids to pressure waves and particle motion, and especially farmed salmonids, which are believed to have higher incidences of vateritic otoliths and other deformities that could affect hearing sensitivity (Reimer et al., 2017; Reimer et al., 2016).

Some sounds in aquaculture may also cause temporary hearing loss or other injuries in fishes (de Jong et al., 2020; Popper and Hawkins, 2019). In the literature, temporary hearing loss has been reported followed multiple exposures to pulses >185 dB re 1 μPa, or else more moderate sounds that persist long enough to produce cumulative SELs upwards of 186 dB re 1 μPa^{2}s (Popper and Hawkins, 2019; Smith and Monroe, 2016). More severe injuries have also been observed following acute and continuous sounds, e.g., SEL ≥177 dB re 1 μPa^{2}s (Halvorsen et al., 2012), peak SPL >207 dB re 1 μPa or cumulative SELs >203 dB re 1 μPa^{2}s (Popper and Hawkins, 2019; Smith and Monroe, 2016). In general, we did not find sound levels approaching these thresholds, except the blast at the smolt facility at Trovåg and the sea hatch closing at Gjermundnes.

There are likely many such examples throughout the fish farming industry of noise sources that can be partly mitigated once identified. However, because sound does not efficiently propagate between air and water, and because the audible range of humans (~20–20,000 Hz, peak sensitivity ~2000–5000 Hz: Masterton et al., 1969) is higher than that of fishes, fish may be stressed or injured by underwater sounds that are inoffensive to farm personnel. Likewise, high frequency sounds that are irritating to humans may be largely imperceptible to fish. Access to hydrophones and basic spectral analysis tools will assist farmers to isolate signals within the relevant frequency band and potentially mitigate the most important noise sources.

4.3. Limitations and future research directions

Salmonids primarily sense sound in the form of particle motion, which was not measured in this study. Instead, we focused on SPL metrics, which are correlated with particle motion, albeit imperfectly or even poorly under certain conditions (Nedelec et al., 2016). Our main rationale was to prioritise coverage of a wide range of farming systems and environments, which required a compact and robust device. Available particle motion measuring devices are currently neither (Nedelec et al., 2021). Moreover, the hearing thresholds of salmonids have not been well established in terms of particle motion (acceleration) units, limiting the short-term applications of any particle motion data gathered.

While we sampled acoustic data from a range of salmon farming systems in this study, we were not able to sample sound levels within any highly exposed or offshore sea-cages, nor within any submerged sea-cages (Warren-Myers et al., 2022) or sea-cages fitted with snorkels (Geitung et al., 2019). Relatively exposed sites are likely to be louder within the frequency range affected by wave action, especially when waves hit the sea-cage structure. This is illustrated by the difference in baseline sound levels at Smørdalen relative to more exposed sea-cage sites, although the sound levels generated by wind waves are expected to be much lower than the sound of vessels working alongside a sea-cage (Deane, 1997). Measurements during high flow conditions will also need to be made with care, as water flow around the hydrophone creates pressure gradients that act directly on the sensor and generate flow noise or 'pseudosound' that can appear much louder than true acoustic signals (Bardyshev, 2007). Holding fish at greater depths is likely to reduce their exposure to sounds emanating from vessels and other surface sounds, simply because deeper cages will increase the distance between the fish and the sound source.

Finally, we have not investigated the effects of aquaculture noise on nearby ecological communities. Aquaculture-related vessel traffic may be the primary concern (e.g., Bedriñana-Romano et al., 2021), including daily workboat activity at sea-cage farms and infrequent visits from wellboats at sea-cage farms and onshore facilities, while construction of aquaculture infrastructure may also involve blasting or pile driving in or near the water. The extent and impact of aquaculture noise beyond the farm footprint remains a significant knowledge gap, but in some coastal/fjordal areas away from shipping or ferry routes, aquaculture-related activities may be the predominant source of anthropogenic noise.

5. Conclusions

Overall, soundscapes at salmon farms were dominated by relatively low frequency sounds that fall within the audible range of salmonids and other fishes. This was especially true within onshore farming or closed sea-cage systems, as noise generated by pumps and other machinery propagates into the rearing environment. Sound levels at sea-cage salmon farms were more variable, with the loudest periods related to the activity of workboats and wellboats on site. However, with rare exceptions, typical sound levels in salmon aquaculture are unlikely to cause significant hearing loss or acoustic injury to farmed fish. Potential for short-term and/or chronic stress in response to sound exposure warrants further investigation, with special consideration of the roles of predictable and unpredictable sounds.

CRediT authorship contribution statement

Luke T. Barrett: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Frode Oppedal:** Writing – review & editing, Resources, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.aquaculture.2025.742334.

Data availability

The data that has been used is confidential.

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