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Short communication

Acoustic environment of aquaculture net-pens varies with feeding status of Atlantic salmon (*Salmo salar*)

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ABSTRACT

Continuous data on the condition of fish is necessary to monitor, control and document biological processes in fish farms in real-time, yet acquiring it from a large net-pen environment is challenging. Tools to rapidly detect change in the entire net-pen population are lacking. Automated passive acoustic monitoring is emerging as an effective monitoring tool in wildlife monitoring but has not before been tested in an aquaculture setting. Here, we explore the possibilities for passive acoustic monitoring in an aquaculture perspective. We investigated whether the soundscape of a net-pen could infer information on the condition of the whole net-pen population. In three cases, conducted at two different fish farms, we tested whether Atlantic salmon (*Salmo salar*) influence the soundscape of the net-pen. We provide evidence that Atlantic salmon alter the acoustic environment when compared to an empty net-pen. We observe from a 24-h recording that the acoustic fingerprint of the net-pen varies over time and mirrors the feeding status of the fish. Our results demonstrate the potential for passive acoustic monitoring in fish farms and provide a new direction for data-driven management in aquaculture to improve fish welfare and operational feeding routines.

1. Introduction

As fish farming is becoming increasingly industrialised, the industry is looking towards applications of emerging digital technologies and automated systems. Continuous data on the condition of the fish is necessary to optimise existing and new operational procedures or management regimes and ensure knowledge-based production (Fore et al., 2018). To achieve this, increased application of emerging technologies and automated systems is needed.

Real-time surveillance, already identified by the aquaculture industry as a key aim (e.g. MOWI (2018)), offers a large step forward in achieving knowledge-based production. Several approaches have been identified and tested including visual methods, individual based biologgers, and telemetry methods (Brijs et al., 2018; Fore et al., 2018). However, observing sounds by monitoring the soundscape of a net pen has not yet been considered. Observing sounds made by animals offers potential for monitoring large groups of animals non-invasively (Rushton et al., 2012). Fish make a varied range of sounds (e.g. Ladich (2014), Kasumyan (2008)) and a recent study confirmed sound production in salmonid species (Rountree et al., 2018). Rountree et al. (2018) demonstrate species specific sounds in four salmonid species, each species emitting several different sounds.

Two types of sounds can be made by fishes; active and involuntary. Active sounds can be considered as those made for communication for example during agonistic interactions, courtship, spawning, feeding, schooling and in distress situations (Amorim and Hawkins, 2000; Amorim et al., 2004; Hawkins and Amorim, 2000; Tricas and Boyle, 2014), while involuntary sounds are those that arise during other activities. Involuntary sounds include hydrodynamic, pneumatic and respiratory sounds, as well as stridulation (rubbing or rasping) and cavitation sounds, which are generated during feeding (Kasumyan, 2008). All fishes, without exception, produce involuntary sounds (Kasumyan, 2008). The focus of passive acoustic studies has until now mainly been on marine species for fisheries management (Bolgan et al., 2018; Hawkins and Amorim, 2000; Zhang et al., 2015), and soniferous species known to have a large repertoire of acoustic communication (Amorim et al., 2016), with potential use for aquaculture remaining unexplored.

Sounds from individual fish contribute to the soundscape (Rountree et al., 2018), the entire acoustic environment of the net-pen, originating

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from biological, geophysical and anthropogenic sources (Farina, 2019). Passive acoustic monitoring can be conducted during poor visibility or darkness, and of high densities of fish in real-time. Monitoring the soundscape of an aquaculture net-pen represents a potentially untapped resource for monitoring fish's status, as regards hunger or stress. Non-invasive passive monitoring of a fish's status, direct from the fish itself, has large scope for both improving welfare and effectivity of feeding.

We hypothesise that by monitoring the soundscape of a net pen, it is possible to identify population level signals as changes in the soundscape. Net-pens, and fish farms in general, are relatively noisy environments. Boat activity, human activity on and around net-pen structures, food transiting through feeding pipelines and the sound of the surrounding marine environment all contribute to the soundscape of a net-pen, in addition to the fish inhabiting that net-pen. We investigate whether changes in the acoustic environment of a net-pen reflect variation in the status of salmon in the net-pen. To decouple salmon-produced sounds from all other components of the soundscape we address three successive research questions which build towards answering the hypothesis: (1) Does the acoustic environment of a net-pen with salmon differ from that of an empty net-pen, (2) Does the acoustic environment of a net-pen represent sound of surface, or underwater origin, and (3) Does the acoustic environment of a net-pen vary with feeding status of the salmon?

2. Material and methods

2.1. Hydrophone deployment

Audio recordings were made at fish farms in two locations. This data was used to tackle our three research questions, addressed as three separate cases – denoted Case 1, Case 2, and Case 3. Case 1 compared recordings from net pens with and without salmon, Case 2 compared peak frequencies at different depths and Case 3 compared soundscape features during and post feeding. Case 1 recordings were made at Korsneset located in Korsnesfjorden at Halsa, Norway, between 11th and 12th November 2020. The net-pen contained approximately 200,000 salmon between 1.8 and 2.2 kg. Case 2 and Case 3 recordings were made at Tennøya, South-West of Frøya, Norway, between 1st and 2nd September 2020. The net-pen contained approximately 180,000 salmon between 4.5 and 5.5 kg. Both facilities had cylindrical net-pens with a 157 m circumference. The net consisted of vertical cylindric wall 15 m deep and a conical bottom of additional 7 m depth. The net-pens were anchored in a frame mooring.

Ocean Sonics icListen RB9-ETH/SB2-ETH omnidirectional hydrophones were used for audio recordings. The hydrophones were set to record continuously with a sampling frequency of 32 kS/s for Case 1 and 64kS/s for Case 2 and Case 3. A new file was created every 10 min.

Case 1 involved the simultaneous deployment of two hydrophones for 24 h. One was deployed at 6 m depth in a net pen with Atlantic salmon. The other was deployed in a similar manner in an identical net pen without fish, 120 m away from the first, to record ambient noise in an empty net pen. The hydrophones for Case 1 were moored as shown in Fig. 1, but with only a single hydrophone mounted in position H_4. The buoy was secured with ropes in two places at the net-pen floating collar. The ropes were placed so that the buoy floated 3 m inside the net pen. The ropes were loosely secured to avoid transmission of sound from the vibrations of the cage structure to audio recordings. The hydrophones were mounted horizontally facing inwards towards the centre of each net-pen.

Cases 2 and 3 use data from the deployment of a hydrophone array containing four hydrophones (Fig. 1) for 22 h. The array was deployed such that the hydrophones were deployed at depths of 3, 4, 5 and 6 m. These depths were selected to investigate the amount of surface noise propagated to different depths. Hydrophones were mounted in fixed horizontal position in a rigid rig. All hydrophones were oriented in the same direction, facing inwards towards the centre of the cage. The four hydrophones were connected to a power supply and a launch box. The launch box synchronised the hydrophones in time (<1 ms). The rig was positioned in the net pen in the same manner as in Case 1, 3 m from the net pen floating collar, from 1200 h CET on September 1, 2020, to 1000 h CET on September 2, 2020. The rig was then moved to 20 m outside the net-pen, pointing away from the net-pen, to record ambient noise in the local environment from 1000- to 1600- h CET.

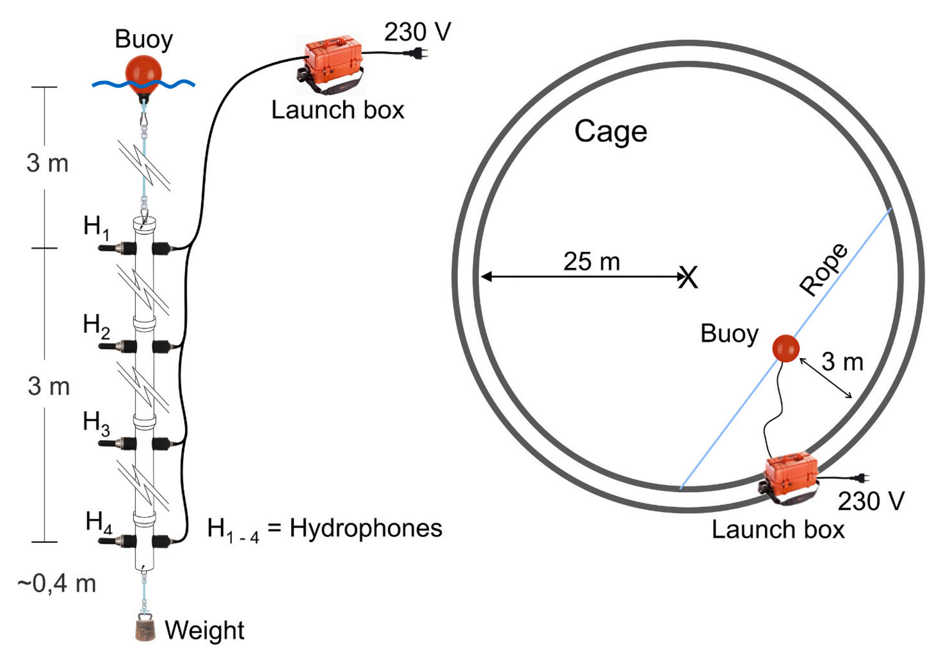

Fig. 1. Hydrophone array configuration and rig placement in the fish cage in Case 2 and Case 3. Case 1 used the same rig, but with only a single hydrophone placed in position H_4. The rig was then placed in the net-pen in the same way as for Cases 2 and 3. The circumference of the fish cages was 157 m (radius of 25 m). The net consisted of vertical cylindric wall and a conical bottom.

2.2. Data analysis

Case 1 addressed the research question of whether the acoustic environment of a net-pen with salmon differs from that of an empty net-pen. Here, representative data from one hour of the recording period, between 1400- and 1500-h CET was used for analysis. Statistical treatment and additional analysis for the entire 22-h period is presented in the supplementary material. Feed was being spread during this hour and fish were actively feeding. Case 2 addressed the research question of whether the acoustic environment of a net-pen represents sound of surface, or underwater origin. Here, representative data from one hour of the recording period 20 m outside the net-pen on September 2, 2020 between 1400 and 1500 h CET was analysed. Statistical treatment for this data and a comparison with a multi-depth recording *inside* a net pen is presented in the supplementary material. For both Case 1 and Case 2, data was subsampled from the full data set of approximately 24 h and 6 h respectively. Since the research questions being addressed were time-independent, representative subsampling was conducted because soundscape features, such as sound intensity and dominant frequency, varied over time (see Fig. 4). Subsampling enabled reduction in the temporal variation in the dataset, enabling underlying patterns to be shown regardless of variation in fish behaviour or operations at the fish farm.

In Case 3 the post-processed spectrogram was assessed over a longer period, from 1200 h CET on September 1, 2020, to 1000 h CET on September 2, 2020 in order to investigate temporal variation. Feeding was ongoing at the time the recording started and stopped at 1700 h CET on September 1, 2020. There was no feeding on September 2, 2020. Peak frequency during a single hour with feeding, 1400–1500 h CET, was then compared in more detail to a single hour without feeding, 1700–1800 h CET.

In all cases, the recorded audio was analysed by first computing the spectrogram, and then post-processing the spectrogram to suppress ambient noise and intermittent loud noises, so as to highlight the sounds of interest. The spectrogram was computed with a non-overlapping flat-top window of size corresponding to a temporal resolution of one second (32,000 samples in the case of recordings done at 32 kS/s, and 64,000 samples in the case of recordings done at 64 kS/s). In other words, for each second of sound there was a single temporal window and 16,000 or 32,000 frequency bins (0–16 kHz or 0–32 kHz), depending on the sampling frequency of the recording.

The spectrograms were post-processed to better distinguish between fish sounds and ambient sounds. Post-processing of the spectrogram involved first chunking the spectrogram into 10-min sections, each consisting of 600 temporal windows and 16,000 or 32,000 frequency bins. For each 10-min section, and for each of the 16,000 or 32,000 frequency bins, the 50th and 5th percentile value of the spectrogram was computed over the 600 temporal windows in the 10-min section. The 5th percentile value roughly corresponds to ambient noise, and the 50th percentile corresponds to the median sound intensity. Intermittent loud noises from boats etc. will be above the 50th percentile, and hence mostly filtered out. To suppress ambient noise, the post-processing included a final step of computing the relative sound intensity between the 50th and 5th percentiles. For each 10-min section, a single post-processed spectrum reflecting relative sound intensity was therefore obtained, consisting of 16,000 or 32,000 frequency bins. These post-processed spectra were combined into a post-processed spectrogram, and hence the temporal resolution of the post-processed spectrogram was 10 min (600 s). All analysis was conducted in MATLAB (The Mathworks Inc., California, USA).

3. Results

Post-processing of the spectrogram successfully suppressed background noise such as feed spreading at the surface and movement of net-pen structures underwater, enabling sounds within the net-pen to be highlighted. The acoustic environment of the fish farm varied both spatially (inside/outside the net-pen, and by depth) and temporally (throughout a 24-h period and during feeding vs non-feeding).

Case 1 addressed the question of whether the acoustic environment of a net-pen with salmon differs from that of an empty net-pen. The net-pen with salmon showed a clear peak in sound intensity at slightly below 400 Hz, which was absent in the net-pen without fish (Fig. 2). Referring to the supplementary material, statistical treatment of the entire 24-h period for Case 1 supports this observation and shows a consistent significant ($p < 0.05$) difference between net pens with and without fish in the frequency range from 200 to 800 Hz.

Case 2 addressed whether the acoustic environment of a net-pen represents surface, or underwater sounds, or a combination. The frequency distribution of the recording 20 m outside the net-pen at 3 m differed noticeably from those at 4, 5 and 6 m. The recording at 3 m had a peak in sound intensity around 100 Hz and in the frequency band from 250 to 600 Hz. Elevation in sound intensity of 250 to 600 Hz was not present in recordings from 4, 5 and 6 m. There was a slight elevation in sound intensity at around 100 Hz at 4 m depth, which was reduced at 5 m and absent at 6 m. Referring to the supplementary material, there is significantly ($p < 0.05$) louder sound in the range from 100 to 600 Hz at 3 m compared to 4 m, and no significant difference (at the $p < 0.05$ level) between the sound intensities for the deeper recordings.

Case 3 investigated whether the acoustic environment of a net-pen varies with feeding status of the salmon, using the recording at 6 m depth. Both peak frequency and sound intensity varied over time during the recording period (Fig. 4). Peak frequency reduced and sound intensity diminished 1.5 h prior to cessation of feeding. While peak frequency gradually rose during the following six hours, sound intensity remained lower until increasing again after nearly six hours at 22:30 CET. Comparison between peak frequencies during feeding (1400–1500 CET) and post-feeding (1700–1800 CET) periods revealed a peak frequency of around 275 Hz post feeding, and around 400 Hz with higher relative sound intensity level during feeding (Fig. 5). Referring to the supplementary material, we observe a significant ($p < 0.05$) difference in magnitude between feeding and non-feeding, in the frequency range 150–600 Hz.

4. Discussion

Presence of Atlantic salmon changed the acoustic environment in the net-pen. In particular, frequencies in the range 300–500 Hz were of higher intensity in the presence of salmon (Fig. 2). Patterns in soundscape features could not be attributed solely to net-pen structures (i.e. net, moorings) or external sounds in the marine environment, since the soundscape of an empty net-pen lacked the frequencies observed in net-pens with salmon (Fig. 2). Surface noise quickly diminished below 3 m depth in a recording taken 20 m outside the net-pen (Fig. 3), meaning that the soundscape used in our analyses consisted predominantly of underwater sounds.

Changes in the soundscape during the presence of salmon may be attributable to one, or several, processes. Active sound production has been documented in several salmonid species (e.g. brook trout, rainbow trout and brown trout) (Rountree et al., 2018). In the same study, Rountree et al., 2018 also described suspected sound production by Atlantic salmon, though visual documentation was not available for confirmation. So, it is possible that some of the sounds present in the soundscape of a full net-pen are the result of active sound production. Non-communication, or involuntary sounds, also likely contribute to the acoustic environment of the full net-pen. Involuntary sounds such as air passage sounds (gulping of atmospheric air, air bubble release or transmission of air between the swim bladder and the stomach) have been described in Salmonidae (Bolgan et al., 2018; Neproshin and Kulikova, 1975; Phillips, 1989; Rountree et al., 2018; Stober, 1969) and may reflect changes in behaviour or activity. Neproshin and Kulikova (1975) attributed the sounds observed in *Salmo*, *Salvelinus* and

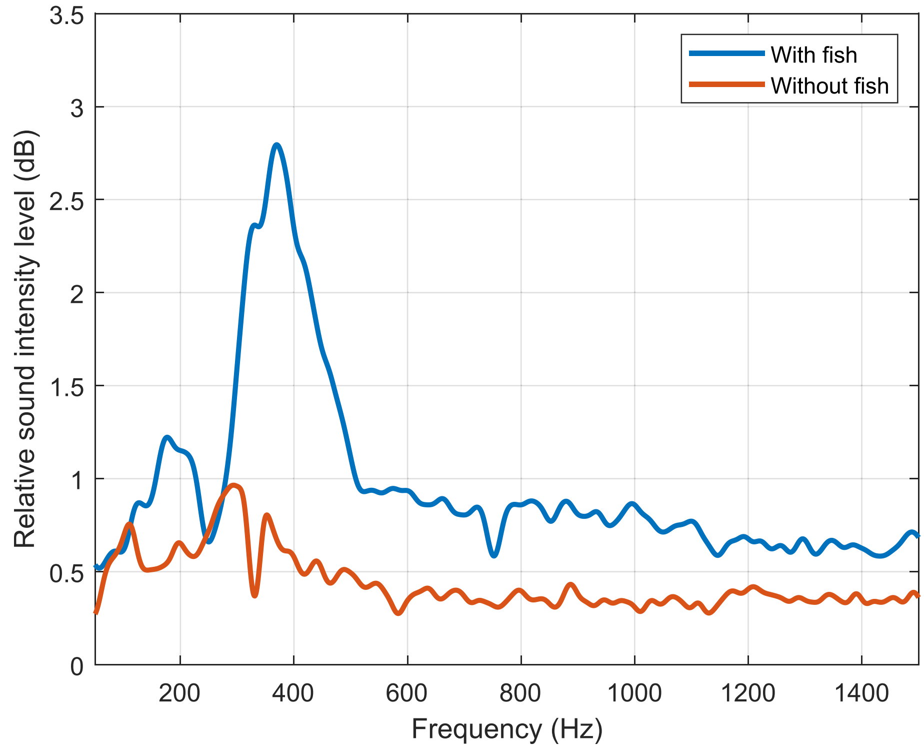

Fig. 2. Time-averaged and smoothed post-processed spectra, comparing relative sound intensity level between 50th and 5th percentiles from a one-hour audio recording demonstrating sound in net-pens 120 m apart, with (approximately 200,000 fish) and without salmon.

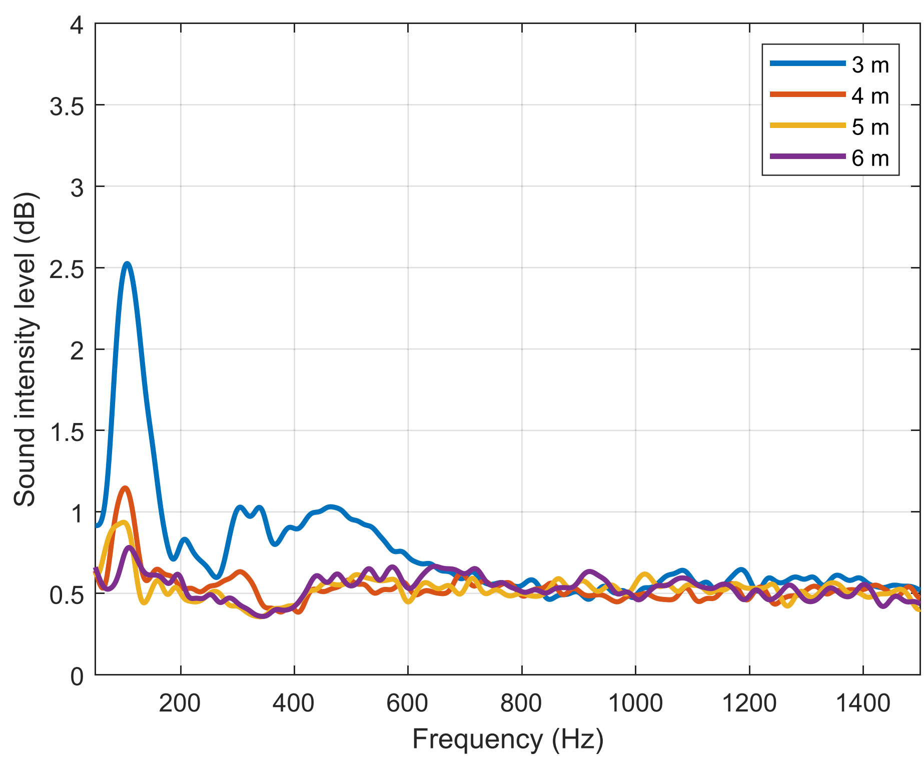

Fig. 3. Time-averaged and smoothed post-processed spectra, comparing relative sound intensity level between 50th and 5th percentiles at depths of 3, 4, 5 and 6 m, approximately 20 m outside a net-pen with salmon.

Oncorhynchus genera to being hydrodynamic sounds emitted when fish ascend to the surface (i.e. for feeding, feed searching or filling the swim bladder) and as air passage sounds (internal movement of air in the body). If these involuntary sounds occur repeatedly during a given behaviour, they too can be used to monitor behaviour of the fish.

The spectrogram varied over time throughout Case 3 (Fig. 4). In particular, the sound intensity, peak frequency and how broad the spectrum was. The net-pen environment varies during the diel cycle due

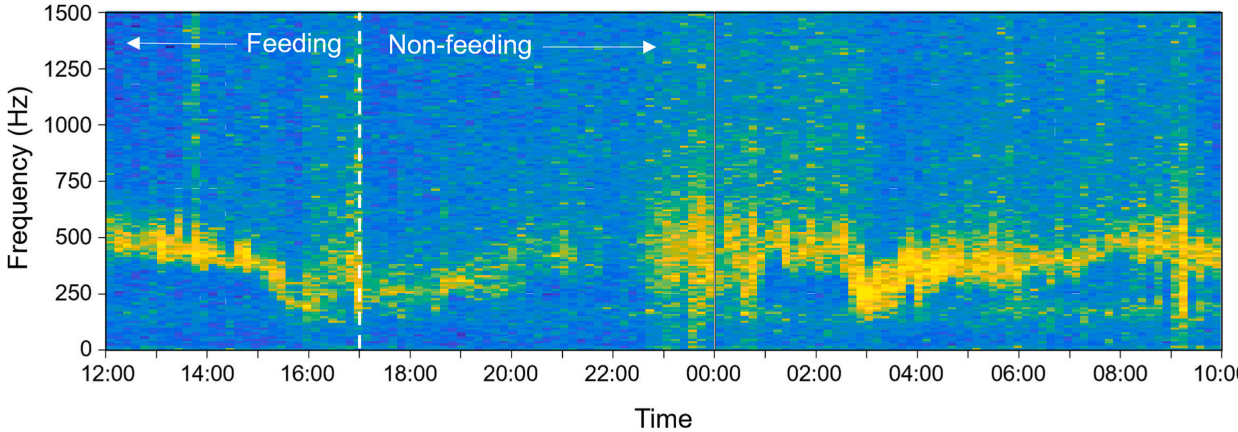

Fig. 4. Post-processed spectrogram, showing changes in the soundscape during and after feeding in a net-pen, on September 1–2, 2020. Highest sound intensity levels are shown in yellow, while lowest are dark blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

to, for example, changes in daylight, current strength and direction, and human activity and operations (e.g. boat activity) on site. The status of the fish also varies over time due, for example, to hunger status or circadian rhythm. Variation in depth dynamics and activity patterns of Atlantic salmon is well documented in net-pens (Fernö et al., 1995; Føre et al., 2011; Johansson et al., 2006; Juell and Westerberg, 1993; Oppedal et al., 2011), with a pattern of high activity in deeper water during the day and low activity at shallower depths during the night.

The spectrogram (Fig. 4) appears subjectively different during the 1.5 h preceding cessation of feeding compared to the previous 3.5 h. This cannot be attributed only to the absence of the sound of the feed itself since changes in the spectrogram occurred prior to the stopping of feed-spreading. Furthermore, the soundscape the following day when the fish were being fasted is similar to that when they were actively feeding, despite no feed being spread. Our hypothesis is therefore that the soundscape reflects the changes in 'hungry' and 'satiated' states of the fish over time. The changes in the spectrogram in the 1.5 h prior to cessation of feeding may indicate that the salmon were satiated and were no longer actively feeding. Such an indicator would enable better adaption of feeding routines to the hunger status of the fish and less feed wastage.

During the six-hour period after feed spreading stopped, sound intensity of salmon-attributed sounds was lower. Peak frequency which had dropped towards the end of the feeding period increased during the six-hour period. (Fig. 4). In addition to circadian rhythm and light levels, the feeding cycle affects the behaviour of salmon in the net-pens, with behaviour varying according to hunger status (Oppedal et al., 2011). Satiated fish tend to exhibit a more structured shoal swimming behaviour, whilst hungry fish immediately prior to and during feeding, demonstrate a more active, and less structured, search behaviour (Ang

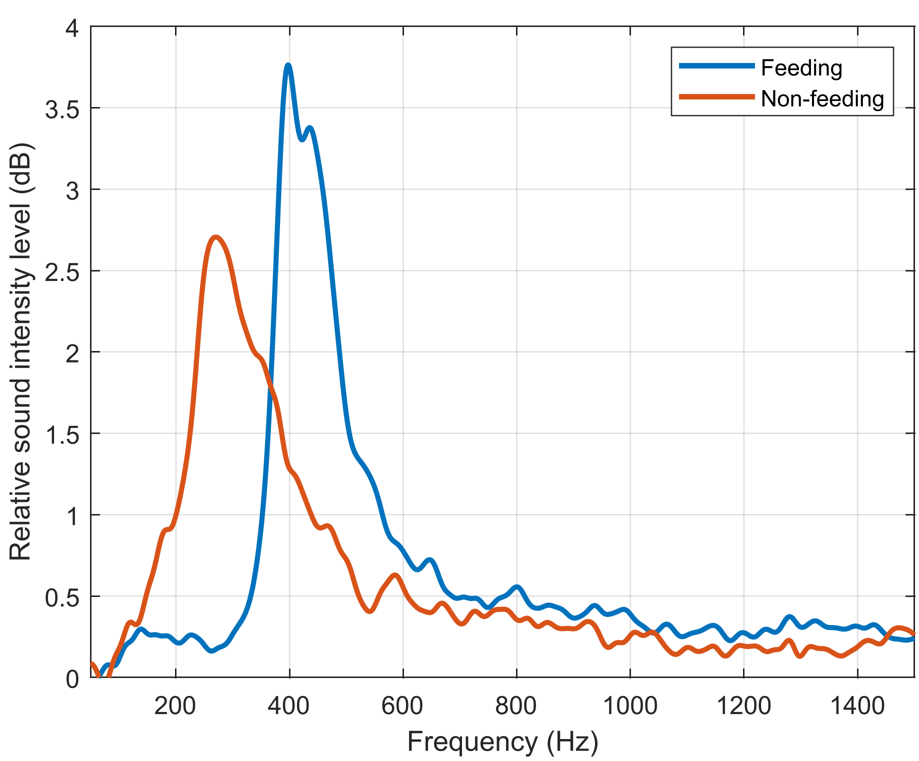

Fig. 5. Time-averaged and smoothed post-processed spectra comparing relative sound intensity level between 50th and 5th percentiles, illustrating feeding and non-feeding periods in a net pen with approximately 180,000 Atlantic salmon, on September 1, 2020.

and Petrell, 1998; Huse and Holm, 1993; Juell et al., 1994). This search behaviour reduces as the salmon become satiated and they move back towards the periphery and schooling behaviour again (Juell et al., 1994). This variation in behaviour will undoubtedly affect involuntary, and potentially active sound production.

To the best of our knowledge, these results present the first documentation of acoustic variation in an aquaculture net-pen caused by production fish, in this case Atlantic salmon. We demonstrate that the acoustic signals are attributable to the salmon, and not only net-pen structures or other environmental sounds. They change over time, likely reflecting changes in status, and may provide important additional information for knowledge driven aquaculture production, such as when to initiate or stop feeding. This study provides short-term, proof of concept data. Further research is required to extract patterns, to discern the source and production method of the sounds and to interpret how the soundscape reflects fish status.

5. Conclusions

This study has demonstrated that passive acoustic monitoring has potential for providing valuable complimentary information on the status of production fish in aquaculture facilities. We provide first evidence that Atlantic salmon (*Salmo salar*) alter the acoustic environment, changes which can be detected at the net-pen scale and demonstrate that variation in sounds mirrors the food-seeking status of the fish. Further research, including longer periods of recording to include different environmental conditions, fish treatments and production phases will enable greater understanding and potential applications of the net-pen soundscape. Following further research, soundscape monitoring may become a valuable tool in the fish farmers toolbox for real-time surveillance of the net-pen.

CRediT authorship contribution statement

Carolyn M. Rosten: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. **John Reidar Mathiassen:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing. **Zsolt Volent:** Conceptualization, Funding acquisition, Investigation, Methodology, Writing – original draft, Writing – review & editing.

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.

Data availability

Data will be made available on request.

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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.2022.738949.

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