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Sounds of Arctic cod (*Boreogadus saida*) in captivity: A preliminary description

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Abstract: Sounds produced by Arctic cod were recorded for the first time and suggest passive acoustic monitoring (PAM) can be an effective additional tool for the study and management of the species. Each of the 38 calls detected in three different aquatic facilities consisted of a single grunt with 6 to 12 pulses and a mean duration of 289 ms. Call frequency ranged between 59 and 234 Hz, with a mean peak frequency of 107 Hz. These preliminary data suggest Arctic cod can be distinguished from other gadids, but additional studies of sympatric species are needed before PAM can be confidently adopted.

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1. Introduction

Arctic cod (*Boreogadus saida*), also known as polar cod, is an abundant forage fish with circumpolar distribution (Scott and Scott, 1988). It is an important component of the Arctic marine ecosystem and has commercial value in the Barents Sea (Gjosaeter, 1995). Despite limited studies, currently known predators include black-legged kittiwakes (*Rissa tridactyla*), harp seals (*Phoca groenlandicus*), and belugas (*Delphinapterus leucas*) (Welch *et al.*, 1993). To monitor cod populations, trawl and active acoustic (echosounder) surveys have been conducted (Gjosaeter and Ushakov, 1997), but because they require several vessels at a time and are limited to small and ice-free areas, they provide only a limited understanding of cod distribution. Passive acoustic monitoring (PAM) is very useful in situations where sampling data are limited or unavailable and has been successfully used in several gadid fisheries in the Atlantic (Rountree *et al.*, 2006). PAM can provide long-term datasets in remote environments when the presence or absence of organisms can be identified by their sound production. However, to date PAM has not been used in Arctic cod studies because their sounds have not yet been described. Listening to isolated species of fish in captivity ensures there is no bias in identifying the source of biological sounds, which is also known as "sound truthing" (Rountree *et al.*, 2006). Our preliminary description of Arctic cod sound characteristics adds a new species to a catalogue of known fish sounds in the Canadian Pacific and Arctic ecosystems, and will enable researchers to use PAM in future ecological and management studies of the species.

2. Methods

2.1 Data collection

Acoustic recordings in tanks containing Arctic cod were obtained at three different facilities: the University of British Columbia (UBC) (BC, Canada), the Vancouver Aquarium (BC, Canada), and the Hatfield Marine Sciences Center (HMSC) (Oregon).

At the UBC facility, approximately 9 Arctic cod kept in a $90 \times 49.5 \times 45$ cm tank were monitored for sound production in real time. Recordings were made at 96 kHz (24 bit), by using a Zoom-H1 recorder system (Zoom North America, Hauppauge, NY) with a calibrated C-55 hydrophone (sensitivity $= -165$ dB re: 1 V/μPa, Cetacean Research Technology, Seattle, WA). External noise was greatly reduced during recording sessions by turning off water pumps, oxygen flow, and air conditioning.

Autonomous recorders were used to collect data at the other two locations on a continuous duty cycle at 96 kHz (16 bit) for up to 13 days. At the Vancouver Aquarium, a Sound Trap 300 (Standard, Ocean Instruments, Auckland, New Zealand) was used in a $80 \times 79 \times 74$ cm tank with approximately 11 Arctic cod. At the HMSC, a Song Meter SM4 recorder (Wildlife Acoustics, Maynard, MA) with an HTI

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hydrophone (sensitivity = −165 dB re: 1 V/μPa, High Tech Inc., Long Beach, MS) was deployed in a 457 × 91 × 91 cm tank that held approximately 38 fish. No alterations were made to the regular schedules of pumps and filters at the latter two locations, thus resulting in higher background noise levels than for the UBC recordings.

2.2 Data post-processing

Post-processing of acoustic signals was conducted by listening to recordings while simultaneously viewing the sound's spectrogram [4800 FFT (fast Fourier transform), Hann window, 85% overlap] and waveform with Raven Pro 1.5 acoustic software (Bioacoustics Research Program, 2014) in search of Arctic cod vocalizations. Sounds were played with the spectrogram displaying frequencies between 0 and 700 Hz and 15 s at a time, but were expanded or zoomed further when necessary.

Since recordings at UBC were monitored in real time, and they only amounted to 3.75 h, the whole dataset was examined. A subset of recordings made at the other two locations was selected for manual inspection. For the Vancouver Aquarium data, the first 10 min out of every 120 min were examined in the manner described above. When a grunt was detected, the 240 min before and after the grunt were also examined.

Recordings obtained from operating hatcheries are inherently noisy (Caiger *et al.*, 2012), with water pumps and vibrations being the most predominant sources. This situation was particularly acute at the HMSC, where fish sounds were completely masked by flow noise while the pumps were running. Broadband sound pressure levels in dB re 1 μPa (with 10 s time-averaging) were therefore plotted to identify periods when the pumps were off and fish sounds could be appropriately identified over the background noise. These data revealed two 10-min periods a day (between 0700 and 0800 h, and between 1500 and 1600 h) when the background noise levels were low enough for the detection of fish sounds above 60 Hz (Fig. 1).

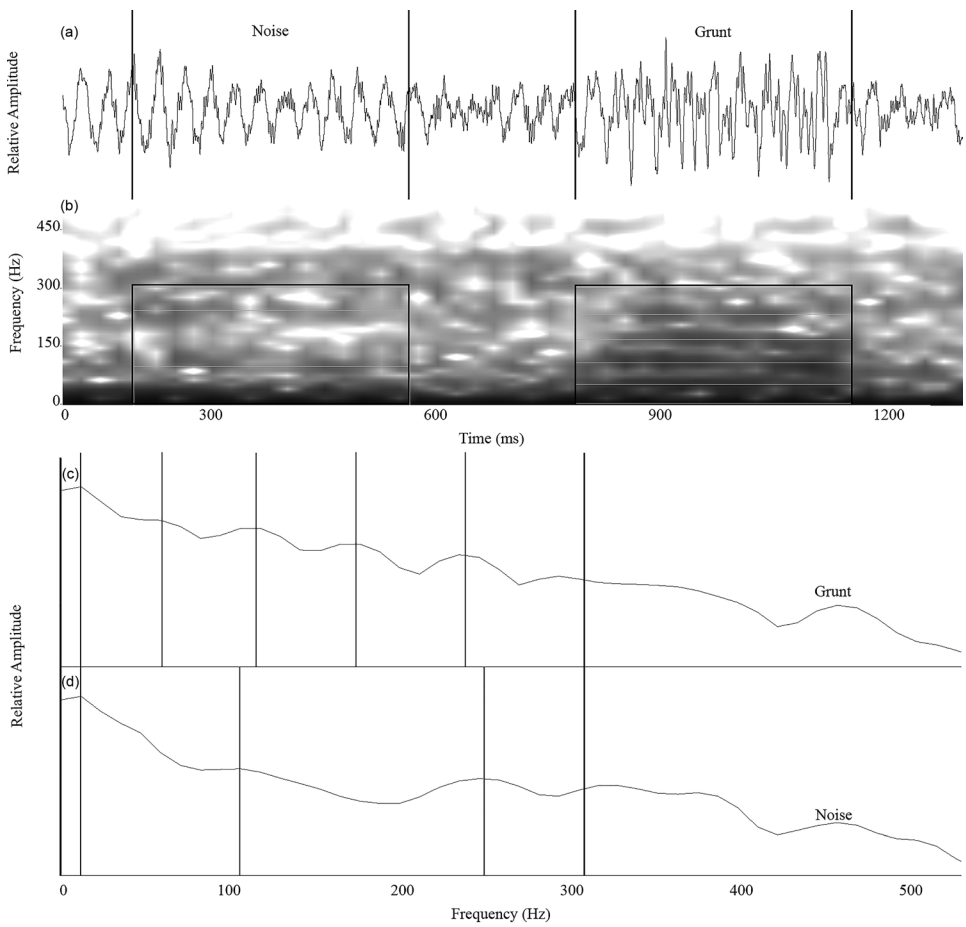

Fig. 1. Waveform (a) and spectrogram (b) of an Arctic cod (*Boreogadus saida*) grunt recorded at the HMSC (4800 FFT Hann window with 85% overlap). The box on the right delimits the Arctic cod grunt and the box on the left delimits a selection of equal dimensions of background noise preceding the grunt. The power spectrum of the grunt (c) and of the noise (d) show their respective frequency peaks, indicated by vertical bars. A clip of the sound is available as a multimedia file (Mm. 1).

Acoustic measurements of frequency parameters were performed on unfiltered sound clips for each of the grunts detected at all three locations by drawing a selection box around them on the spectrogram view with Raven Pro 1.5 (Bioacoustics Research Program, 2014). However, to obtain accurate estimates of the number of pulses in a grunt (here we define a pulse as the unit that gets repeated in the amplitude-modulated oscillations that make out a grunt), the waveform was examined after application of a 50–800 Hz bandpass filter. Only the grunts with the highest signal-to-noise ratio were used for sound measurements (e.g., Fig. 1).

3. Results and discussion

The inspection of the recordings revealed one type of sound that resembled those described for Atlantic cod (*Gadus morhua*) (Brawn, 1961; Hawkins, 1993; Hernandez *et al.*, 2013) and therefore they were referred to as grunts (Fig. 1 and Multimedia files Mm. 1–Mm. 3). The recordings contained one grunt from UBC, one grunt from the Vancouver Aquarium, and 36 grunts from HMSC providing evidence that the Arctic cod is capable of sound emission. Arctic cod peak frequency was 107 ± 4 Hz on average ($\pm$ standard error), ranging between 59 and 234 Hz. Frequency- and time-based measurements of Arctic cod grunts are shown in Table 1. This is the first description of Arctic cod grunts and their features were consistent across three different facilities suggesting that this call type is characteristic of the species.

Mm. 1. Audio clip of Arctic cod grunt #30 from HMSC. This is a file of type "wav" (0.353 Mb).

Mm. 2. Audio clip of Arctic cod grunt #11 from HMSC. This is a file of type "wav" (0.367 Mb).

Mm. 3. Audio clip of Arctic cod grunt #32 from HMSC. This is a file of type "wav" (0.260 Mb).

The frequency distributions overlap strongly between Arctic and Atlantic cod, ranging between 36 and 851 Hz for Arctic cod (Table 1) and between 27 and 539 for Atlantic cod (Hernandez *et al.*, 2013). Our data suggest a higher maximum frequency for Arctic cod. In terms of peak frequency, Hernandez *et al.* (2013) reported a bimodal peak frequency for Atlantic cod, of about 103 and 50 Hz whereas Arctic cod peak frequency is around 107 Hz. Our peak frequency of 107 and their peak frequency of 103 are similar. We do not know if there is a lower mode in Arctic cod because it would have been masked by the high noise levels below 60 Hz (Fig. 1) and we only see the higher mode.

Arctic cod grunts had a longer duration than those of Atlantic cod (289 ± 13 ms compared to 167.6 ± 5.9 ms, average $\pm$ standard error). However, the number of pulses was the same (9 ± 1 vs 9 ± 0.3), indicating the pulse rate and period were different. This difference suggests that Arctic cod can be acoustically distinguished from Atlantic cod, pending confirmation with additional data.

Having Arctic cod recordings, even noisy ones, is of high importance because it is extremely hard to obtain this type of data and it is better than no data at all. These fish are difficult to keep, there are very few facilities in the world that keep them in captivity, and this type of recordings without bias for sound source are extremely challenging to obtain in wild conditions. Knowing that Arctic cod can be vocal means it is included in the list of possible sources of fish sounds recorded during PAM studies of polar areas populated by this species. The data described here make it possible to identify Arctic cod grunts collected in locations in which they are the only gadid

Table 1. Acoustic variables for the Arctic cod (*Boreogadus saida*) grunts recorded at the HMSC ($n = 36$), UBC ($n = 1$), and Vancouver Aquarium ($n = 1$).

Acoustic variables	Minimum	Maximum	Average ($\pm$ standard error)	Sample size
Low frequency (Hz)	36	157	79 ± 3	38
Peak frequency (Hz)	59	234	107 ± 4	38
High frequency (Hz)	184	851	400 ± 22	38
Duration (ms)	184	536	289 ± 13	38
Number of pulses	6	12	9 ± 1	6
Pulse rate (pulses/s)	14	64	30 ± 8	6
Pulse period (ms)	16	73	43 ± 8	6

present. But sounds from related species could be very similar (Hawkins, 1993) and in areas where they co-occur with other gadids it would be possible to misidentify grunts of one species for another. In addition to Atlantic cod, there are six other species of gadids that co-occur with Arctic cod in some areas of their range, such as Pacific cod (*Gadus macrocephalus*), saffron cod (*Eleginus gracilis*), walleye pollock (*Gadus chalcogrammus*), Pacific tomcod (*Microgadus proximus*), Greenland cod (*Gadus ogac*), and polar cod (*Arctogadus glacialis*). It is therefore necessary to determine whether these other species are sound-producing and if so, whether they can be distinguished from Arctic cod. To date there have been only two limited studies of gadids in the region. Walleye pollock has been reported to produce threatening, aggressive-attacking, courting, and mating calls with frequencies up to 800 Hz (Park *et al.*, 1994). Sakurai and Hattori (1996) studied the reproductive behaviour of Pacific cod and did not find any evidence of sound production. More studies are needed in order to be able to positively identify Arctic cod grunts and distinguish them from other gadid sounds. Compiling that type of information into a catalogue of known fish sounds from the Canadian Pacific and Arctic ecosystems would be extremely useful for PAM studies in the region.

In addition to describing the sounds when they are produced, understanding the acoustic behaviour of Arctic cod and the contexts in which they are vocal can further help distinguish their sounds from other gadid species. For example, if they only produce sounds during courtship or mating, and the reproductive season of co-occurring species does not overlap with theirs, the season during which the sound is detected can indicate which species is most likely to have produced it. The grunt heard at UBC was produced in the context of feeding the fish. Several of the grunts recorded at the HMSC were also heard during feeding. There were many gravid females in that tank and spawning was still occurring during the study period.

Other than seasonal, temporal patterns in sound production could be circadian. Hernandez *et al.* (2013) found Atlantic cod grunts throughout the 24-h period but they were more prevalent during daylight hours. Arctic cod are believed to breed under ice between January and April and this season corresponds to the Polar night (Nahrgang *et al.*, 2016), so diel patterns are unlikely.

Aquaculture environments are often noisy due to equipment and machines like water pumps, air ventilation systems, and vibrations (Caiger *et al.*, 2012). The HMSC and the Vancouver Aquarium were very noisy during the study period. As a result, 37 of the 38 grunts were recorded in low signal-to-noise ratio conditions, which made some measurements like peak count, peak frequency, and maximum frequency challenging. At the HSMC, where 36 grunts were found, noise levels only became low enough to detect grunts during a backwash cycle that happened twice daily (between 7 and 8 am and between 3 and 4 pm), during which the water flow slowed or stopped. It is unknown if the call times reflected a natural periodicity in calling, whether the cod sounds were masked by high noise levels, whether high noise levels inhibited sound production, or perhaps even whether the cod had adapted to the noise regime by producing sounds only during low noise periods. These questions highlight the risk of biased conclusions when the observations conducted on diel pattern of sound production occur in inconsistent noise conditions. To avoid such bias, it is important to conduct studies on temporal patterns of sound emission in consistently quiet environments whenever possible, to reduce masking nor noise-induced variations in vocal behaviour.

Obtaining more examples of Arctic cod grunts with better acoustic quality is necessary to train neural networks to recognize them and build automatic detectors to search for these signals in acoustic recordings. Such detectors would be vastly useful for long-term studies of Arctic soundscapes, especially those with large acoustic datasets.

Finally, this study highlighted the prevalence and the impacts of background noise in aquatic facilities. Working toward quieter captive environments may lead to healthier fish and will also reduce the probability of biased interpretations of behaviour.

In summary, this work provides evidence that Arctic cod produce sounds like the grunts described for Atlantic cod. Although based on limited data, it is the first description of the grunts made by Arctic cod in which the species was known with certainty. However, more studies are needed to get better measurements and train automatic detectors to recognize them in long-term PAM studies. This could have important applications for PAM studies of Arctic ecosystem health.

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