Passive- and active-acoustic properties of a spawning Atlantic cod (*Gadus morhua*) aggregation

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A spawning aggregation of Atlantic cod (*Gadus morhua*) was observed at depths of 40–50 m with passive- and active-acoustic sensors at the Bar Haven grounds in Placentia Bay, Newfoundland, in April 2003. A hydrophone was positioned on the seabed beneath the aggregation, while a 38-kHz split-beam echosounder was moored at the sea surface above it for 18.5 h. Ten grunts were recorded with peak frequencies ranging from 30 to 250 Hz and durations of nearly 300 ms. These grunts are similar to the sounds recorded in the presence of captive, spawning cod from the same substock. The echogram reveals that cod exhibit diel, vertical-migratory behaviour, densely aggregating near the seabed by day and forming columns that extend approximately halfway to the surface at night. This is the first study to demonstrate that cod produce sounds and form columns while migrating vertically during night-time spawning.

Keywords: active acoustics, cod, cod sounds, passive acoustics, spawning behaviour, vertical migration.

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Introduction

The spawning behaviour of Atlantic cod (*Gadus morhua*) has been observed in detail in both laboratory and natural conditions. Laboratory studies have revealed that cod have elaborate courtship behaviour (Brawn, 1961b; Rowe and Hutchings, 2006), with Brawn (1961b) observing both distinct courtship behaviour performed by males towards females and territorial aggressive behaviour of males towards males.

Echosounders have been used for many years to observe aggregations of wild spawning cod and their behaviour (Sund, 1935; Rose, 1993; Lawson and Rose, 1999). Males are the first to arrive at spawning grounds (Lawson and Rose, 2000; Robichaud and Rose, 2003) and compete with each other to attract females (Hutchings *et al.*, 1999; Nordeide and Folstad, 2000; Windle and Rose, 2007). The spawning aggregations exhibit vertical migrations with magnitudes dependent on the water depth.

Many fish produce low-frequency sounds, specifically members of the families Sciaenidae, Gadidae, Ictaluridae, Cyprinidae, Batrachoididae, Haemulidae, Lutjanidae, and Serranidae (Luczkovich *et al.*, 2008). Both sexes of cod can produce sound with the drumming muscles surrounding their swimbladders. The males produce sound to defend their territories and to attract females during spawning (Brawn, 1961c). Drumming-muscle weight is possibly correlated with the intensity of sound production (Rowe and Hutchings, 2006).

Finstad and Nordeide (2004) investigated the acoustic repertoire of cod in captivity. Rowe and Hutchings (2006) further studied captive groups of cod from two Northwest Atlantic populations and quantified temporal patterns and behavioural contexts. They found sound production occurred most frequently during the peak spawning season at the onset of darkness and was positively associated with egg production. In the only known passive-acoustic study of *in situ* cod, Nordeide and Kjellsby (1999) recorded an increase in ambient sound during spawning, within the frequency range of cod sounds (~30–250 Hz).

One of the largest coastal-spawning aggregations of Atlantic cod in Newfoundland waters is located in Placentia Bay on the south coast of the island of Newfoundland (NAFO regulatory area 3Ps). During the spawning season, cod aggregate on shallow slopes within the bay. The most consistently used area is the Bar Haven spawning grounds, located in the inner part of Placentia Bay (Lawson and Rose, 2000; Brattey and Healey, 2003). This area is characterized by a series of islands separated by shallow (<90 m) channels. During the May–June spawning season, aggregations of cod are found typically on the shallow banks surrounding the islands, most notably the Corner Bank area off the northeast shore of Bar Haven Island (Rose *et al.*, 2008). Although cod have been observed to migrate throughout the bay, lekking (i.e. displays by males competing to attract females) has been observed at Bar Haven (Robichaud and Rose, 2002, 2003; Windle and Rose, 2007).

In this study, both passive- and active-acoustic sensors were used to study the sounds and associated behaviours of *in situ* and *ex situ* spawning cod. It is hypothesized that cod sound production is associated with spawning and increased diel, vertical-migratory (DVM) behaviour.

Methods

During April 2003, the behaviour of *in situ* cod spawning was studied at Corner Bank of the Bar Haven spawning grounds in

Placentia Bay. The seabed depth ranged from 48 to 53 m, modulated by spring tides.

From February to April 2003, *ex situ* observations were also made of this substock at an aquaculture facility of Memorial University of Newfoundland. Approximately 50 captive cod were kept in a tank, 4 m in diameter and 3 m high with water at 6°C flowing at 100 l min^{-1}. They were fed frozen baitfish and were subjected to a 4-month, phase-shifted photoperiod.

Acoustic recordings

A 38-kHz echosounder (Simrad EK500) was used to survey a cod-spawning aggregation on the Bar Haven grounds in 2003. The transducer (Simrad ES38B; 7° 3 dB beam width) was towed from the Canadian Coast Guard Ship "Shamook" (Rose *et al.*, 2008). Before the survey, the echosounder was calibrated following Foote *et al.* (1987). During the survey, pulses of 1 ms duration were transmitted each second, and the echoes were sampled at 7.5 kHz.

Vertical movements of cod and their densities were estimated by integrating measurements volume-backscattering coefficients in bins 3 m deep by 2 min long using Echoview software (Myriax, Hobart, Australia). The range of the spawning aggregation off the seabed was measured from the start of the seabed to the average height of the fish echoes. Fish densities were estimated according to Rose and Porter (1996) using the target-strength model

$$TS = 20\log(L) - 66, \quad (1)$$

where L is the mean total fish length (56 cm) obtained from sampling.

The resulting map of the spawning aggregation was used to identify an optimal spot for a stationary experiment. The vessel was three-point moored (47°44′37.50″N 54°12′48.24″W), and the transducer was fixed to a boom and positioned ~3 m from the boat and 1 m beneath the surface. Active-acoustic measurements were then made to observe the vertical distributions and densities of fish for 18.5 h [14:30 (NST) on 16 April to 09:00 on 17 April 2003]. High winds prevented the intended 24 h recording period from being achieved. Underwater-video observations were also unsuccessful owing to problems with video quality.

During this period, a hydrophone mounted in a weighted stand was positioned on the seabed beneath the echosounder. Initially, this action made the cod disperse, but they returned ~10 min later, presumably resuming their natural location and behaviour. The hydrophone was positioned near the seabed to increase the cod signals and decrease noise (A. Hawkins, pers. comm.). In addition, during the mooring period, vessel noise was reduced by using a small gas generator for power. The signals from the hydrophone (ITC 8212) were preamplified (SR560; Stanford Research System) over a 3 Hz − 1 kHz bandwidth, digitized, stored in wav format, and analysed using Avisoft SASLab Pro software (Avisoft Bioacoustics). The time before the start of the sound that triggers the recorder (pre-trigger) was 0.03 s, and the minimum recording time (hold time) was 3 s. Only the passive-acoustic data collected after the cod were again observed by the stationary echosounder were analysed. To validate and compare sounds from *in situ* and *ex situ* spawning cod, the same hydrophone, preamplifier bandwidth, and recording system were used for both experiments.

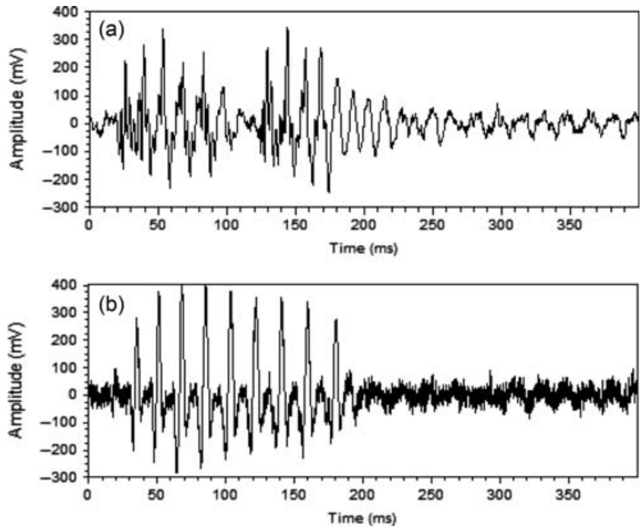

Figure 1. Voltage (proportional to pressure) vs. time. (a) Double grunt from an *in situ* cod and (b) single grunt from an *ex situ* cod.

Biological sampling

In situ cod were fished using handlines. Weights and lengths were measured after the fish had been sexed and otoliths extracted for ageing. Cod were identified as mature, immature, or spent. The maturity stages were determined by visual inspection of gonads according to Morrison (1990) and Templeman *et al.* (1978). Mature males had testes full of milt, whereas spent testes were stringy in appearance, with little or no remaining milt. Mature females had gonads with either ripening or hydrated eggs, whereas spent females had deflated, thick-walled gonads, with few or no eggs and no signs of ripening. In all, 772 cod were sampled from Bar Haven bank before the stationary experiment.

For *ex situ* cod, spawning was verified by the presence of eggs. Released eggs floated to the water surface, which was continuously filtered for eggs. Their volumes were measured at 08:30 (NST) each day during spawning. The sex ratio of the ~50 captive cod was assumed equal.

Results

Ex situ

With eggs in the holding tanks as evidence, the spawning period was 10 December 2002 to 28 April 2003. From 20 February to 26 March 2003, ~312 h of recordings were made, including 110 cod sounds. These single- and double-grunt sounds (Figures 1 and 2) have an average duration of 300 ms, with peak frequencies ranging from 30 to 210 Hz (Table 1). The number of grunts peaked at 20 d^{-1} on 24 March 2003, and the egg volume peaked at 2000 ml on 9 March 2003. Egg volume and the number of grunts were not significantly correlated ($p > 0.05$). Some 85% of the grunts were recorded during night-time. Sounds indicative of fish bumping the hydrophone suspended directly below the surface were more frequent at night, suggesting that fish activity increased during spawning.

In situ

The biomass of the spawning aggregation at Bar Haven bank observed in 2003 was acoustically estimated as 14 000 t. Sampled fish ranged in age from 3 to 13 years and length (L) from 32 to

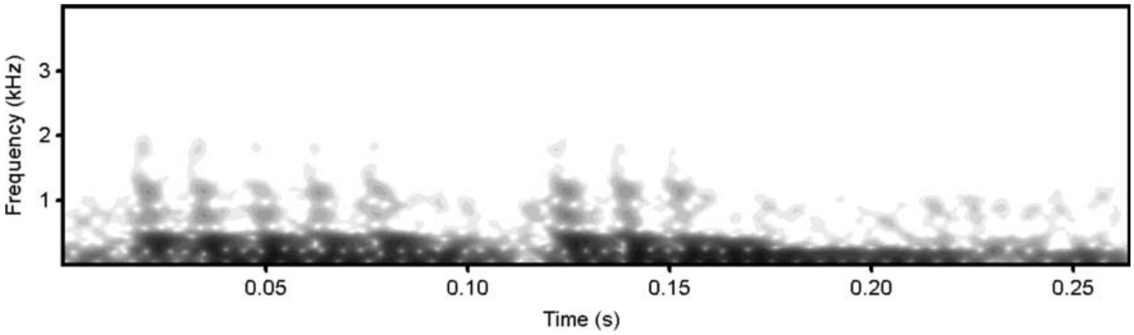

Figure 2. Spectrogram of double grunt from an *in situ* cod.

Table 1. Physical characteristics of grunt sounds from *in situ* and *ex situ* cod (n = number of sounds recorded).

Cod	Statistic	Duration (ms)	Number of sound pulses	Peak frequency (Hz)
In situ $n = 10$	Mean	303.0	11.2	61.6
	s.d.	71.6	3.0	65.0
	Minimum	242.3	9.0	30.0
	Maximum	407.2	16.0	250.0
Ex situ $n = 110$	Mean	294.4	8.6	92.4
	s.d.	184.4	2.2	43.3
	Minimum	117.0	3.0	30.0
	Maximum	1 000.0	16.0	210.0

Table 2. Cod maturities and sex from tow-sampling data.

Sex	*n*	Mature	Immature	Spent	Length (cm)
Females	365[a] (47%)	246 (67%)	76 (21%)	42 (<3%)	35–91
Males	407 (53%)	351 (86%)	37 (9%)	19 (<1%)	32–74
Total	772	597	113	61	32–91

[a]One female maturity undetermined.

91 cm. There was an almost equal ratio of males and females in the aggregation inferred from sampling, and most of these fish were in spawning condition (Table 2). Only 21% of the females and 9% of males were immature.

Over 18.5 h, ten *in situ* cod sounds were recorded. Grunt duration ranged from 242 to 407 ms, and their peak frequencies ranged from 30 to 250 Hz. A double-grunt sound, which was recorded on 16 April 2003, is illustrated as voltage (proportional to sound pressure) vs. time (Figures 1a and 2) as an example. It is not known whether double grunts originate in single cod. A single-grunt sound from an *ex situ* cod is illustrated for comparison (Figure 1b). Although captive cod produced sounds at a much higher rate than wild cod, their grunt durations and peak frequencies were not significantly different ($p > 0.05$; all cases).

The echogram recorded from the stationary platform (Figure 3) demonstrated DVM behaviour of *in situ* cod. Their distance from the seabed varied significantly with time-of-day (ANOVA; $p < 0.001$). By day, cod were more tightly aggregated with densities reaching 0.8 kg m^{-2}, and they were significantly closer to the seabed (<5–10 m; *post hoc* Tukey test; $p < 0.05$) compared with night, when they were more evenly distributed (minimum density 0.05 kg m^{-2}) throughout the water column (Figure 4). The cod were closest to the seabed at dawn and dusk.

Discussion

Cod spawn on Bar Haven bank from March to early July (Lawson and Rose, 2000). The DVM behaviour of these cod may not be influenced so much by light intensities (Neilson and Perry, 1990) as by their spawning activities.

Pelagic aggregations of spawning cod were first observed with echosounders by Sund (1935) near Lofoten, Norway, and off Newfoundland by Rose (1993) and Lawson and Rose (2000). Rose (1993) suggested that the observed columns might comprise pairs of fish that meet near the seabed and ascend to spawn. Such behaviour may increase reproductive success by reducing “sneak fertilization” by competing males (Bekkevold *et al.*, 2002) and selections of quality sperm by females (Tripple *et al.*, 2005).

In this study, ascents of *in situ* cod at night appeared as waves on echograms recorded from a stationary platform. This phenomenon might appear as stacks or columns of fish on echograms from a moving vessel (Rose, 1993; Lawson and Rose, 2000). Cod may also increase sound production at night to increase their pairing and mating successes in low light (Anthony, 1981). However, other studies suggest that cod do not necessarily migrate vertically or form columns in association with spawning (Nordeide, 1998; Hutchings *et al.*, 1999). Perhaps different populations of cod exhibit different spawning behaviours.

Ex situ cod increased their sound production and swimming during night-time spawning (this study; Kjesbu, 1989; Rowe and Hutchings, 2006). Low-frequency grunts were associated with territorial males acting aggressively towards other males (Brawn, 1961a), courtship displays, and ventral mounting. Cod produce sounds via muscles drumming on their swimbladders (Brawn, 1961c). They may also produce click sounds in the presence of predators (Vester *et al.*, 2004). While no such sounds were recorded during this study, no predators were observed in the area either.

Sounds recorded in small tanks may be distorted by the superposition of echoes off the walls and the water surface (Parvulescu, 1966; Rowe and Hutchings, 2006). It is therefore uncertain whether the grunts recorded in the presence of *ex situ* cod in a tank were undistorted. The grunt rate was much lower for *in situ* than for *ex situ* cod. Perhaps captive cod must make sounds more frequently to compete and successfully mate in small tanks.

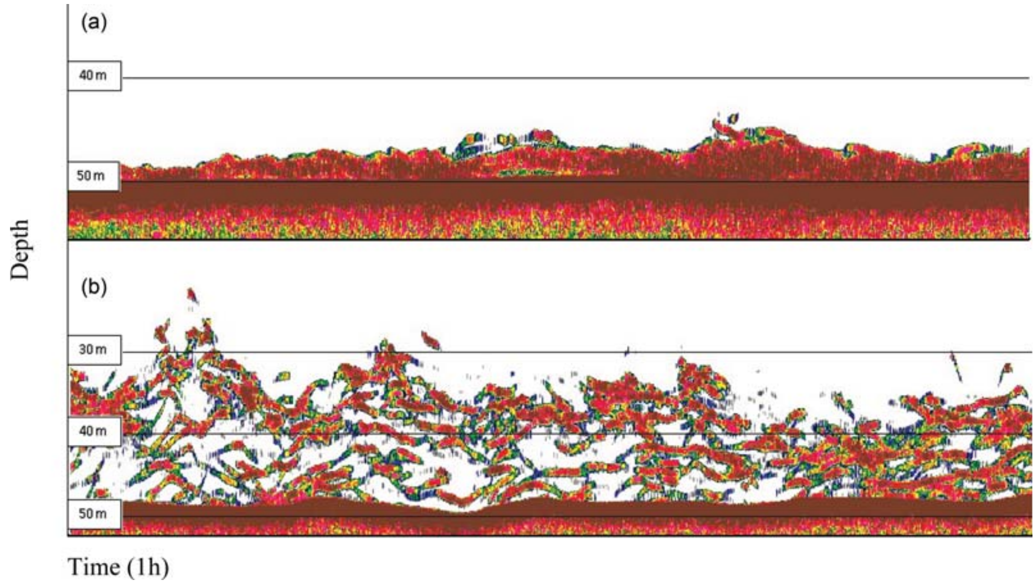

Figure 3. Echograms (38 kHz S_v vs. depth and time) for (a) spawning cod during daytime [14:48 (NST)] and (b) night-time (21:14), on 16 April 2003. Sunset on 16 April was at 19:55; sunrise the following day was at 06:15.

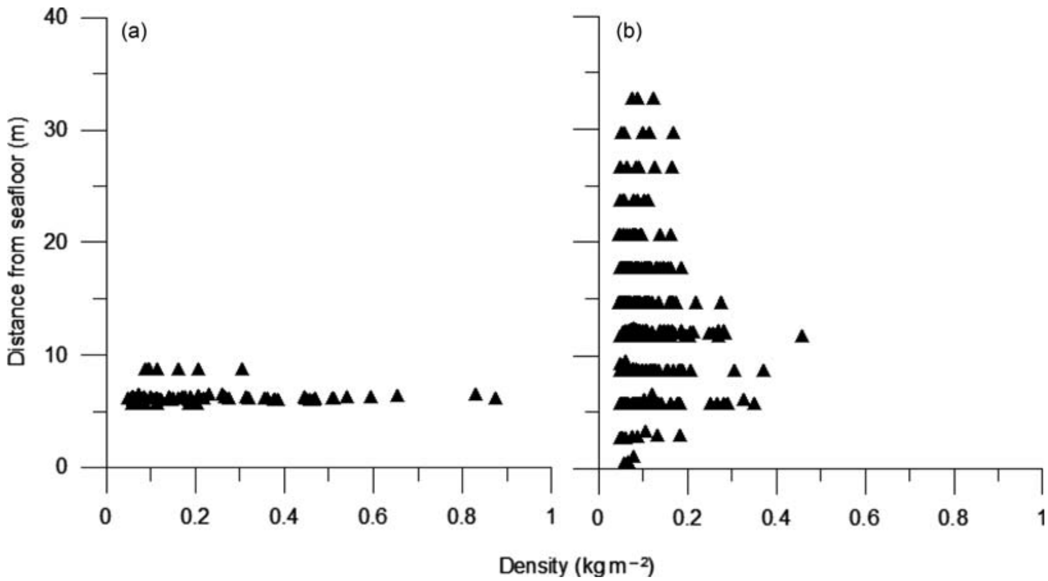

Figure 4. Density of cod vs. distance from the seabed by (a) day and (b) night. Densities $\geq$0.1 kg m^{-2} are illustrated.

Both passive- and active-acoustic methods are useful for observing cod-spawning behaviour. In future, concurrent video observations might allow cod sounds to be attributed directly to specific behaviours (e.g. as in Brawn, 1961b). In addition, frequent sampling of eggs from *in situ* cod might better identify peak spawning.

Conclusion

This is the first study to use active and passive acoustics to measure the sounds of Atlantic cod in relation to their vertical-migration and column-forming behaviours during night-time spawning. It appears as though *in situ* and *ex situ* cod produce sounds associated, respectively, with vertical ascents and increased swimming activity during night-time spawning.

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