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First attempt to use a remotely operated vehicle to observe soniferous fish behavior in the Gulf of Maine, Western Atlantic Ocean

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Abstract Underwater sound and video observations were made at noon, sunset, and midnight in sand, gravel, and boulder habitat in the Stellwagen Bank National Marine Sanctuary, Gulf of Maine, USA in October 2001 using a remotely operated vehicle (ROV). Seventeen species of fish and squid were observed with clear habitat and time differences. Observations of feeding behavior, disturbance behavior, and both interspecific and intraspecific interactions provided numerous opportunities for potential sound production; however, sounds were recorded only during a single dive. Although high noise levels generated by the ROV and support ship may have masked some sounds, we conclude that fish sound production in the Gulf of Maine during the fall is uncommon. The recorded fish sounds are tentatively attributed to the cusk *Brosme brosme*. Cusk sounds consisted variously of isolated thumps, widely spaced thump trains, drumrolls, and their combinations. Frequency peaks were observed at 188, 539, and 1195 Hz. Use of a remotely operated vehicle (ROV) as a passive acoustic observation platform was problematic due to high ROV self-noise and the ROV's inability to maintain a fixed position on the bottom without thruster power. Some fishes were clearly also disturbed by ROV noise, indicating a potential ROV sampling bias. Based on our observations, we suggest that new instruments incorporating both optic and passive acoustic technologies are needed to provide better tools for *in situ* behavioral studies of cusk and other fishes [*Current Zoology* 56 (1): 90–99 2010].

Key words Passive acoustics, Soniferous, Gulf of Maine, ROV, Sound production, Fish behavior

Sound production is widespread in fishes and is generally associated with courtship, spawning, and disturbance behavior (see review in Hawkins, 1993). Recent advances in passive acoustic technologies have led to increased interest in their use for *in situ* studies of fish behavior (Rountree et al., 2006; Luczkovich et al., 2008). In this paper we report on the first attempt to conduct a passive acoustic survey for fishes in the Gulf of Maine in the Western Atlantic Ocean. A remotely operated vehicle (ROV) was used as a passive acoustic platform to obtain *in situ* observations of soniferous fish behavior. The project was largely unsuccessful due to the inadequacy of existing technology for this type of study and to an apparent rarity of fish sounds during the fall sampling season. Herein we relate our attempt to adapt an ROV for passive acoustic applications, report observations of fish behavior and reactions to the ROV, and provide recommendations to future researchers.

Cusk *Brosme brosme* (Ascanius 1772) is a deep-water gadid inhabiting both sides of the North Atlantic that has been listed as a "species of concern" by the National Marine Fisheries Service (NMFS) since 2004 and was proposed as a candidate for listing as endangered or threatened under the Endangered Species Act in 2007. Unfortunately, little is known of its behavior and habitat requirements. Due to the cusk's imperiled status, the lack of basic behavioral data on the species is particularly problematic. Cusk spawning appears to peak in late spring and summer in the Gulf of Maine and Georges Bank, as inferred from egg collections by the MARMAP survey program (Berrien and Sibunka, 1999). On the Scotian shelf, spawning occurs from May to August, peaking in June, but it may be earlier in the Gulf of Maine (COSEWIC, 2003). Cusk are thought to inhabit primarily hard bottom, especially near rocks or boulders, and occasionally gravel and mud (Svetovidov, 1986; Collette and Klein-McPhee, 2002; COSEWIC, 2003); however, no observations of animals in the wild have been published to date. Cusk have been reported to vary in color according to the bottoms on which they

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live (Collette and Klein-MacPhee, 2002). Color on the flanks varies, with dark slate, dull reddish brown, or pale yellow dorsally and pale gray ventrally. The belly is typically off-white in color.

Hawkins and Rasmussen (1978) suggested that cusk are soniferous due to the presence of well-developed drumming muscles used to produce sound. This is not surprising, as many members of the Gadidae are known to be vocal, including Atlantic cod *Gadus morhua*, haddock *Melanogrammus aeglefinus*, and the European pollock *Pollachius pollachius* (Hawkins and Rasmussen, 1978; Nordeide and Kjellsby, 1999; Hawkins and Amorim, 2000; Rountree et al., 2006; Luczkovich et al., 2008). Unpublished observations of cusk sounds have been made in the eastern Atlantic (Soldal, Institute of Marine Research, Bergen, Norway, personal communication), but no data are available from the western Atlantic.

1 Materials and Methods

The study was conducted aboard the *R/V Connecticut* from October 19 to October 22, 2001 within the Stellwagen Bank National Marine Sanctuary (SBNMS), where extensive prior research provided a wealth of information on habitat and fish distribution patterns. Sampling was conducted within sand, gravel, and boulder habitats at specific sites used in the SBNMS Seafloor Habitat Recovery Monitoring Program (SBNMS, 2009). All sampling was conducted within 200 m of each habitat site (Fig. 1). Sites within the Western Gulf

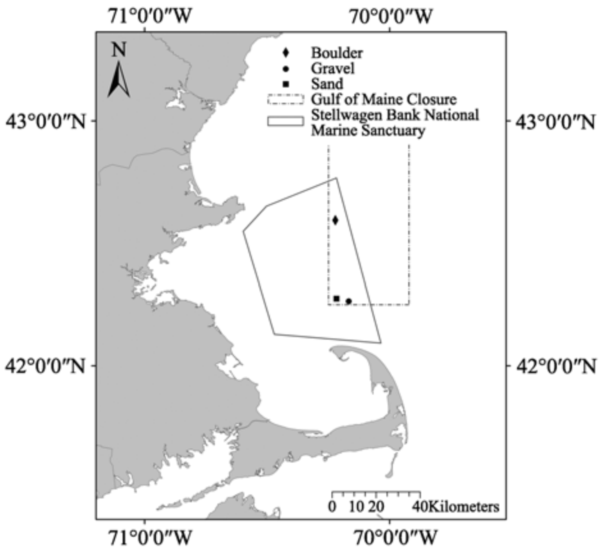

Fig. 1 Map of the study area indicating location of sand, gravel, and boulder habitat sampling locations within the closed fishing area section of the Stellwagen Bank National Marine Sanctuary

of Maine Closed Area, where commercial fishing operations are limited, were chosen to minimize sampling problems that might arise from ship noise from nearby fishing operations.

1.1 ROV deployments

Hydrophones were deployed on a Phantom III S2 ROV operated by the Northeast-Great Lakes National Undersea Research Center (NE-GL NURC). The ROV was equipped with both color and black-and-white video cameras (forward- and downward-facing; 12.7-mm CCD, 3.5-mm lens, 470 horizontal lines of resolution, NTSC format, IR filter removed) and two downward-facing parallel lasers for image calibration and estimating the height off the bottom. The system is tethered to an electro-mechanical cable for streaming video imagery and controlling camera functions and altitude in real time and it is normally flown over the seafloor while the support vessel drifts over a station. The ROV was modified to carry an array of infrared lasers to provide infrared lighting. Lights were switchable from ambient (off) to infrared or white lights. In order to minimize ship noise, all sampling was conducted with the ship moored at anchor and the engines shut down. Ship and instrument power was maintained by running either the starboard or port electric generators.

Because the ROV dive time was limited to eight hours per day, and the diel soniferous activity patterns of marine fishes in the region are unknown, we planned to make dives at noon (11:00–13:00 h), sunset (16:00–20:00 h) and evening (23:00–01:00 h) periods in each habitat. Whenever possible, the ship remained at anchor in the same location throughout the sampling for each habitat to minimize location changes. Initial dockside ROV self-noise measurements indicated that noise levels were far too high to allow monitoring of fish sounds while under power. We therefore planned to conduct each ROV dive as a roving survey in which 10-min search periods were followed by 20-min observation periods during which the ROV rested on the seafloor with its thrusters and acoustic tracking system turned off (stationary period). During the stationary period, acoustic and video observations were recorded for 10 min each with either infrared or white lights. Visibility was typically 2 m or less under infrared lights and was highly variable under white light. In addition, because our focus was to survey fish sound production, the cameras were baited with chopped fish, clams, and crabs in separate mesh bags in an effort to induce aggressive interactions among fish. Species abundances and frequency of occurrence in each habitat could not be quantified because individuals could not be tracked and in many cases appeared to follow the ROV or were resident in the immediate sampling area and repeatedly moved in and out of the field of view. In addition, quantification was made difficult because the ROV pilot frequently had to engage the ROV thrusters, acoustic tracking, and lights to correct the position of the ROV when it moved off station due to currents or heavy seas. We therefore used a subjective index to indicate fish frequency and abundance. Species sighted only once were coded as rare (R) and those sighted two or more times as present (P). Species that occurred five or more times, or that occurred in groups of three or more individuals, were coded as common (C).

1.2 Passive acoustic sampling

Three hydrophones, model TH608-40, manufactured by Engineering Acoustics, Inc. (933 Lewis Drive, Suite C, Winter Park, FL 32789) were mounted on the ROV to monitor underwater sounds. The hydrophones had a nominal sensitivity at the preamplifier output of –160.5 dB. Video and audio data were simultaneously recorded to both Hi-8 and VHS-format tapes. Multichannel audio data of selected sounds were recorded to a laptop computer. To provide system calibration information, a 1-k Hz sine wave of known voltage was played through a portable CD player into the system and recorded on the video media. In this way, the calibration signal remained part of the original video recording and was used to calibrate the received signal source level when sounds were later digitized.

Sound signal processing was conducted using Signal 4.0 (Engineering Design, Belmont, MA 02478) and SpectraPRO 3.32.18d (Sound Technology Inc., Campbell, CA 95008) acoustic software. Sounds were digitized from the video tapes at 48 kHz and 16-bit resolution. Signals were processed with a 2048-point Hanning windowed FFT with 50% FFT overlap. Power spectra were normalized to 1-Hz bandwidth by dividing by the square root of the frequency. The three hydrophones were arranged in a precisely measured triangular array to enable sound source localization in two dimensions based on time of arrival differences among hydrophone pairs (Sutin et al., in prep.)

Background noise levels were measured with the ROV sitting motionless on the bottom with all thrusters off and included ROV self-noise and noise from the nearby support ship, as well as true ambient background noise levels. Power spectra were computed for the ROV flying with all thrusters on and the acoustic tracking system off; here, we simply used periods between acoustic pings for estimating ROV noise. In addition, power spectra were computed for the acoustic tracking system with the ROV at rest and for ROV impacts (bumps) with the bottom as it drifted off station with thrusters off. Power spectra for ROV thrusters, ROV tracking system (trackpoint), and ROV bumps were compared against power spectra for the background noise to determine their frequency structure. Because recorded fish sounds also contained the background noise, we attempt to reduce noise bias on the resulting frequency structure by comparing the background noise power spectra with the fish sound power spectrum.

2 Results

Due to numerous weather delays and technical difficulties, we conducted only 10 of the 24 planned ROV dives. Dives were made in all three time periods for sand, gravel, and boulder habitats, with an additional noon dive in the boulder habitat (Table 1). We were not able to achieve stationary observations for more than a few minutes in the sand habitat dives, but good results were obtained by allowing the ROV to drag slowly along the seafloor without using thrusters (i.e., sound recordings were still possible). Observations in gravel habitats were limited due to strong currents and poor visibility from heavy suspension loads in the water column. Only two 10-min sound recordings could be obtained during each of the noon and midnight dives, while no usable recordings were obtained during the sunset dive due to saturation with ROV noise. Sunset and midnight dives were terminated early due to poor weather conditions. Stationary sampling within the boulder habitat was more successful but still problematic. Stationary durations ranged from 1–67 min, though few periods lasted more than 10 min before thrusters had to be engaged to stabilize the ROV. Bottom depths varied little in each habitat, ranging from 36–38 m, 48–53 m, and 66–70 m in sand, gravel, and boulder, respectively.

Sixteen species of fishes and one squid were observed (Table 1). Atlantic cod *Gadus morhua*, haddock *Melanogrammus aeglefinus*, Pollock *Pollachius virens*, ocean pout *Macrozoarces americanus*, and skate (*Leucoraja* spp.) were present in at least one time period in all three habitats. However, pollock were observed only at night. Atlantic cod juveniles were common in sand and gravel habitats at night, while adults were common in the boulder habitat at all times. Cunner *Tautogolabrus adspersus*, cusk, and juvenile Acadian redfish *Sebastes fasciatus* were common in boulder habitat but absent

Table 1 Species observed during October 2001 ROV survey (R = single sighting, P = present, C = common/abundant)

Common name	Species	Sand			Gravel			Boulder		
		Noon	Sunset	Midnight	Noon	Sunset	Midnight	Noon	Sunset	Midnight
Atlantic cod	*Gadus morhua*		C	C	C		C	C	C	C
Atlantic herring	*Clupea harengus*								R	
Bluefish	*Pomatomus saltatrix*			P						
Cunner	*Tautogolabrus adspersus*							C		
Cusk	*Brosme brosme*							C	C	C
Haddock	*Melanogrammus aeglefinus*			P	P			C	C	C
Atlantic hagfish	*Myxine glutinosa*						R			
Longhorn sculpin	*Myoxocephalus octodecemspinosus*	C	C	C	P	P	C			
Ocean pout	*Macrozoarces americanus*	P			P	P				P
Pollock	*Pollachius virens*			P			P		C	C
Acadian redfish	*Sebastes fasciatus*[1]							C	C	C
Red hake	*Urophycis chuss*				R					
Skate	*Leucoraja* spp.[2]	P	P	P		P	P	P	P	
Spiny dogfish	*Squalus acanthias*	C	C	C	C		C			
Longfin squid	*Loligo pealeii*			C						
Windowpaine	*Scophthalmus aquosus*		P							
Winter flounder	*Pseudopleuronectes americanus*	C	C	C	C	P	C			
No. species		5	6	9	7	4	7	6	7	6
Effort (hours)[3]		2.02	4.03	1.98	2.32	2.13	1.25	1.98	1.87	4.1

[1] Potentially includes *Helicolenus dactylopterus*. [2] *Leucoraja erinacea* and *L. ocellata*. [3] ROV thrusters on most of the time in gravel habitat sampling, where night observations were conducted in poor visibility (1 – 2 m).

from other habitats. Cunner were also only observed during noon dives. Longhorn sculpin *Myoxocephalus octodecemspinosus*, spiny dogfish *Squalus acanthias*, and winter flounder *Pseudopleuronectes americanus* were present to common in sand and gravel habitats but absent in boulder habitats.

Despite the difficulties obtaining stationary or slowly drifting observation periods without thruster noise, the methodology did yield interesting behavioral observations. Video clips illustrating observed behavior are available as an online supplement at <http: //www. fishecology.org/soniferous/stellwagen.htm>. Although not quantified, the reactions of fishes to the ROV were varied. Startle responses to ROV bumps were observed on one or more occasions for cusk, Acadian redfish, cunner, pollock, and juvenile Atlantic cod. On several occasions, Acadian redfish appeared to startle in response to the ROV acoustic tracking signal. While cunner and Acadian redfish were frequently observed in the boulder habitat by the mobile ROV, they often displayed alert behaviors such as moving away and flared fins and quickly disappeared into the background once stationary observations commenced. Neither species were observed in the vicinity of the ROV when lights were turned on after a dark observation period. Atlantic cod, haddock, longhorn sculpin, spiny dogfish, and cusk appeared to be unaffected by white lights and did not react when lights were suddenly turned on. However, Atlantic cod, spiny dogfish, and haddock appeared to be less alert and approached the ROV more closely when observed under ambient or infrared light conditions than when under white lights.

Though many species were clearly attracted to the baited ROV, only Atlantic cod, haddock, spiny dogfish, winter flounder, and cusk were observed to approach the ROV closely and attempt to feed on the bait. Cusk was the only species observed to remain in the immediate vicinity of the bait for extended periods (Fig. 2), while the other species usually remained several meters away and then moved in to briefly attack the bait before quickly moving off. Most species were attracted most frequently to the fish bait. Only cod, cusk, and haddock were occasionally observed to approach the clam bait. No species were observed to approach the chopped crab bait. All these species, together with skate and pollock, also clearly followed the drifting ROV on one or more occasions. Skate, longhorn sculpin, and winter flounder were observed feeding in the sand within the field of view of the ROV. On several occasions, large swarms of amphipods were attracted to the ROV lights as it drifted slowly just above the sea floor, creating a feeding frenzy among Atlantic cod, haddock, and pollock.

Fig. 2 Photograph of a cusk *Brosme brosme* recorded in the Stellwagen Bank National Marine Sanctuary. Two other cusk are hidden among the boulders 彩

Cusk appeared indifferent to the presence of conspecifics even when feeding, with individuals often bumping into each other and swimming over each other without obvious reactions (Fig. 2). However, cusk were highly aggressive to other species and were observed to chase away pollock, Atlantic cod, and haddock on one or more occasions. Living cusk exhibited a striking pattern of alternating dark and golden yellow bars (Fig. 2). Yellow streaks also appeared on the head through the eye and on the cheeks. The edge of the dorsal fin was trimmed with a thin black outer margin followed by a wider yellow band below.

High levels of noise were produced by the ROV thrusters, tracking system, and bumps (Fig. 3, 4, and 5). The background noise levels included strong ROV self-noise and ship noise below 3000 Hz, as well as several narrow-band peaks above 5000 Hz (Fig. 5). ROV thrusters, trackpoint, and bumps produced significant noise levels above the background throughout the measured frequency range (up to 20000 Hz; Fig. 5). Perhaps most important, each of these sources produced significant noise above the background in the frequency range below 2500 Hz, which is the range at which most fish vocalize. In particular, they all produced noise in excess of 10 dB re 1 μPA above the background below 1000 Hz. Bumps produced the greatest noise above the background below 500 Hz. However, when the ROV was stationary or drifting silently, sound quality should have been sufficient to detect soniferous fishes if present (Fig. 3, 4, and 5).

Fish sounds were not recorded in either sand or gravel habitat and occurred during only one stationary observation period in the boulder habitat. A prolonged series of intermittent calls consisting variously of isolated thumps, thump trains, and drumrolls were recorded over a 21-min period when the ROV was sitting stationary in a boulder field at a depth of approximately 65 m from about 12:02–12:22 EST (22 October 2001, Lat. N42°35.682, Lon. W70°13.2743). Although it was daylight at the surface, visibility on the bottom with the infrared lights was limited to approximately 1 m. Throughout this time, a large cusk approximately 60 cm TL was observed to slowly move in and out of the camera's field of view and apparently remained in the

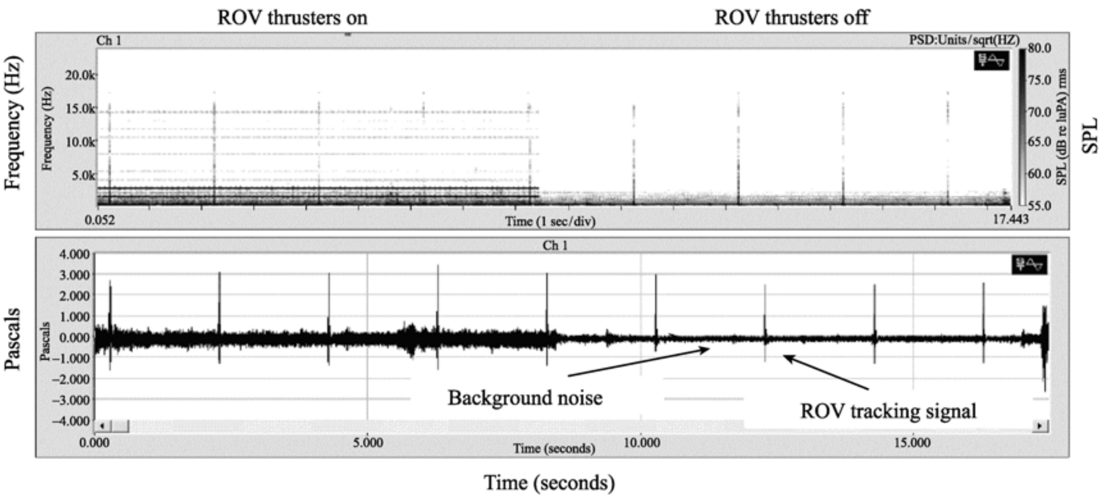

Fig. 3 Waveform (bottom) and spectrogram (top) of the noise produced by the ROV while running and sitting stationary on the bottom (2048-point Hanning windowed FFT with 50% FFT overlap)

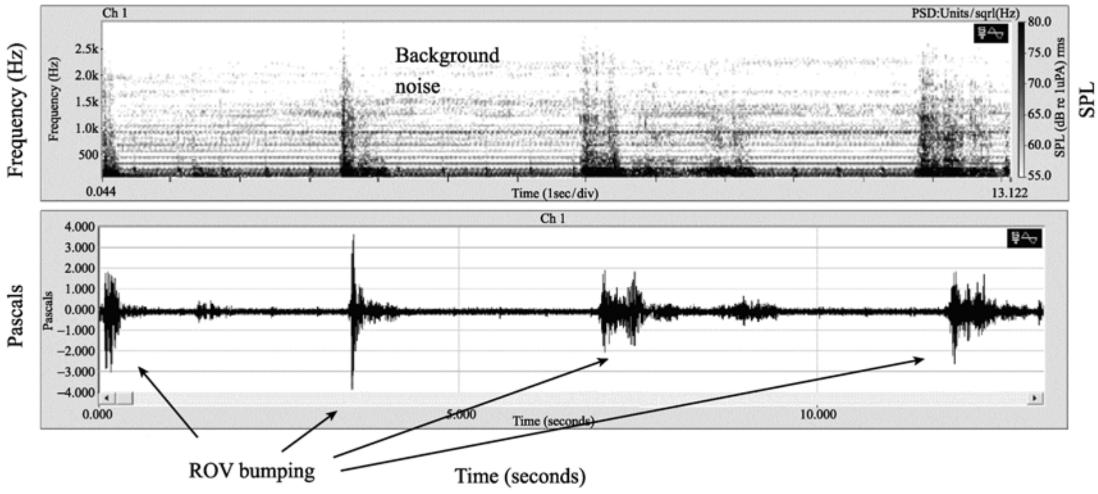

Fig. 4 Waveform (bottom) and spectrogram (top) of noise generated by the ROV bumping on the sea floor while drifting with all thrusters off and acoustic tracking system off

Amplitude and frequency structure of the background noise (including ambient background noise, ROV self-noise, and support ship noise) is evident in the space between bumps (2048-point Hanning windowed FFT with 50% FFT overlap).

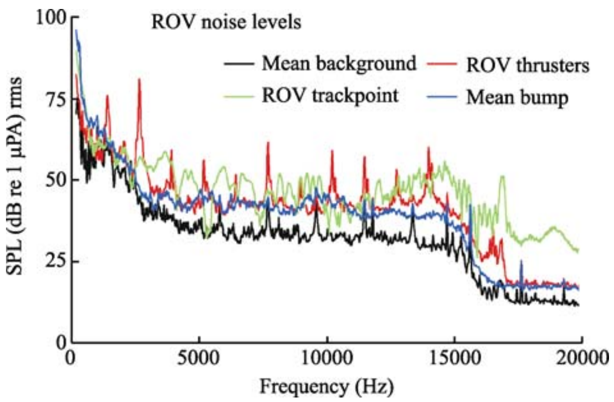

Fig. 5 Comparison of the normalized frequency power spectra of the background (black line), ROV thrusters (red line), ROV acoustic tracking signal (green line), and ROV bumps on the bottom (blue line)

immediate vicinity the entire time. The source location for one call was determined to be a maximum of 1.5 m from the ROV. Other species observed in the area during the same dive were Atlantic cod, haddock, cunner, and Acadian redfish.

A total of 34 calls averaging 27 seconds (range 2 – 264 s) apart were recorded during this 21-min period. We divided calls into three types: 1) isolated thumps or thump trains ($n = 7$), 2) closely spaced thump trains termed "drumrolls" ($n = 20$), and 3) composite calls ($n = 7$) consisting of a thump train followed by a drumroll. The signal to noise ratio was too low to determine call characteristics for many of the calls. Thump trains averaged 832 msec in duration (range 253–1163 msec; $n = 5$) and contained 2–5 thumps, with a pulse period averaging 186 msec (range 63–233 msec). Drumrolls averaged 925 msec (range 163–1697 msec; $n = 11$) and contained 5–22 thumps. However, this is likely an underestimate, since the drumroll quickly fell below the noise level as it progressed. Composite calls were difficult to measure but typically contained a thump train with 1–13 thumps followed by a drumroll after a pause of 558–1419 msec. In one example, the thump train consisted of 13 thumps spaced at intervals of 197–249 msec followed by a drumroll with 16 thumps spaced at intervals of 32–37 msec (Fig. 6). Duration of a single knock ranged from 2.1–2.5 msec. High noise levels below 200 Hz and strong noise bands at higher frequencies are also evident in the spectrogram (Fig. 6). The normalized power spectrum of the thump train and drumroll components of the call are similar and most pronounced above the background noise below 1000 Hz, though a secondary peak occurs at about 1200 Hz (Fig. 7).

The determination of the average frequency structure of the unknown call was complicated by the high levels of ROV and ship noise. We attempted to correct for this by comparing average power spectra for background noise ($n = 3$), thump trains ($n = 5$), and drumrolls ($n = 12$). Although the dominant peaks were 117, 188, 305, 891, and 1195 Hz, only peaks at 188, 539, and 1195 Hz contained significant energy above the background noise (Fig. 8). We conclude that the dominant frequency of the call was 188–539 Hz, with a secondary peak at 1195 Hz.

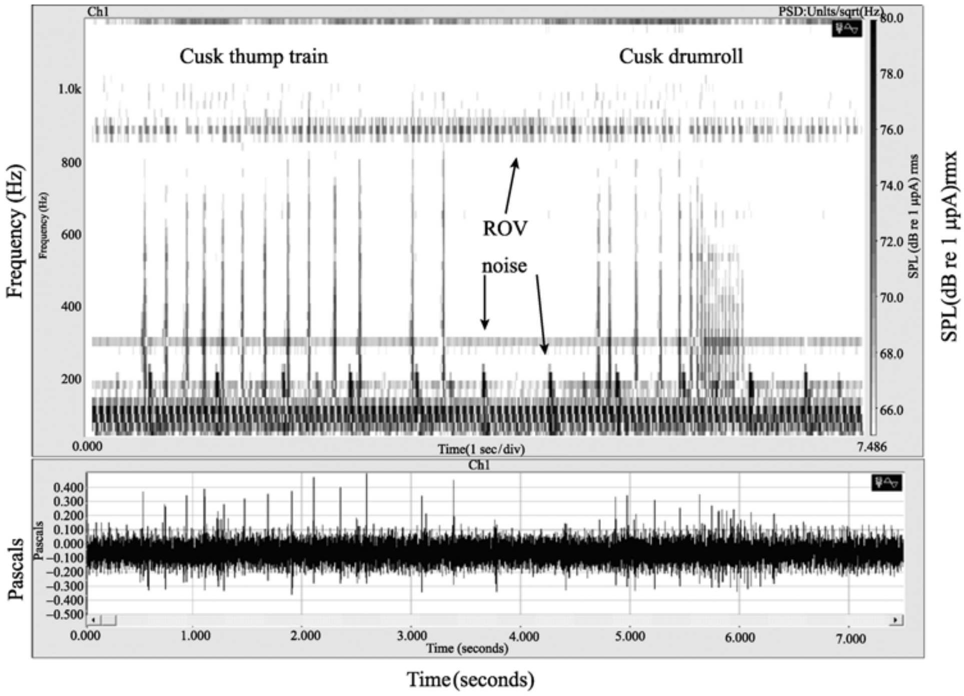

Fig. 6 Waveform (bottom) and spectrogram (top) of a representative example of a composite-type presumed cusk call consisting of a thump train followed by a drumroll (2048-point Hanning windowed FFT with 50% FFT overlap)

An audio file of this, and other sound samples, are available as an online supplement at http://www.fishecology.org/soniferous/stellwagen.htm>

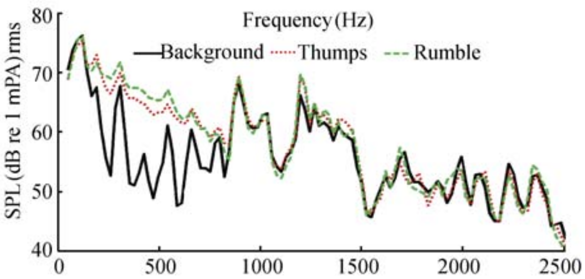

Fig. 7 Comparison of the normalized power spectra of the thump train (dotted line) and drumroll (dashed line) sections of the presumed cusk call shown in Figure 6 with the power spectrum of the background noise measured immediately prior to the cusk call (solid line)

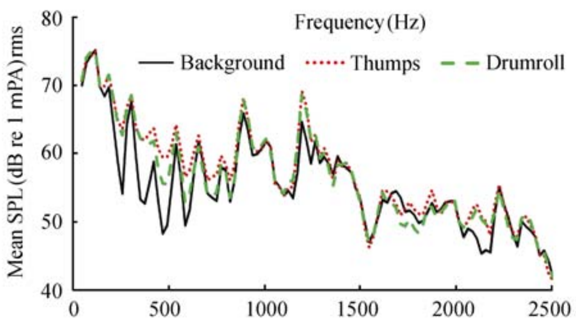

Fig. 8 Comparison of mean normalized power spectra for presumed cusk thump trains (dotted line, *n* = 5), drumrolls (dashed line, *n* = 12), and background noise (solid line, *n* = 3) averaged over multiple calls

3 Discussion

The ROV was not an ideal platform for a passive acoustic survey because it is not designed to make prolonged observations at a specific location without using the noise-generating thrusters. However, when operating under ideal field conditions, we were able to obtain useful behavioral information and sound recordings adequate to monitor potential sound production by fishes. Our observations of fish behavior were significant, as so little is known of the behavior of many of Gulf of Maine fishes, especially for the imperiled cusk. Information on species' competitive interactions is necessary to fully understand habitat use patterns and community structure. The surprising lack of interest in crab bait was among the more interesting observations. Based on our knowledge of the diets of Gulf of Maine fishes (Rountree, 1999), we expected crabs to attract a variety of species such as cunner. Indeed, we have observed juvenile cunner to aggressively attack baited drop cameras in regional estuaries. Another interesting observation was the apparent visual signaling behavior exhibited by the longhorn sculpin. This species is noted for its long head spines, which it can erect when threatened (Munroe, 2002). Although its soniferous behavior is not well studied, longhorn sculpin are known to produce a low-amplitude humming sound when disturbed

(Fish, 1954; Fish and Mowbray, 1970). We suspect that the humming disturbance sound may have accompanied the visual display but was masked by the ship and ROV noise. Our hypothesis of combined visual and acoustic signaling to ward off a potential predator could be tested in the laboratory, since the species is not difficult to maintain in captivity.

Why cunner and Acadian redfish apparently avoided the ROV is uncertain, but both species were observed to frequently exhibit agitated behavior when near the ROV and startle responses to ROV noises. We were surprised to observe apparent startle responses of Acadian redfish to the acoustic trackpoint pings on several occasions. The trackpoint system produces an intense broadband acoustic signal with significant energy below 1000 Hz, which is within the auditory range of many fishes (Kasumyan, 2005). If these observations are verified in future studies, ROV designers should consider using higher frequency signals for ROV tracking. It is also obvious that ROV-generated noise can constitute a significant bias in visual surveys for some species and suggests that new ROVs should be designed for low noise production.

Probably the most significant problem in using an ROV for this type of survey was the difficulty in setting the ROV on the sea floor for extended lengths of time to obtain behavioral observations. In hindsight, we suspect that better results could have been achieved by allowing the ROV to drift without power several meters above the sea floor and to dive to the sea floor if fish sounds were detected. In that way, a larger area could be surveyed. Ultimately, however, we suggest that new instruments are needed that are designed to make prolonged bottom observations at a location, but are capable of moving to new locations as desired. Such machines would more closely emulate underwater surveys conducted by human divers. Another significant problem limiting our ability to observe soniferous fish behavior is that it is often disturbed by artificial lights. Instruments that couple passive acoustics with acoustic imaging, sonar, and low-light video technologies would be more effective (Rountree, 2008).

Our observations of the high noise production of the ROV, together with startle responses of fishes to ROV thruster and bumping sounds as well as the tracking signal, suggest a potential source of bias from platform self-noise in underwater video surveys. It is also clear that the high amount of noise generated by the ROV in flight (Fig. 4) would completely mask the unknown fish sounds over their dominant frequency range (Fig. 8). It was also apparent that ROV bumps were much more likely to induce alarm and startle response of fishes than were ROV thruster pulses, which is likely due to the higher energy of the bumps below 1000 Hz compared to the ROV thruster sounds. The potential biasing effects of ROV noise on fish behavior research has only recently been recognized and is poorly understood at this time (see review by Stoner et al., 2008). Although largely anecdotal in nature, our observations are among the most detailed currently available and strongly suggest the need for additional studies of the influence of observation system self-noise on fish behavior.

The most striking observation during our survey was the scarcity of fish sounds in the study area. However, we see a pattern of limited fish sound production in regional estuaries during the fall months and diverse sound production in the sring and summer (Rountree and Juanes, unpublished data), suggesting these results are likely due to the low diversity of species that spawn during the fall in the Gulf of Maine (Collette and Klein-MacPhee, 2002).

Among the species observed during our study, 10 are known or potential sound producers (Table 2). We can immediately rule out Atlantic cod, Atlantic herring *Clupea harengus*, and longhorn sculpin as candidates for the unknown sound source due to important differences in call structure. Atlantic cod calls are well studied and consist of isolated low-frequency groans, rather than knock trains (Hawkins and Rasmussen, 1978). Atlantic herring sounds are high-frequency, fast repetitive ticks produced by air bubbles release from the anus (Wilson et al., 2003). Longhorn sculpin produce low-frequency growls with strong harmonic structure and fundamental frequencies well below 100 Hz (Fish and Mowbray, 1970). We can also safely rule out bluefish *Pomatomus saltatrix*, pollock, and red hake *Urophycis chuss* as candidates. Bluefish have only been reported to produce weak, low-frequency knocks during mechanical or electrical stimulation, and their status as true soniferous species is uncertain. In addition, bluefish were only observed briefly on two occasions in sand habitat and were never observed in boulder habitat. It is therefore very unlikely they could have produced repeated calls within 1.5 m of the ROV over a 21-min period. A similar argument can be made to eliminate red hake as the sound source (Table 2). Pollock were common in the boulder habitat, but were never observed during the day and usually did not approach within 2 m of the ROV except for rapid dashes to forage on amphipods. In addition, although pollock have been reported to produce weak

Table 2 Soniferous and potentially soniferous fishes observed during the October ROV survey in the Stellwagen Bank National Marine Sanctuary

Common name	Sound production	Stimulus	Peak frequency (Hz)	Source
Atlantic cod	Strong	S	95	Hawkins and Rasmussen, 1978
Atlantic herring	Strong	S	3000 – 5000	Wilson et al., 2003
Bluefish	Weak	MS, ES	<50 – 140>	Fish, 1954; Fish and Mowbray, 1970
Cunner	Weak	ES	150 – 300 <188>	Fish, 1954; Fish and Mowbray, 1970
Cusk	Unknown		<109, 250, 500>	Sodal (pers. comm., Inst. Mar. Res. Bergen, Norway).
Haddock	Strong	S	64 – 163	Hawkins and Rasmussen, 1978
Longhorn sculpin	Strong	S	50 – 100 < 64 with harmonics to 1000>	Fish, 1954; Fish and Mowbray, 1970
Pollock	Weak	MS	?	Fish, 1954; Fish and Mowbray, 1970
Acadian redfish	Unknown		?	
Red hake	Weak	ES	<48>	Fish, 1954; Fish and Mowbray, 1970

The sound production column refers to our subjective interpretation of the strength of sound production based on descriptions in the literature and our examination of the original sound recordings. Stimulus codes are MS = mechanical, ES = electrical, and S = spontaneous sound production. MS includes chasing, touching, handling, catching, holding, etc. Peak frequency estimates enclosed in < > were determined by the authors based on examination of original source materials.

thumps during mechanical stimulation in the laboratory (Fish, 1954; Fish and Mowbray, 1970), Hawkins and Rasmussen (1978) concluded that they are not soniferous because adults lack sonic muscles typical of other gadids.

The remaining four species, haddock, cusk, cunner, and Acadian redfish are potential candidates. The unknown call shares some similarities with haddock calls, which also often consist of a variable length thump train followed by a drumroll (Hawkins and Rasmussen, 1978). However, haddock sounds are well described and occur primarily during the spring spawning season rather than the fall. Sonic muscles atrophy after the spawning season and follow the same seasonal development cycle as the gonads (see review in Rountree et al., 2006), making it more unlikely that a haddock could have produced such sounds in the fall. Finally, the dominant frequency of haddock is below 64–163 Hz and of long duration (up to 10000 msec), whereas we report dominant frequencies of 188–539 Hz and durations only up to 1697 msec for the unknown call.

Little is known about the potential soniferous behavior of either cunner or Acadian redfish. Adult cunner were common in the boulder habitat and have an extended spawning season from May through November (Munroe, 2002), but appeared to strongly avoid the ROV and were unlikely to have remained within 1.5 m of the ROV during the 21-min sound production period. Fish and Mowbray (1970) only recorded isolated thumps from electrically shocked individuals and failed to record sounds under natural conditions in the laboratory. They further noted that cunner do not appear to have a specialized sonic mechanism. Although Fish and Mowbrey (1970) failed to obtain sounds in limited laboratory testing of Acadian redfish, they noted reports of potential sounds from other scorpaenids. Most recently, sounds of several Pacific species of *Sebastes* have been reported (Sirovic et al., 2009) with frequency ranges overlapping the lower range of those we observed in the unknown sounds. In addition, Acadian redfish are known to mate in the late fall and winter (Klein-MacPhee and Collette, 2002), and thus it is possible that our October sampling occurred in the early stages of the reproductive period. However, we suggest Acadian redfish are unlikely to be the source of the unknown calls, since no adults were observed and the species appeared to avoid the immediate vicinity of the ROV, which is where the sounds originated.

By this process of elimination, we conclude that the cusk is the most likely candidate for the unknown sound source. Cusk have long been hypothesized to be soniferous based on the presence of well-developed sonic muscles (Hawkins and Rasmussen, 1978), but their sounds have not yet been described. The cusk behavior we observed during the period of sound production also supports this conclusion, as it was the only species observed to remain within the immediate vicinity of the ROV throughout the period and was frequently observed within 1 m of the cameras. A comparison with recent unpublished observations of cusk sounds while defending bait attached to cameras in the eastern Atlantic supports our conclusion (A. Sodal, Inst. Mar. Res. Bergen, Norway, personal communication). One example of an aggression call provided to the authors was similar to the drumroll calls we observed, with 38 thumps, a duration of 1.99 s, and dominant frequency peaks at 109, 250, 500, and 687 Hz. The interval between thumps was 33–38 msec, which also agreed well with our drumroll sounds, but thumps were approximately 11.5 msec in duration and were composed of two pulses, while ours were only 2.1–2.5 msec and composed of a single pulse. Therefore, although we have tentatively attributed our unknown sounds to cusk, additional field and laboratory data are needed to confirm our findings.

The lack of observations of cusk in habitats other than boulder agrees with previous research and confirms the importance of rock outcroppings to the species, which likely serve as refuges from fishing. Our observations on the alternating yellow- and dark gray-barred color pattern of cusk differ slightly from that previously described (Collette and Klein-MacPhee, 2002), probably because the bars fade quickly upon death. Due to the cusk's imperiled status and the paucity of existing data, research on the species' behavior, ecology, and habitat requirements is urgently needed. Unfortunately, its cryptic behavior, high sampling mortality, and restriction to deep-water boulder habitats make the cusk a particularly problematic species to study. Acoustical technologies provide a means to learn more about the behavior and distribution of elusive fish species such as the cusk.

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References

Berrien PL, Sibunka J, 1999. Distribution patterns of fish eggs in the U.S. northeast continental shelf ecosystem, 1977 – 1987. NOAA Tech. Rept. NMFS No. 145.

Collette BB, Klein-MacPhee G, 2002. Bigelow and Schroeder's Fishes of the Gulf of Maine. Washington, DC: Smithsonian Institution Press.

COSEWIC 2003. COSEWIC Assessment and Status Report on the Cusk *Brosme brosme* in Canada. Ottawa: Committee on the Status of Endangered Wildlife in Canada.

Fish MP, 1954. The character and significance of sound production among fishes of the western North Atlantic. Bull. Bing. Ocean. Coll. 14: 1–109.

Fish MP, Mowbray WH, 1970. Sounds of Western North Atlantic Fishes. Baltimore, MD: Johns Hopkins Press.

Hawkins AD, 1993. Underwater sound and fish behavior. In: Pitcher TJ, ed. Behavior of Teleost Fishes, 2nd edn. London: Chapman & Hall, 129–169.

Hawkins AD, Amorim MCP, 2000. Spawning sounds of the male haddock *Melanogrammus aeglefinus*. Environ. Biol. Fish. 59: 29–41.

Hawkins AD, Rasmussen KJ, 1978. The calls of gadoid fishes. J. Mar. Biol. Ass. U.K. 58: 891–911.

Kasumyan AO, 2005. Structure and function of the auditory system in fishes. J. Ich. 45: S223–S270.

Klein-MacPhee G, Collette BB, 2002. Scorpionfishes. Family Scorpaenidae. In: Collette BB, Klein-MacPhee G ed. Bigelow and Schroeder's Fishes of the Gulf of Maine, 3rd edn. Washington, DC: Smithsonian Institution Press, 331–338.

Luczkovich JJ, Mann DA, Rountree RA, 2008. Passive acoustics as a tool in fisheries: An introduction to the American Fisheries Society Symposium. Trans. Am. Fish. Soc. 137(2): 533–541.

Munroe TA, 2002. Wrasses. Family Labridae. In: Collette BB, Klein-MacPhee G ed. Bigelow and Schroeder's Fishes of the Gulf of Maine, 3rd edn. Washington, DC: Smithsonian Institution Press, 448–466.

Nordeide JT, Kjellsby E, 1999. Sound from cod at their spawning grounds. ICES J. Mar. Sci. 56: 326–332.

Rountree RA, Gilmore RG, Goudey CA, Hawkins AD, Luczkovich J, et al., 2006. Listening to fish: applications of passive acoustics to fisheries science. Fish. 31(9): 433–446.

Rountree RA, 1999. Diets of NW Atlantic fishes and squid. <http://www.fishecology.org> Accessed 20 August 2009.

Rountree RA, 2008. Do you hear what I hear? Future technological development - and needs - in passive acoustics underwater observation. Marine Tech. Rep. 51(9): 40–46.

Sirovic A, Cutter GR, Butler JL, Demer DA, 2009. Rockfish sounds and their potential use for population monitoring in the Southern California Bight. ICES J. Mar. Sci. 66: 981–990.

Stellwagen Bank National Marine Sanctuary (SBNMS), 2009. Seafloor Habitat Recovery Monitoring Program. <http://stellwagen.noaa.gov/science/shrmp.html> Accessed 20 August 2009.

Stoner AW, Ryer CH, Parker SJ, Auster PJ, Wakefield WW, 2008. Evaluating the role of fish behavior in surveys conducted with underwater vehicles. Can. J. Fish. Aquat. Sci. 65: 1230–1243.

Svetovidov AN, 1986. Gadidae. In: Whitehead PJB et al. ed. Fishes of the northeastern Atlantic and the Mediterranean, Vol. 2. Paris: UNESCO, 680–710.

Wilson B, Batty RS, Dill LM, 2003. Pacific and Atlantic herring produce burst pulse sounds. Biol. Lett. 271: 95–97.