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Passive acoustic monitoring of Haddock in the Gulf of Maine: Preliminary results

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A “Passive Acoustic Monitoring” (PAM) survey of haddock sounds was conducted in collaboration with commercial fishers in the inshore regions of the Gulf of Maine (GOM) during 2003-2004 and 2006-2007 using bottom mounted “Autonomous Underwater Listening Stations” (AULS). Haddock sounds were observed in 34 of 59 deployments, however call rates were highly variable both spatially and temporally. Haddock sounds averaged 0.7 call/h and 40.5 knocks/h. A strong nocturnal spawning pattern was observed. A significant correlation between haddock call rate and the “Catch Per Unit Effort” (CPUE) of ripe-and-running female haddock demonstrates that PAM is a potentially powerful tool to supplement stock assessment surveys. Haddock sounds indicative of spawning behavior were observed well into July suggesting that spawning of inshore populations of haddock in the GOM extends over a longer season than generally thought. Further the intro- and inter-annual variability in diel periodicity of both haddock sound production and CPUE of haddock in spawning condition suggest spawning behavior is highly plastic in the species and caution is advised when attempting to extrapolate observation from one region to another. This study demonstrates that PAM is an important new tool that can provide supplemental data to traditional fisheries data for haddock and other soniferous fishes.

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1. INTRODUCTION

Although haddock (*Melanogrammus aeglefinus*, Gadidae) is one of the historically most important fish stocks in the northwest Atlantic (Bigelow and Schroeder, 1953; Collette and MacPhee, 2002), relatively little is known of their essential fish habitat (EFH) requirements (Cargnelli *et al.,* 1999). Resource managers and commercial fishers recognize the need for a better understanding of haddock habitat requirements. The essential fish habitat source document for haddock concludes that "Detailed information on spawning is needed; our literature search uncovered few spawning details, other than the fact that spawning occurs at the bottom over gravel substrate" (Cargnelli *et al*., 1999). Although Georges Bank and Browns Bank are considered the major spawning areas in the Gulf of Maine (GOM), Jefferies Ledge and Stellwagen Bank are important inshore spawning areas. Ames (1997) reported other important inshore spawning areas including Casco Bay based on interviews with commercial fishers and historical records. The relative contribution of these inshore spawning areas to the GOM haddock stock is uncertain.

Reports on the haddock spawning season are somewhat confused by geographic and inter-annual differences. Spawning is most often reported as occurring during January-June with average peak spawning during late March to early April primarily over pebble and gravel substrates (Cargnelli *et al*., 1999) which appears to be based primarily on information from offshore locations. However, haddock spawning has been reported as late as August and September on the Scotian Shelf (Templeman and Bishop 1979, Waiwood and Buzeta 1989). There appears to be a general pattern of earlier spawning within the southern range, and progressively later spawning moving north (Cargnelli *et al.,* 1999). On Stellwagen Bank haddock were found to exhibit a strong diel periodicity in spawning based on macroscopic examination of gonad maturation stages (Burchard *et al.,* 2014). On average, spawning peaks during the night but some spawning occurs throughout the day. Diel periodicity was only observed in late maturation stages indicative of imminent spawning (e.g., ripe-and-running females). However, there was considerable variation in the diel spawning pattern between early and late season and between years (Burchard *et al.,* 2014).

Passive acoustic monitoring (PAM) is becoming an increasingly important tool in fisheries (Rountree *et al.,* 2006; Luckovich *et al.,* 2008) and ecological studies (see review in Lindseth and Lobel, 2018). A strong correlation between vocal activity and the spawning cycle appears to be a trait of most gadids (Hawkins and Rasmussen, 1978; Hawkins, 1986; Hawkins and Picciulin, 2019). Soniferous behavior of haddock has been well described based on observations of captive individuals (Hawkins and Chapman, 1966; Hawkins *et al.,* 1967; Hawkins and Amorim, 2000; Casaretto and Hawkins, 2002; Bremner *et al.,* 2002; Casaretto *et al.,* 2015a,b; 2016). Haddock produce sounds predominantly in the frequency range of 80-500 Hz by the drumming of sonic muscles attached to the gas bladder. The sonic muscle is sexually dimorphic in haddock being significantly larger in the mature males than in females (Templeman and Hodder, 1958; Hawkins *et al.,* 1967; Templeman *et al.,* 1978). In addition, the sonic muscle undergoes a seasonal maturation cycle in concert with the gonad maturation cycle. Haddock produce variable trains of knock or thump sounds that vary in the repetition rate at different stages of courtship. Individual haddock knocks are distinguishable from other gadid sounds by their unique double-pulse structure (Hawkins and Rasmussen, 1978; Casaretto *et al.,* 2014), however, the specific pattern of the double pulses can also be used to differentiate between haddock gender and between juvenile and adult haddock (Casaretto *et al.,* 2015a,b; 2016).

Despite the high importance of the haddock fishery and significant gaps in our knowledge of the habitat requirements of the species, few studies have attempted to use PAM methodologies to examine their distribution and spawning patterns. Field studies have been primarily limited to the eastern Atlantic (Soldal *et al.,* 2000; Casaretto *et al.,* 2014; Hawkins 2002; Hawkins *et al.,* 2002; Langård *et al.,* 2008). Rountree and Juanes (2010) attempted the first PAM survey of Stellwagen Bank in the Gulf of Maine, but failed to record haddock sounds despite extensive observations of haddock behavior around baited cameras. However, cusk (*Brosme brosme*, Gadidae) were observed to produce similar knock trains as that of haddock but their knocks were composed of single pulses. Most recently Stanley *et al.* (2017) reported haddock sounds during a survey of anthropogenic noise on Stellwagen Bank in the months of January-March 2006 and concluded that vessel noise can significantly mask haddock sounds which had a reduced effective vocalization range of 2.2 m or less.

In this study a survey of haddock sounds was conducted in the inshore regions of the Gulf of Maine in collaboration with commercial fishers operating primarily on traditional groundfish fishing grounds off Casco Bay, on Jefferies Ledge, and on Stellwagen Bank in order to examine the utility of using PAM to document haddock distribution and spawning patterns in the region. In addition, the spawning activity of haddock captured while simultaneously monitoring sound production in the capture vicinity was determined to examine the

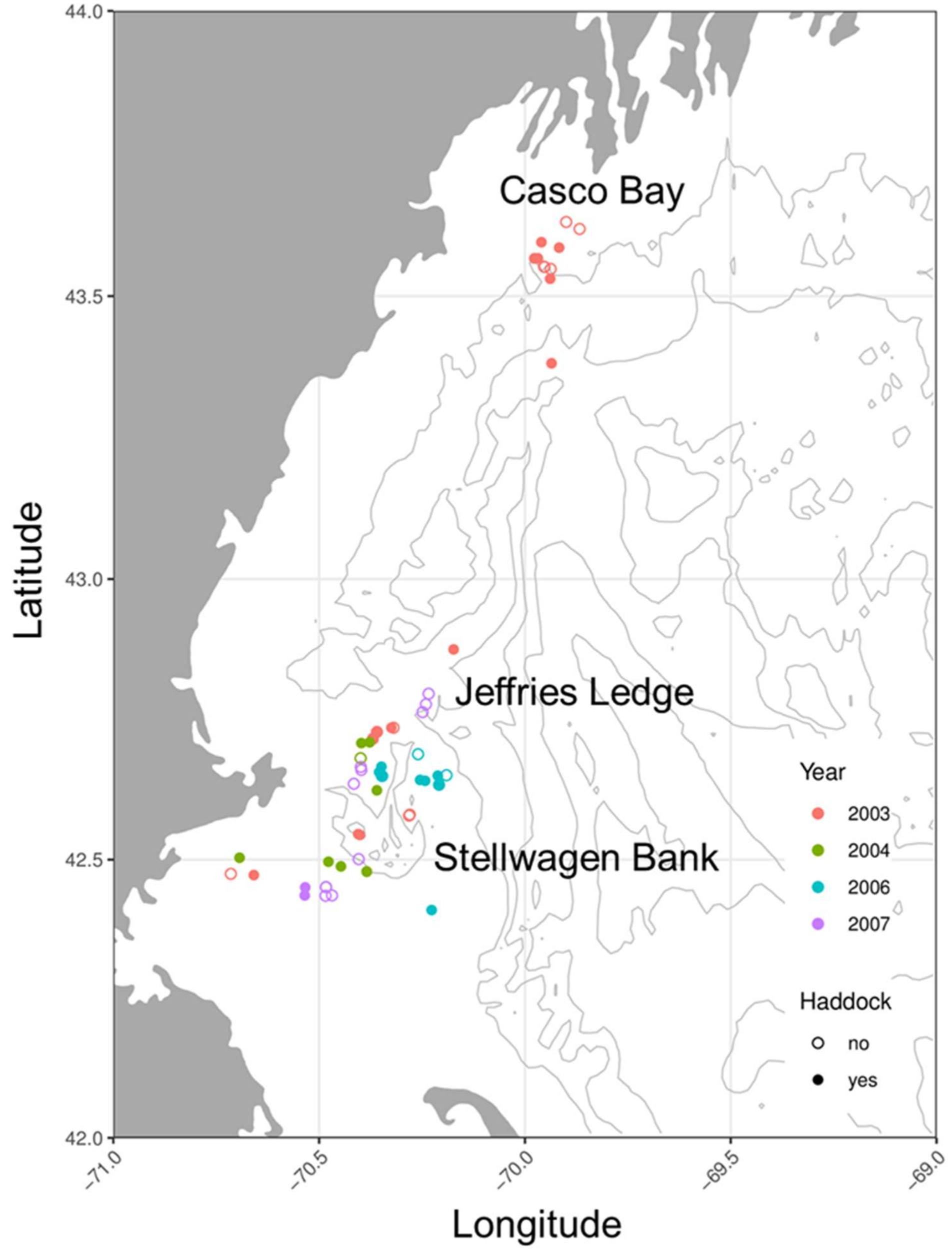

Figure 1. Study area within the Gulf of Maine. Locations where automatic underwater listening stations were deployed are shown by year. Haddock sounds were recorded at the locations indicated by the filled circles.

correlation between spawning activity and sound production in the wild.

2. METHODS

Bottom mounted passive acoustic monitoring equipment hereafter referred to as "Autonomous Underwater Listening Stations" (AULS) were deployed on the commercial fishing grounds in the Gulf of Maine during 2003-4 and 2006-7 (Fig. 1). The AULS housing contained a Nomad Jukebox® (Creative Labs, Inc., Milpitas, CA) digital recorder and an HTI-96-MIN hydrophone (High Tech Industries, Gulfport, MS; sensitivity -165 dB re: 1 V/□Pa, frequency response: 2 Hz to 30 kHz). The Nomad, gel cell, and custom interface circuitry fit into a compact pressure housing made from polyethylene gas pipe end caps machined to accommodate an O-ring and held together with a band clamp (Fig. 2). The housing was pressure tested to the equivalent of 250 m of seawater. The Nomad had a 10 GB hard drive and was programmed to record continuously an 11 kHz sampling rate for up to 60 hours and saved uncompressed wav files every 15 minutes. Because the AULS were deployed on heavily fished commercial fishing grounds, they were protected by a steel frame which also provided stability on the seafloor. Fishers deployed the AULS using a two-anchor system (Fig. 3). An AULS was positioned mid-way between two buoyed anchors along a sinking groundline. This mooring system reduced sound contamination from strumming of the mooring line, and allowed recovery of the AULS if the buoys were lost.

Figure 2. Automatic Listening Station (AULS) used to record haddock sounds in the Gulf of Maine during 2003-2004 and 2006-2007. Left: Complete AULS in protective steel mount ready for deployment. Right: Nomad recorder shown inside housing prior to sealing.

During 2003-4 commercial fishers deployed the AULS in 44 to 106 m depths on active fishing grounds primarily in the areas of Casco Bay, Jefferies Ledge and Stellwagen Bank within the Gulf of Maine (Fig. 1). The Nomad recorders were programmed and set to record prior to being sealed in the housing and up to several hours before being deployed. Typically, the AULS were retrieved two or more days after deployment when the fisher returned to the area. Recording times ranged from 28 to 54 h (mean = 50 h). During 2006-7 the AULS were deployed on Stellwagen Bank as part of a study of haddock spawning periodicity (Burchard *et al.,* 2013; 2014). AULS were deployed near baited longlines for 3 to 12 h (mean = 9 h) prior to retrieval. Spawning condition of haddock were assessed from the long-line catches (see Burchard *et al.,* 2013; 2014) for comparison with sound production. Briefly, baited long lines were set in the vicinity of an AULS in one of four six-hour time bins over a one to two-week period to obtain representative 24-hour sampling. Sex, fork length and reproductive maturity of approximately 2000 haddock were recorded at sea. Catch per unit effort (CPUE) was standardized as hook-hours. Subsamples of haddock from each deployment were obtained for histological examination of maturation stage, and for determination of the gonadosomatic index. A detailed description of the sampling methodology and temporal spawning patterns based on maturation stage are provided in Burchard *et al.* (2013; 2014).

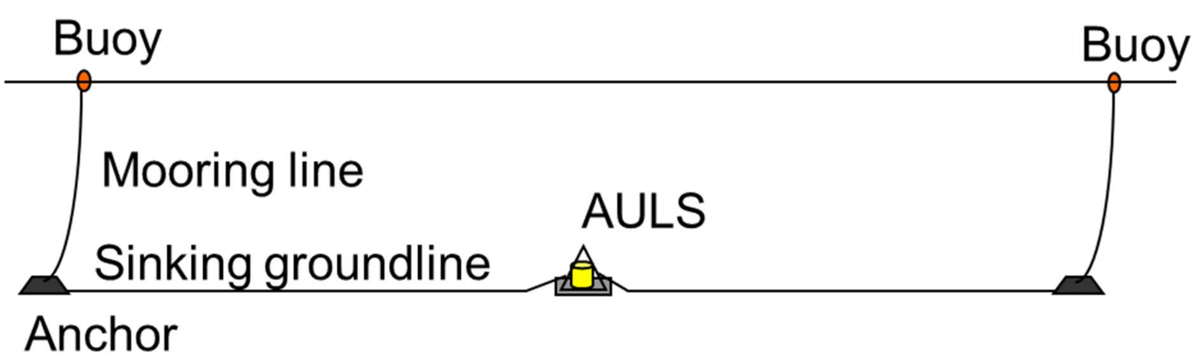

Figure 3. Mooring configuration used to deploy the AULS on the fishing ground.

Post-processing of acoustic signals was conducted by viewing the sound's spectrogram (1024 FFT, Hanning window, 50% overlap) and waveform of the entire file in 15 s windows with Raven Pro 1.5 acoustic software (Bioacoustics Research Program, 2014). In addition, all haddock sounds were listened to. Haddock sounds were identified based on the double pulse waveform previously described for the species from European waters (Hawkins and Rasmussen, 1978; Casaretto *et al.,* 2014). In addition, an automatic detector of haddock knocks was applied to the data for comparison with manual detections (results to be presented elsewhere). All haddock knocks were examined for the diagnostic double pulse waveform in the 2006-2007 data set. Haddock knock trains were arbitrarily grouped into individual "calls" separated by at least two seconds between the last knock of one call and the first of knock of the next call. Due to the high number of haddock sounds in the 2003-2004 data, the double pulse structure of individual knocks was only examined for one or more knocks within each call. The number of knocks were counted for each haddock call. Call duration was measured as the time between the start of the first knock and the end of the last knock. Knock rate was determined as the number of knocks divided by the call duration. The number of calls and call rate were measured for each 15-minute recording and converted to mean call and knock rate per hour for each deployment for spatial and temporal comparisons.

3. RESULTS

Table 1. Percent of deployments with haddock sounds (nd = no data).

Year	February	March	April	May	June	July	Total
2003	nd	nd	nd	100	69	33	67
2004	nd	nd	100	100	100	100	100
2006	100	25	100	83	100	nd	71
2007	nd	0	0	17	nd	nd	8
Total	100	14	60	67	75	43	59

Table 2. Haddock call and knock rates per deployment by month and year (SE = standard error).

			Calls/h			Knocks/h		
Year	**Month**	**Deployments**	**Mean**	**SE**	**Maximum**	**Mean**	**SE**	**Maximum**
2003	May	5	2.98	0.69	4.70	68.71	31.60	191.77
2003	June	13	0.86	0.60	7.87	133.04	118.02	1547.08
2003	July	6	0.25	0.19	1.20	13.73	13.29	80.15
	2003 total	24	1.15	0.40	7.87	89.81	63.98	1547.08
2004	April	5	0.31	0.15	0.85	4.20	2.28	12.54
2004	May	1	0.00		0.00	0.00		0.00
2004	June	1	0.05		0.05	2.29		2.29
2004	July	1	0.49		0.49	111.88		111.88
	2004 total	8	0.26	0.11	0.85	16.89	13.65	111.88
2006	February	1	0.15		0.15	0.30		0.30
2006	March	4	1.46	1.46	5.85	14.31	14.31	57.23
2006	April	1	0.44		0.44	1.33		1.33
2006	May	6	0.46	0.17	1.14	2.31	1.07	6.86
2006	June	2	0.95	0.15	1.09	11.95	8.95	20.91
	2006 total	14	0.79	0.40	5.85	6.90	4.14	57.23
2007	March	3	0.00	0.00	0.00	0.00	0.00	0.00
2007	April	4	0.00	0.00	0.00	0.00	0.00	0.00
2007	May	6	0.15	0.15	0.91	0.79	0.79	4.73
	2007 total	13	0.07	0.07	0.91	0.36	0.36	4.73
All		59	0.71	0.20	7.87	40.54	26.33	1547.08

A. HADDOCK OCCURRENCE

Haddock sounds were observed in 34 of 59 deployments (Fig. 1, Table 1), however call rates were highly variable both spatially and temporally (Fig. 1, Table 2). Haddock sounds averaged 0.7 call/h and 40.5 knocks/h, with a maximum mean rate of 2.98 call/h in May 2003 and 1547 knocks/h in June 2003. Maximum rates of 8 calls/h and 1547 knocks/h were observed during one deployment in June 2003. Haddock sounds were recorded on both the earliest (22 February 2006) and latest deployments (18 July 2004) within the year (0.15 calls/h and 0.30 knocks/h, and 0.5 calls/h and 112 knocks/h, respectively).

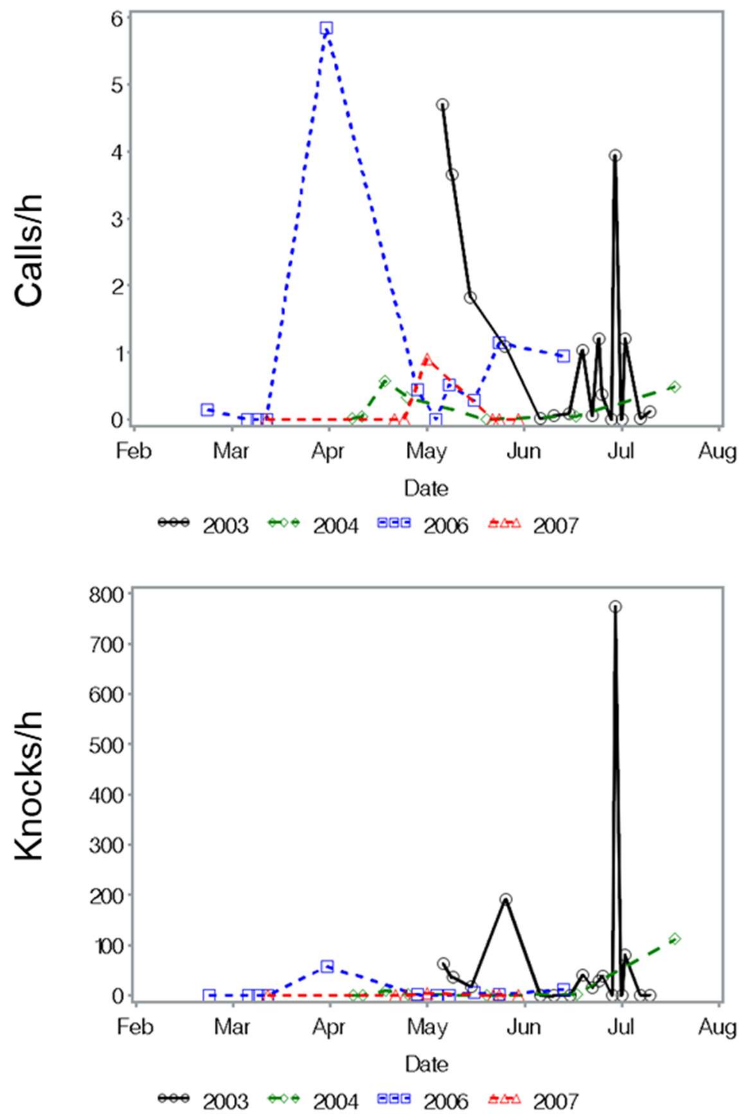

Figure 4. Comparison of mean call (top) and knock (bottom) rates by date among years.

B. DIEL AND SEASONAL TRENDS

Haddock call and knock rates were highly variable throughout the season and among study years (Table 2, Fig. 4). Significant sound production occurred in both spring and summer, with some of the highest rates occurring in June and July. Haddock were recorded on only one deployment during 2007 despite high catches of spawning haddock nearby (Buchard *et al.,* 2014). Despite the high variation in sound production, a weak correlation between the seasonal occurrence of haddock calls with the abundance of ripe and running male and female haddock was observed during 2006 (Fig. 5). Sound production was not correlated with any other

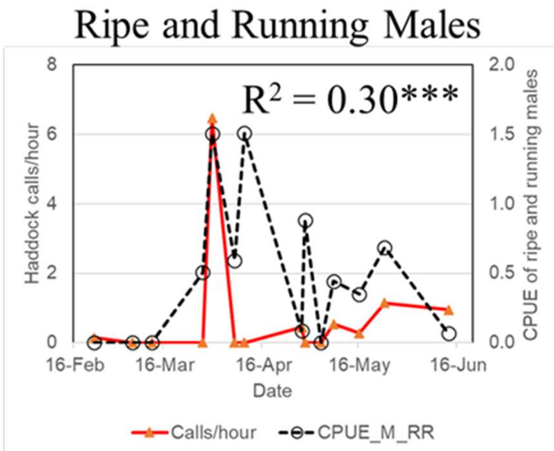

Figure 5. Correlation between haddock call rate and the catch per unit effort of ripe and running male (left) and female (right) haddock in nearby longlines. (R^2 = squared spearman correlation coefficient)

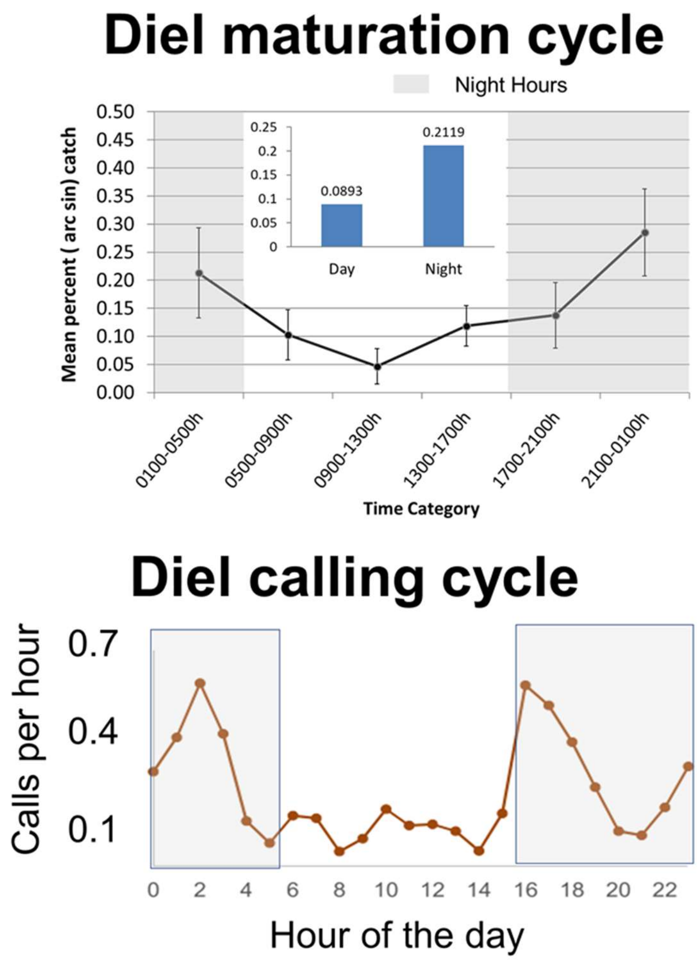

Figure 6. Comparison of CPUE of Ripe and Running female haddock by time of day during 2006-7 with mean call rate by hour of the day from 2003-2004.

maturation stage, or with total male or female haddock. Correlations were not found between knock rate and the CPUE of any maturation stage or for total male and female haddock. A composite diel sound production pattern is shown in Fig. 6 based on the mean call rate per hour of the day pooled over all deployments. A strong nocturnal spawning pattern is indicated in good agreement with the diel spawning pattern observed for haddock based on gonad maturation (Fig. 6, see also Burchard *et al.,* 2014).

4. DISCUSSION

This study demonstrates the utility of PAM for providing detailed behavioral information to supplement traditional fishery assessment methods. However, it also underscores the high variability of haddock behavior and suggest that spawning patterns are highly dependent on local factors. The high levels of haddock sound production in June and July relative to the spring months suggests that the often-cited peak spring spawning season based primarily on offshore spawning grounds may underestimate the importance of inshore spawning areas in the Gulf of Maine. A protracted spawning season for inshore haddock in the GOM could provide unexpectedly high contributions to the spawning stock biomass during some years. Similarly, PAM provided the first clear evidence of important inshore spawning of haddock in the eastern Atlantic (Hawkins, 2002; Casaretto *et al.,* 2014).

The weak correlation between haddock sound production and CPUE of spawning haddock (Fig. 5) was puzzling. In fact, the low occurrence of haddock sounds during 2007 (Tables 1 and 2) despite nearby spawning (Burchard *et al.,* 2014) suggests that PAM may not always be an accurate indicator of spawning activity. We suspect the low correspondence between the two observations results in part from a low detection range for haddock. Although sound source levels of individual haddock have not been published, and hence, detection ranges are unknown, Stanley *et al.* (2017) estimated effective vocalization ranges of less than 2.2 m on Stellwagen Bank due to vessel noise (effective vocalization incorporates haddock's hearing threshold and is not necessarily the same as the effective detection range of PAM). In this study, AULS were purposely deployed in active fishing areas of the GOM under the assumption that the likelihood of observing haddock sounds would be increased, rather than attempting to conduct a randomized survey. However, as a result, vessel noise was chronic and likely masked our detection of haddock sounds at times, particularly during the 2006-7 survey. In addition, their appeared to be a lag of approximately 10 h between AULS deployment and onset of haddock sound occurrence in the 2003-4 survey, suggesting that the short duration deployments used in the 2006-7 survey may have underestimated haddock activity. Therefore, the combination of high chronic noise levels, low detection range, short soak times and territorial behavior of male haddock likely contributed to the low occurrence of haddock sounds on Stellwagen Bank during 2006-7. It is notable that the strongest correlation between call rate and haddock CPUE was observed for females rather than males. Although at first counterintuitive, it likely resulted because males exhibit a high proportion of spawning ready individuals in the catch over much of the study period, and it is the presence of the females that stimulates increased sound production by males (e.g., Bremner *et al.,* 2002; Casaretto and Hawkins, 2002; Casaretto *et al.,* 2014) so it makes sense that the call rate would be more closely correlated with spawning females.

Nearly constant trains of haddock sounds were observed for long periods at a couple of the deployment sites. It is suspected that an individual male took up residence at the AULS where it produced long sequences of "patrolling sounds" (e.g. Casaretto *et al.,* 2014), thereby inflating both the call rate and knock rate. The use of long-term bottom mounted instruments is known to have the potential to produce biased observations due to recruitment of fish to an artificial habitat (Rountree *et al.,* in press). Caution in the interpretation of temporal patterns in fish sound production rates from instruments deployed at specific sites for long periods is needed. Conversely such behavior suggests the potential use of bottom mounted instruments like the AULS as tools to conduct *in situ* behavioral observations. The addition of cameras and other observational instrumentation can provide tools not only for recording soundscape data, but for cataloging unknown sounds and documenting soniferous behavior *in situ* (Rountree, 2008; Mouy *et al.,* 2018).

5. CONCLUSIONS

Haddock sounds were successfully surveyed in the GOM and demonstrated a strong diel trend similar to that observed in spawning activity providing further evidence of the importance of nocturnal spawning behavior in the species. In addition, although weak, the correlation of haddock call rate to the CPUE of ripe-and-running female haddock demonstrates a potentially powerful tool to supplement stock assessment surveys. Haddock sounds indicative of spawning behavior were observed well into July suggesting that spawning of inshore populations of haddock in the Gulf of Maine extends over a longer season than generally thought. Further the intro- and inter-annual variability in diel periodicity of both haddock sound production and CPUE of haddock in spawning condition suggest spawning behavior is highly plastic in the species and caution is advised when attempting to extrapolate observation from one region to another. This study demonstrates that PAM is an important new tool that can provide supplemental data to traditional fisheries data for haddock and other soniferous fishes.

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