

**Abstract**—Acoustic recorders were used to document black drum (*Pogonias cromis*) sound production during their spawning season in southwest Florida. Diel patterns of sound production were similar to those of other sciaenid fishes and demonstrated increased sound levels from the late afternoon to early evening—a period that lasted up to 12 hours during peak season. Peak sound production occurred from January through March when water temperatures were between 18° and 22°C. Seasonal trends in sound production matched patterns of black drum reproductive readiness and spawning reported previously for populations in the Gulf of Mexico. Total acoustic energy of nightly chorus events was estimated by integration of the sound pressure amplitude with duration above a threshold based on daytime background levels. Maximum chorus sound level was highly correlated with total acoustic energy and was used to quantitatively represent nightly black drum sound production. This study gives evidence that long-term passive acoustic recordings can provide information on the timing and location of black drum reproductive behavior that is similar to that provided by traditional, more costly methods. The methods and results have broad application for the study of many other fish species, including commercially and recreationally valuable reef fishes that produce sound in association with reproductive behavior.

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## Diel and seasonal timing of sound production by black drum (*Pogonias cromis*)

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Knowledge of the timing and location of spawning provides fundamentally important information for the management of fish species. Traditional methods for acquiring this knowledge have entailed 1) the collection of fishes for examination of spawning condition by means of gonad histology and gonadosomatic indices and 2) the calculation of the time of spawning by back-calculation from the ages of eggs or larvae at the time of collection (Peters and McMichael, 1990; Nieland and Wilson, 1993; Fitzhugh et al., 1993). In some cases direct observations of spawning have been made at fish aggregation sites with the use of scuba, remote cameras, and submersible vehicles (Domeier and Colin, 1997; Erisman and Konotchick, 2009). Although effective, these methods are labor intensive, costly, and not necessarily practical for providing high-resolution data over an entire spawning season or synoptically at multiple sites within a season.

Many fishes produce sounds associated with reproductive behavior, and hydrophone recordings used to document this behavior have been conducted for many years (Breder, 1968; Gilmore, 2003; Mann et al., 2008). Relatively recent advances in technology have made low-cost submersible acoustic recording systems available for recording high-resolution acoustic data over long time periods. These recording systems, along with signal processing algorithms, now represent the most practical method available to collect long-term, high-resolution data on spawning behavior of soniferous fishes, many of which include commercially and recreationally man-

aged species (i.e., drums and groupers [families Sciaenidae and Serranidae, respectively]). Such data can be collected synoptically over wide spatial scales and in remote environments that may not be accessible with other gear types. When acoustic data are combined with environmental data collected on similar time scales, a great deal can be learned about the ecology of sound production and the environmental requirements associated with spawning site selection and spawning behaviors of fishes.

The black drum is a large, long-lived sciaenid that ranges from the Bay of Fundy to Argentina (Hoes and Moore, 1998; Sutter et al.<sup>1</sup>). In the Gulf of Mexico black drum spawn in bays and estuarine habitats from late fall through early spring (Murphy and Taylor, 1989; Peters and McMichael, 1990) and produce high intensity sounds associated with courtship and spawning (Mok and Gilmore, 1983; Saucier and Baltz, 1993; Tellechea et al., 2010) that may exceed 170 dB re: 1 $\mu$ Pa (Locascio, 2010). In this study our main objectives were to record and describe patterns of black drum sound production during the spawning season and to compare these data to previous data collected with traditional methods to document the spawning season of black drum.

<sup>1</sup> Sutter, F. C., R. S. Waller, and T. D. McIlwain. 1986. Species profiles: life histories and environmental requirements of coastal fisheries and invertebrates (Gulf of Mexico)—black drum. U.S. Fish. Wildl. Serv. Bio. Rep. 82(11.51), U.S. Army Corps of Eng. TR EL82-4, 10 p.

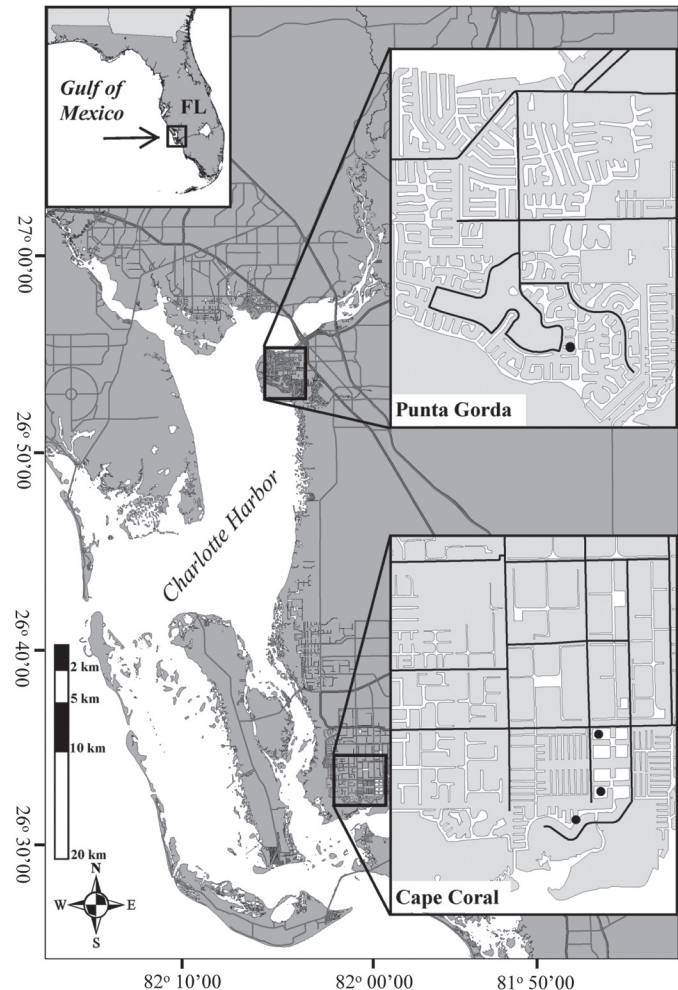
## Materials and methods

Long-term acoustic recording systems (LARS) were deployed in estuarine canals at one site in Punta Gorda and at three sites in Cape Coral, Florida, to document patterns of sound production by black drum (*Pogonias cromis*) during their spawning season. The canals are extensive sea-walled residential systems which allow access to the Gulf of Mexico via Charlotte Harbor (Fig. 1). One LARS was deployed at the Punta Gorda site from 22 March to 3 May 2004, and from 12 December 2004 to 4 May 2005. At Cape Coral sites 1 and 3 (CC1 and CC3), LARS were deployed from 12 February to 6 April 2005, and at Cape Coral site 2 (CC2) from 12 February to 6 May 2005, and from 21 October 2005 to 7 June 2006. These sites were selected on the basis of information provided by canal-side residents of loud booming sounds produced there in the evening during winter months.

Surface and bottom water temperature data were recorded at CC2 during the October 2005–June 2006 deployment with Hobo® temperature data loggers (model UA-002-08; Onset Computer Corp., Bourne, MA) programmed to record data at 10-minute intervals. The surface temperature data logger was attached to a buoy and suspended one half meter below the surface. The bottom temperature data logger was attached to the LARS and recorded data at one half meter above the bottom. All LARS were anchored and remained positively buoyant one half meter above the bottom. Water depth at all sites was approximately seven meters, and the bottom was a soft muddy composite. During the October 2005–June 2006 deployment, the LARS stopped recording after the first week and was reprogrammed and redeployed on 3 December 2005. With this exception all LARS functioned according to schedule during deployments.

Two LARS models were used for recordings: a Persistor CF2 computer (Persistor Instruments Corp., Marston Mills, MA) (sample rate: 2634 Hz) and a Toshiba pocket PC model E755 (Toshiba Computer Corp., Tokyo, Japan) (sample rate: 11,025 Hz). Sample rates used for recording were well above the frequency range where most of the acoustic energy in black drum calls is concentrated (<300 Hz) and therefore aliasing (i.e. under sampling of signals) was not a problem (Locascio, 2010). The Persistor-based LARS was used for all recordings, except for the 21 October 2005–7 June 2006 deployment at CC2. High Tech Inc. (Gulfport, Mississippi) 96-min series hydrophones were used with all LARS (sensitivity:  $-164\text{dB re: }1\text{V}/1\mu\text{Pa}$  and flat frequency response of 2 Hz–37 kHz). The sensitivity of each recorder was calibrated with a 0.1 V peak sinusoidal signal.

Each 10-second file was analyzed with a fast Fourier transform (FFT) to generate a power spectrum from which the band sound pressure level (SPL) in 100-Hz-wide bins was calculated. The SPL was greatest in the 100–200 Hz band and a five-point moving average of



**Figure 1**

Locations where calls of black drum (*Pogonias cromis*) were recorded in residential estuarine canal systems of Punta Gorda and Cape Coral, Florida. The study sites are indicated by filled black circles. The three study sites in Cape Coral are: CC1 (northernmost); CC2 (central); and CC3 (southernmost).

data in this frequency range was used for each time series analysis. Black drum calls were identified in recordings by comparison with previously published descriptions by Mok and Gilmore (1983). All data were analyzed with MATLAB, version R2007a software (The Mathworks, Inc., Natick, MA).

To be considered a chorus event the SPL was required to exceed an arbitrarily defined threshold of two standard deviations (SD) above the mean daytime background SPL for a minimum of five consecutive recordings (i.e., 50 minutes). Mean daytime SPL was calculated from 0700 to 1500 hours for each site and season separately. Requiring that levels be sustained above the threshold for a minimum of 50 minutes controlled for the infrequent cases where the SPL briefly exceeded the threshold during daytime hours because of vessel noise, weather, or occasional black drum calls.

**Table 1**

Correlation coefficients ( $r$ ) and  $P$ -values calculated for total acoustic energy (TAE) and maximum sound pressure level (Max SPL), and chorus duration and maximum sound pressure level produced by black drum (*Pogonias cromis*) from each site and season. PG=Punta Gorda, FL; CC=Cape Coral, FL. Mean daily background sound pressure levels and chorus thresholds are expressed as dB SPL (re: 1 $\mu$ Pa) of the 100–200 Hz band. df=degrees of freedom, SD=standard deviation.

Site	Dates	df	Background dB SPL		Chorus threshold	TAE Max SPL		Chorus duration Max SPL	
			mean	SD	dB SPL	$r$	$P$	$r$	$P$
PG	3/22/04–5/3/04	25	85.0	4.1	93.2	0.97	<0.01	0.76	<0.01
PG	12/12/04–5/4/05	82	85.7	4.3	94.3	0.98	<0.01	0.79	<0.01
CC1	2/12/05–4/6/05	42	91.6	3.2	98.0	0.99	<0.01	0.93	<0.01
CC2	2/12/05–5/6/05	102	90.7	3.8	98.3	0.99	<0.01	0.75	<0.01
CC2	12/3/05–6/7/06	42	90.0	3.5	97.0	0.99	<0.01	0.85	<0.01
CC3	2/12/05–4/6/05	39	93.1	3.5	100.1	0.95	<0.01	0.59	<0.01

The threshold was used to mark chorus start and end times from which nightly parameters of chorus duration, total acoustic energy (TAE), and maximum SPL were calculated. TAE (dB re: 1  $\mu$ Pa<sup>2</sup>·s) was calculated by converting SPL to  $\mu$ Pa and then integrating the acoustic energy (squared acoustic pressure) over the time period that the SPL exceeded the threshold (i.e., by summing the area under the curve). This method is equivalent to the calculation of sound exposure level described by the American National Standards Institute (ANSI, S1.1-1994).

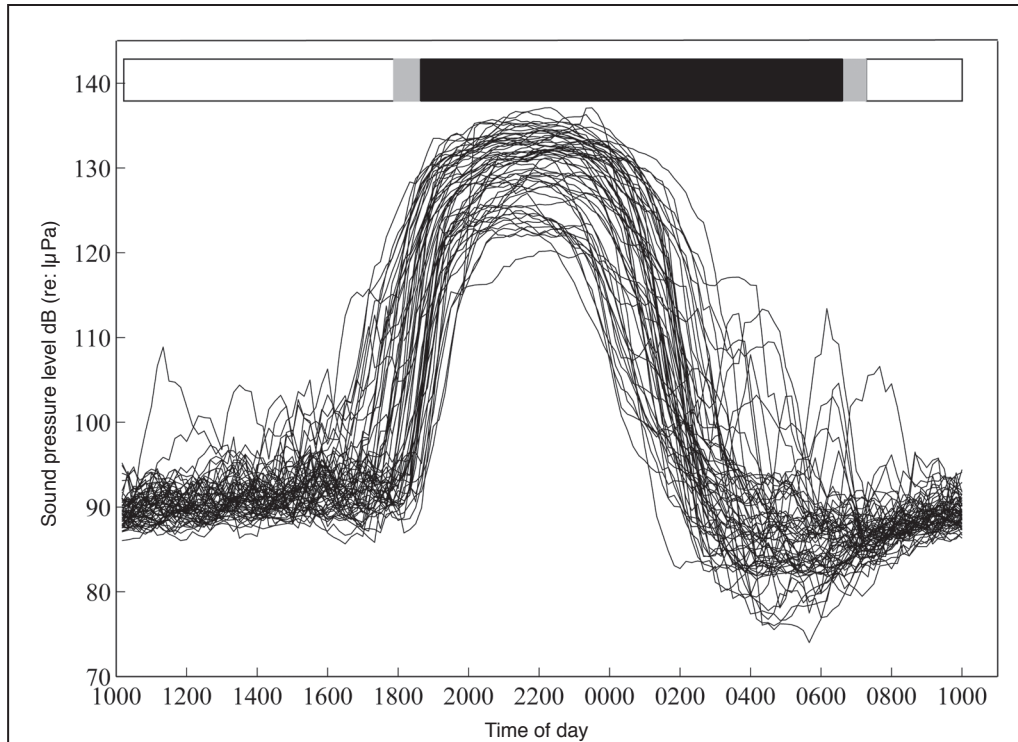
Correlations between TAE and maximum SPL and between chorus duration and maximum SPL were calculated with time series data from each site and for each season. The purpose was to evaluate maximum SPL as a quantitative representation of nightly black drum sound production. Linear regressions were calculated between chorus start time and time of sunset. Correlations between chorus start and end times, between chorus start time and time of maximum SPL, and between chorus start time and maximum SPL were calculated for each time series. Data were tested for normality on the basis of standardized kurtosis and skewness. If data were non-normal, a Spearman nonparametric correlation was calculated instead of a Pearson correlation. The ascending and descending slopes of nightly chorus events were calculated from the chorus start to the time when the sound level first reached 6 dB below maximum SPL and from the time the sound level decreased from 6 dB below maximum SPL to the chorus end. Ascending and descending slopes were compared by using the Wilcoxon signed rank nonparametric test. Correlations between sites for data of chorus start time, chorus end time, chorus duration, and time of maximum SPL were calculated from data recorded concurrently at all sites during 14 February–6 April 2005. Alpha values were adjusted by using sequential Bonferroni tests to correct for experiment-wise error (Sokol and Rolf, 1995). Cross correlations between nightly maximum SPL and surface and bottom water temperature were calculated

for the 2005–06 CC2 time series. Fourier analysis was used to examine for patterns of lunar periodicity in black drum sound production in the Punta Gorda time series recorded during December 2004–May 2005 and the CC2 time series recorded during October 2005–June 2006.

## Results

Total acoustic energy (TAE) and maximum sound pressure level (SPL), and chorus duration and maximum SPL, were positively and significantly correlated for all sites and seasons (Table 1). The high association between TAE and maximum SPL ( $r=0.95$  to  $0.99$ ) qualified maximum SPL to quantitatively represent black drum sound production on a nightly basis. The gulf toadfish (*Opsanus beta*) was the only other soniferous fish recorded. The call of this species has a fundamental frequency of approximately 280Hz (Thorson and Fine, 2002) and therefore did not contribute to the SPL calculated in the 100–200 Hz frequency band used for analysis of black drum acoustic data. Invertebrate sounds (so called “snapping-shrimp”) were not recorded at the study sites.

Black drum sound production was strongly periodic. Calls were occasionally recorded during the mid-morning through early afternoon but increased sharply from late afternoon to early evening, and chorus duration lasted up to 12 hours during peak season (Fig. 2). Regressions of chorus start time and time of sunset resulted in higher  $r^2$  values for the shorter time series, which began during the mid to late season in February 2005 (CC1, CC2, CC3) and March 2004 (PG) ( $r^2=0.39$  to  $0.54$ ), than for the two longer time series which covered the majority of the season, CC2 2005–06 ( $r^2=0.04$ ) and PG 2004–05 ( $r^2=0.02$ ). Data used for all correlations were normally distributed, except for chorus start time data from CC3. Chorus start and end times were negatively and in most cases significantly correlated and indicated that later start times



**Figure 2**

Diel periodicity of black drum (*Pogonias cromis*) sound production (expressed as sound pressure level) represented by an overlay plot of consecutive 24-hour periods recorded from 15 February–16 March 2005 at Cape Coral site 2. The white portion of the diel bar at the top of the figure represents daylight hours, the black represents night hours, and the gray represents time of sunset and sunrise over the dates when these data were recorded.

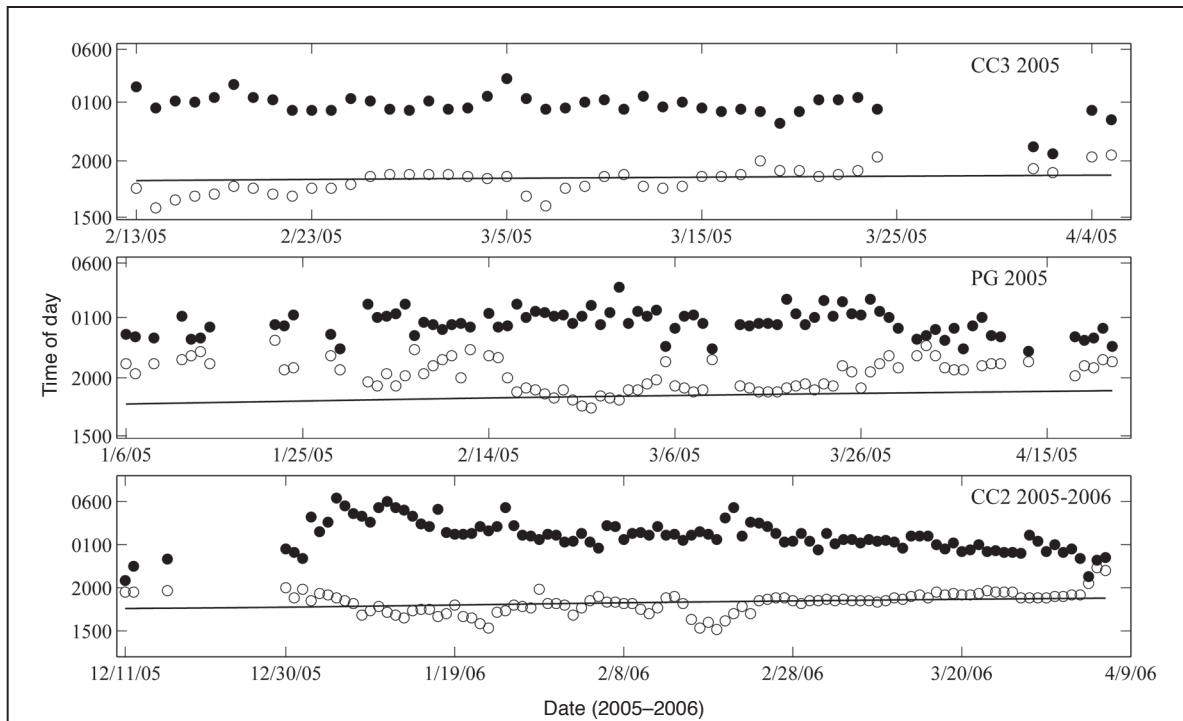
**Table 2**

Regression coefficients ( $r^2$ ) and  $P$ -values calculated for chorus start time vs. time of sunset, and correlation coefficients ( $r$ ) and  $P$ -values calculated for chorus start time and chorus end time, chorus start time and time of maximum SPL (Max SPL), and chorus start time and maximum SPL produced by black drum (*Pogonias cromis*). Asterisks denote a Spearman correlation was calculated instead of a Pearson correlation. PG=Punta Gorda, FL; CC=Cape Coral, FL. df=degrees of freedom.

Site	Dates	df	Chorus start time time of sunset		Chorus start time chorus end time		Chorus start time time of max SPL		Chorus start time max SPL	
			$r^2$	$P$	$r$	$P$	$r$	$P$	$r$	$P$
PG	3/22/04–5/3/04	25	0.41	<0.01	-0.65	0.01	0.28	0.12	-0.67	<0.01
PG	12/12/04–5/4/05	82	0.02	0.33	-0.56	<0.01	0.19	0.10	-0.74	<0.01
CC1	2/12/05–4/6/05	42	0.54	<0.01	-0.34	0.03	0.41	0.06	-0.78	<0.01
CC2	2/12/05–5/6/05	102	0.43	<0.01	-0.28	0.07	0.38	0.01	-0.78	<0.01
CC2	12/3/05–6/7/06	42	0.04	0.06	-0.61	<0.01	0.02	0.81	-0.85	<0.01
CC3	2/12/05–4/6/05	39	0.39	<0.01	*-0.27	0.10	*0.31	0.06	*-0.56	<0.01

generally meant earlier end times, and conversely, that earlier start times were associated with later end times (Fig. 3, Table 2). Correlations of chorus start time and maximum SPL were strongly negative and significant for comparisons of all time series and indicated that

earlier chorus start times were associated with higher maximum SPL; however, chorus start time and time of maximum SPL were only weakly and slightly positively correlated (Table 2). Monthly mean chorus start and end times were more variable than the monthly mean



**Figure 3**  
 Times of chorus start (open circles), chorus end (filled circles), and sunset (solid line) for select time series of black drum (*Pogonias cromis*) sound production recorded at Cape Coral site 3 (CC3, top graph) and Punta Gorda (PG, middle graph) during 2005, and Cape Coral site 2 (CC2, bottom graph) during 2005–06. (Further details are given in Tables 2 and 3).

**Table 3**

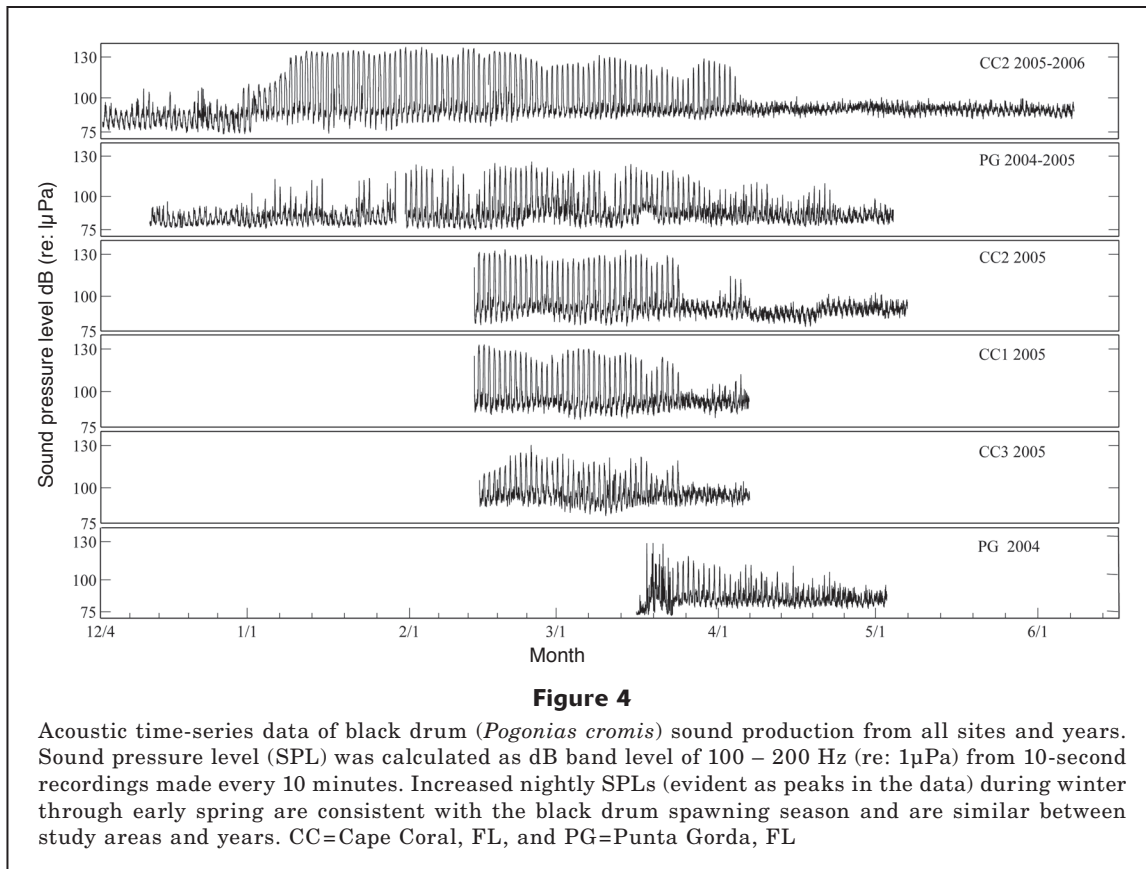
Wilcoxon signed-rank test statistics (*T*) and *P*-values of ascending vs. descending slopes and mean and standard deviation (SD) of black drum (*Pogonias cromis*) chorus events. Slopes were measured from chorus start time to 6 dB below maximum sound production level (SPL) (ascending) and from 6 dB below maximum SPL to chorus end time (descending). Ascending slopes were significantly greater for each time series. PG=Punta Gorda, F; CC=Cape Coral, FL. df=degrees of freedom.

Site	Dates	df	Chorus ascending slope		Chorus descending slope		Wilcoxon <i>P</i>	Wilcoxon <i>T</i>
			mean	SD	mean	SD		
PG	3/22/04–5/3/04	25	2.10	0.80	1.50	0.85	0.03	2.4
PG	12/12/04–5/4/05	82	2.40	1.44	1.70	1.10	<0.01	3.1
CC1	2/12/05–4/6/05	42	3.10	1.32	1.70	0.62	<0.01	6.0
CC2	2/12/05–5/6/05	102	2.90	0.95	2.30	0.87	0.01	2.7
CC2	12/3/05–6/7/06	42	3.00	1.42	1.80	0.90	<0.01	7.9
CC3	2/12/05–4/6/05	39	1.80	0.85	1.20	0.88	<0.01	3.2

time of maximum SPL. Ascending chorus slopes were significantly greater than descending slopes for all time series (Table 3).

A distinct seasonal pattern was evident in black drum sound production in all acoustic time series, and sound production patterns were consistent between years for each site (Figs. 4 and 5, Table 4). Subchorus threshold

levels of black drum calls were recorded as early as the third week of October (at CC2 in 2005) and as late as the first week of May (at PG in 2004). Sound production first exceeded threshold levels by mid December in CC and early January in PG and were last recorded in early and late April, respectively (Table 4). Monthly mean maximum SPLs were greatest during January



and February at the CC sites and during February and March at the PG site (Figs. 4, and 5).

The CC2 2005–06 time series began and ended somewhat abruptly relative to chorus threshold levels. Data recorded at each of the CC sites during 2005 revealed a similar pattern at the end the season. In contrast, maximum SPL recorded during both years at the PG site increased and decreased more gradually at the start and end of each season and sound production continued for two to three weeks longer than at the CC sites. Maximum SPLs at PG were also generally lower and more variable than at the CC sites (Figs. 4 and 5, Table 4).

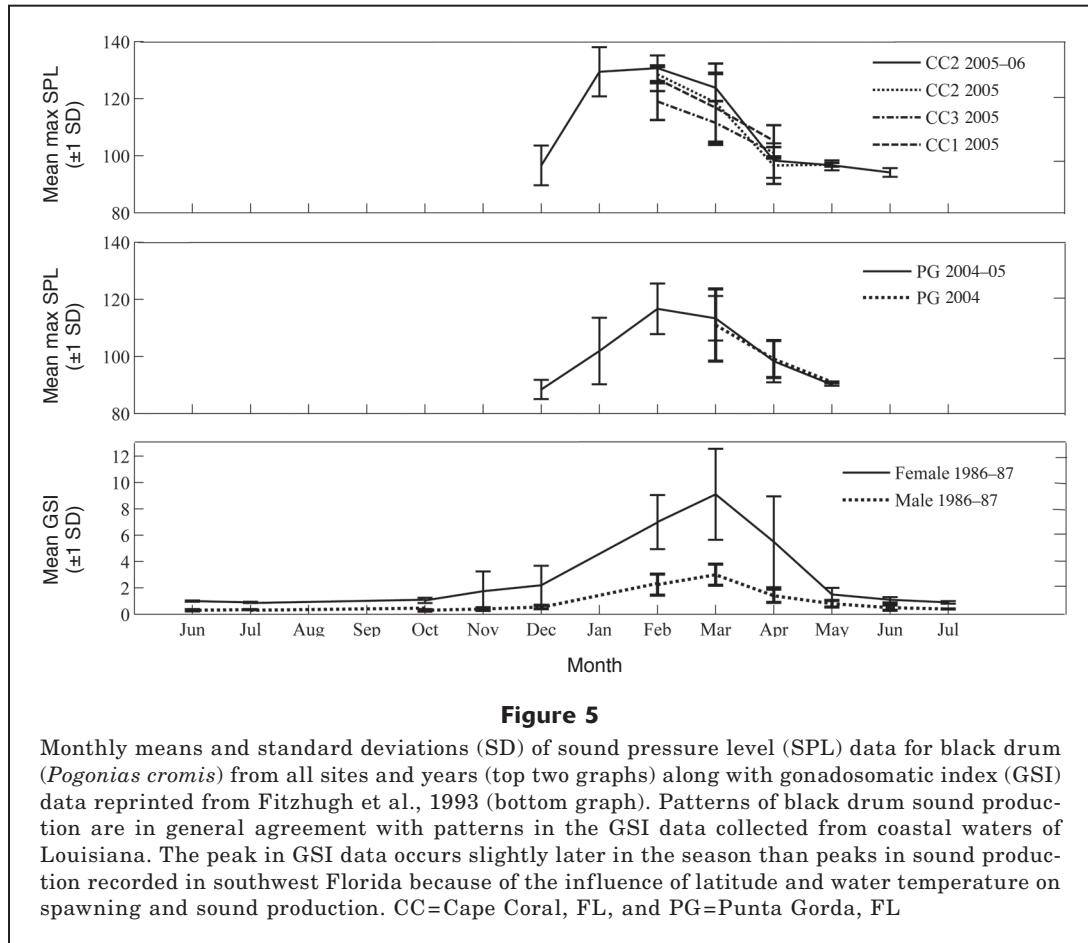
The greatest coefficient produced by the cross correlation of maximum SPL and bottom temperature was  $-0.81$  at 0 days lag. The correlation coefficient produced by surface temperature and maximum SPL at 0 days lag was  $-0.14$  and the greatest coefficient was  $-0.4$  at 22 days lag. Surface temperatures ranged from approximately  $17.5^{\circ}$  to  $26^{\circ}\text{C}$  during the seasonal period of black drum sound production (4 December 2005–10 April 2006) but fluctuated within a range of about  $18^{\circ}$  to  $22^{\circ}\text{C}$  during 4 December 2005–20 February 2006 ( $\bar{x}=20.3$ , standard deviation [SD]=1.8,  $n=78$ ) and  $22.5^{\circ}$  to  $26^{\circ}\text{C}$  ( $\bar{x}=23.9$ , SD=1.2,  $n=48$ ) during 21 February–10 April 2006. Surface temperatures during these two periods were significantly different ( $t=-14.8$ ,  $P<0.01$ ). Cross correlations between maximum SPL and surface tem-

perature produced maximum correlation coefficients of  $-0.33$  at two days lag for 4 December 2005–20 February 2006 and  $-0.69$  at one day lag for 21 February–10 April 2006. Bottom temperatures ranged from approximately  $17^{\circ}$  to  $24^{\circ}\text{C}$  over the entire time series and were less variable than surface temperatures. The seasonal peak in maximum SPL occurred when surface and bottom temperatures were both between  $18^{\circ}$  and  $22^{\circ}\text{C}$  during early January through late February. Time series data of maximum SPL and corresponding temperature data for CC2 are shown in Figure 6.

Chorus start, end, and duration were positively correlated between all sites, except PG and CC1 (Table 5). A stronger association existed among the Cape Coral sites for each of these variables and in particular for chorus start time (Fig. 7). The time of maximum SPL was weakly correlated between sites (either slightly positive or negative and insignificant). The FFT results of maximum SPL data did not indicate that black drum sound production occurred on a lunar cycle.

## Discussion

The black drum spawning season has been defined within the Gulf of Mexico through histological examination of oocyte development, gonadosomatic indices, and collection of eggs, larvae, and juveniles (Murphy



and Taylor, 1989; Peters and McMichael, 1990; Nieland and Wilson, 1993; and Fitzhugh et al., 1993). Results of these studies are in general agreement and have shown that the spawning season occurs from late fall through early spring and that peak spawning occurs during February and March, given some variability with latitude. Seasonal patterns of black drum sound production recorded in this study are consistent with the timing of the spawning season defined in the literature and show that passive acoustics can be as effective as traditional methods for documenting the seasonal reproductive period of black drum. Figure 5 features data of gonadosomatic indices of black drum, reprinted from a study by Fitzhugh et al., (1993) which illustrate the relationship between reproductive condition and sound production during the spawning season.

Although the time series of black drum sound production at all sites and for all years conformed to the same general seasonal pattern, clear similarities and differences existed among them. Sound production at PG varied between the 2004 and 2005 seasons by only one day for the date of the last chorus and four days for the date of the last recorded black drum call. The dates of the last recorded chorus and call were identical among CC sites during 2005 and differed from the CC2

2006 time series by only two and five days, respectively. Sound production consistently lasted two to three weeks longer at the PG site than at the CC sites. We do not have data to explain the similarities between years at the same sites or the differences that existed between the PG and CC sites, but the simplest explanation could be that water temperatures were responsible for these patterns. The PG and CC sites are only 40 km apart and therefore the influence of latitude alone may not be responsible for differences in water temperature. It is possible that local effects such as exposure to sun, wind, and influence of adjacent water bodies may have contributed to the temperature differences responsible for the later end to seasonal calling in PG.

Differences were also evident in the lower and more variable maximum SPLs recorded at PG and CC3 and these may be associated with the distribution of calling fish relative to hydrophone locations. Because black drum source levels do not appear to be highly variable among individuals (Locascio, 2010) the patterns of maximum SPL at these sites may not be due to lower intensity calls, but rather to calls from fish at greater or more variable distances from the hydrophone. Both sites were located within smaller, narrower areas of the canal systems compared to the locations of CC1 and

CC2 and may have accommodated fewer fish especially if (male) black drum establish territories which require some space between individuals (Locascio, 2010). Another interesting pattern was apparent in the correlation of synoptically recorded data from all sites. The higher correlations among the CC sites for chorus timing revealed that acoustic signaling by black drum may occur in the context of a communication network, where the calling behavior initiated by some individuals elicits responses from others and propagates throughout the population. We were not able to confirm this pattern in the Punta Gorda canal system because of having only one study site there. It is also possible that some overarching environmental condition(s) helped initiate calling at each of the three Cape Coral sites. These results emphasize the need that complementary environmental data be collected along with acoustic data.

In two previous studies, hydrophone recordings were used to investigate black drum spawning behavior. Saucier and Baltz (1993) conducted mobile hydrophone surveys in coastal southeast Louisiana and recorded black drum calls from January through April, in 15.0° to 24.0°C water temperatures, and peak sound production in March and April. The highest SPLs were recorded in 20.8°C ( $\pm 1.01$ ) and 18.9°C ( $\pm 1.43$ ) water temperatures for presumed large and moderate-size black drum aggregations, respectively. Mok and Gilmore (1983) also conducted mobile hydrophone surveys and recorded black drum during the winter and early spring in Indian River Lagoon, Florida. They reported maximal sound production during January in 18.0° to 20.0°C water temperatures and no sound production occurred below 15.0°C. Although water temperature did not reach the apparent 15.0°C lower limit for sound production in our study, the temperature range over which black drum were recorded (bottom: 17–24°C, surface: 17.5–26°C) and the range associated with highest levels of sound production (18–22°C) are consistent with these previous studies. Black drum are a demersal species which would account for the higher correlation between SPL and bottom water temperatures in this study. The higher correlation between surface water temperatures at a one day lag and sound production during the latter half of the season could indicate that black drum were higher in the water column or possibly that this was a response to increasing photoperiod, which would be positively correlated with temperature.

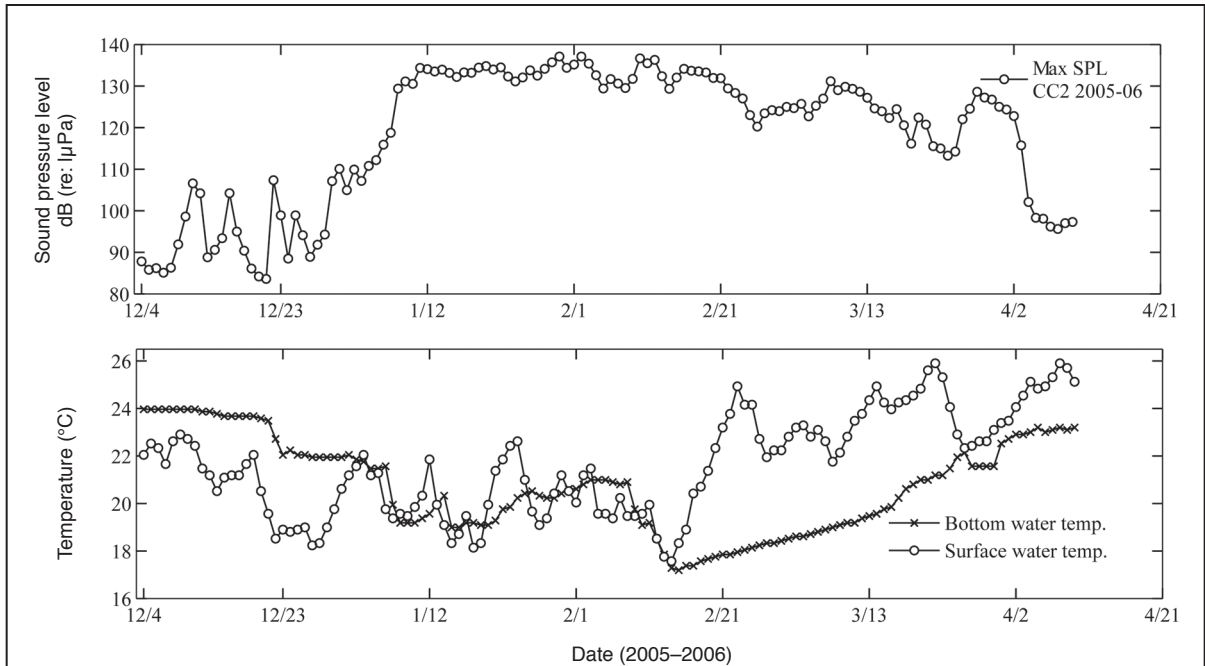
The range of water temperatures associated with black drum sound production has also been reported for spawning. Peters and McMichael (1990) back-calculated larval black drum birthdates from collections made in Tampa Bay, FL, and estimated that water temperatures were 16–20°C during the early part of the spawning season and 21–24°C during peak season. Holt et al. (1988) collected black drum eggs in water temperatures of 18–25°C in the Gulf of Mexico near Port Aransas, Texas. Within the geographic range of black drum in U.S. waters, spawning has been documented to occur later in the year at more northern latitudes (Murphy and Taylor, 1989) but apparently within the

**Table 4**

Monthly means and standard deviations (SD) of the maximum sound pressure level (dB re:1 $\mu$ Pa) of the 100–200 Hz band recorded at each site and season and dates of the last black drum (*Pogonias cromis*) chorus and last recorded black drum calls. The last acoustic activity of black drum occurred on similar dates of different years at each study site. PG=Punta Gorda, FL; CC=Cape Coral, FL.

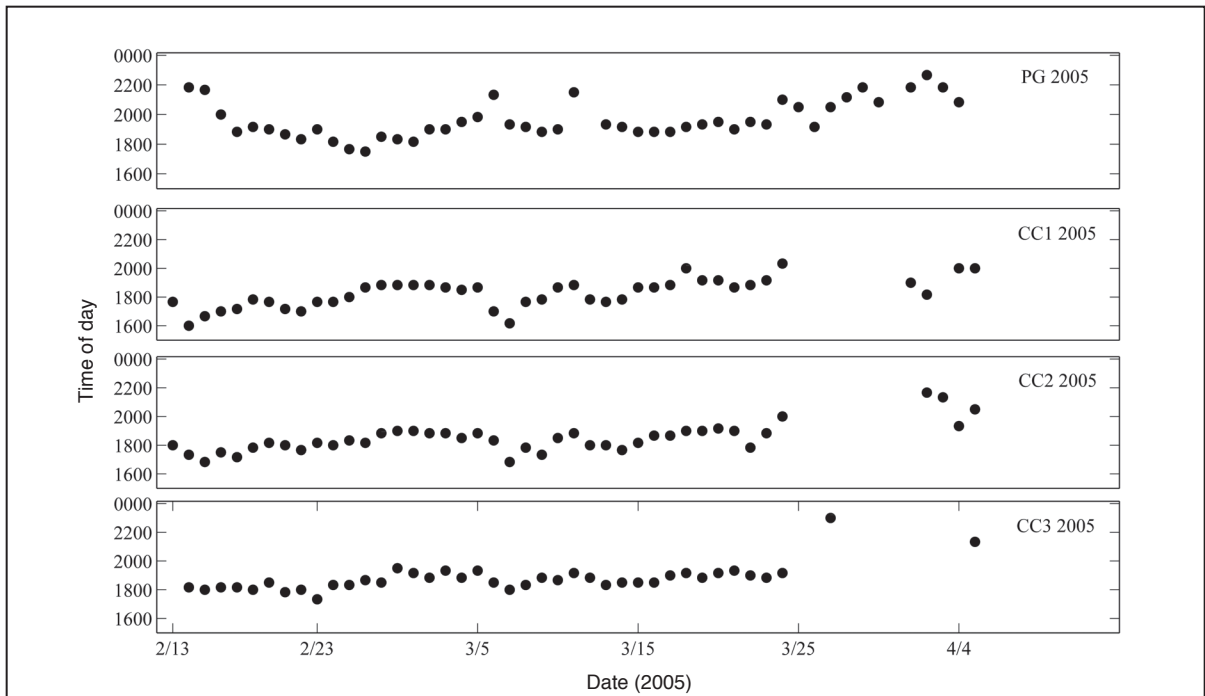
Site	Dates	December		January		February		March		April		May		Last chorus	Last call
		mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD		
PG	3/22/04–5/3/04													4/21/2004	5/1/2004
PG	12/12/04–5/4/05	88.4	3.4	101.9	11.6	116.7	8.9	113.4	7.8	99.1	6.5	91.0	0.0	4/22/2005	4/27/2005
CC1	2/12/05–4/6/05					126.9	4.2	116.8	12.3	105.2	5.5	90.1	0.4	4/4/2005	4/5/2005
CC2	2/12/05–5/6/05					128.5	3.1	118.6	13.7	96.6	6.4	96.9	0.7	4/4/2005	4/5/2005
CC2	12/3/05–6/7/06	96.6	7.0	129.4	8.6	130.7	4.5	123.8	4.8	98.3	6.0	96.6	1.7	4/6/2006	4/10/2006
CC3	2/12/05–4/6/05					119.0	6.5	111.5	7.7	101.0	2.0			4/4/2005	4/5/2005





**Figure 6**

Nightly maximum sound pressure level (SPL) data for black drum (*Pogonias cromis*) calls from the Cape Coral site 2 (CC2) 2005–06 time series (top graph) and bottom and surface water temperature data (bottom graph) recorded every ten minutes during the period 4 December 2005–10 April 2006.



**Figure 7**

Synoptically recorded data of chorus start time of black drum (*Pogonias cromis*) sound production from all study sites. Data recorded at the Cape Coral (CC) sites were highly correlated with each other but not with data recorded at the Punta Gorda site (PG) (details are given in Table 5).

Table 5

Correlation coefficients ( $r$ ) and  $P$ -values calculated for chorus parameters determined for black drum (*Pogonias cromis*) from synoptically recorded acoustic data at all study sites. Asterisks denote alpha values adjusted for experiment-wise error. PG=Punta Gorda, FL; CC=Cape Coral, FL. df=degrees of freedom.

Sites	Chorus start time			Chorus end time			Chorus duration			Time of max SPL		
	df	$r$	$P$	df	$r$	$P$	df	$r$	$P$	df	$r$	$P$
PG, CC1	40	-0.06	0.71	39	0.31	0.05	40	0.15	0.35	39	0.21	0.21
PG, CC2	40	0.37	*0.02	40	0.29	0.07	40	0.41	0.01	40	-0.08	0.64
PG, CC3	38	0.16	0.34	38	0.32	*0.05	38	0.26	0.11	38	0.12	0.48
CC1, CC2	42	0.72	<0.01	42	0.57	<0.01	42	0.79	<0.01	42	0.19	0.24
CC1, CC3	39	0.72	<0.01	39	0.38	0.02	39	0.52	<0.01	39	-0.02	0.91
CC2, CC3	39	0.77	<0.01	39	0.61	<0.01	39	0.69	<0.01	39	-0.10	0.53

same water temperature range regardless of latitude. In Chesapeake Bay for example, black drum spawn from late April through June (Wells and Jones, 2002) when water temperatures are within approximately the same range as that reported for the Gulf of Mexico during the spawning season (MDNR<sup>2</sup>). Johnson (1978) estimated that black drum spawning at the mouth of Chesapeake Bay probably occurred in water temperatures of 15–21°C. Spawning by black drum later in the year at higher latitudes (June in Chesapeake Bay), but in the same water temperature range that occurs in Florida during February, indicates that temperature may be more influential than photoperiod on black drum reproduction.

Peters and McMichael (1990) noted that peak spawning occurred around new and full moons and suggested this was due to increased tidal amplitude. We found no patterns in lunar periodicity associated with black drum sound production, but because the precise relationship between the timing of sound production and spawning has not yet been explained for black drum, it is possible that these different behaviors may vary on lunar (or other) time scales. Associations with moon phase and fish sound production have been reported (Breder, 1968; Gilmore, 2003; Mann et al., 2008). Aalbers (2008) found increased calling rates were associated with spawning by white seabass, which occurred throughout the lunar cycle but more so at the time of the new moon to four days after.

Establishing chorus start and end times at two standard deviations above mean daytime levels is a conservative approach for measuring chorus timing parameters because the earliest and latest parts of the chorus are ignored. Still, there was sufficient variability in chorus duration over the course of the season to show the strong association between TAE and maximum SPL. Although TAE would appear to be a better choice to quantitatively represent nightly black drum sound production because it is a more comprehensive measure,

maximum SPL has the advantage of not depending on the threshold level that is chosen, whereas TAE tends to increase at lower threshold levels. The correlation between maximum SPL and chorus duration was not as strong as that between maximum SPL and TAE because threshold points from which chorus duration was measured did not account for variability in duration of signal amplitude above threshold as did the TAE calculation. In a previous study, we found a weak negative relationship between maximum SPL and chorus duration of sand seatrout (*Cynoscion arenarius*) ( $r=-0.24$ ) (Locascio and Mann, 2008). The relatively low correlation among *C. arenarius* data was because they were collected during peak spawning season when signal amplitude and chorus duration were consistently high and variability was low compared to the range that exists when data are recorded across an entire spawning season as in this study (with *P. cromis*).

Black drum exhibited a diel pattern of sound production consistent with general descriptions found in the literature for many fishes that produce sound associated with courtship and spawning. Calling levels increase rapidly within an hour or two before sunset and reach maximal levels within a few hours after dusk (Breder, 1968; Mok and Gilmore, 1983; Luczkovich et al., 1999; Aalbers, 2008). In the previous hydrophone studies by Saucier and Baltz (1993) and Mok and Gilmore (1983), black drum calling was noted as early as 1300 and 1400 h, respectively, and the majority of sound production occurred between 1800 and 2200 h. The earliest chorus start time in this study occurred at 1510 h on 19 February 2005 at CC2, but individual calls were occasionally recorded throughout the day during peak season.

Earlier chorus start times occurred during the peak spawning season and generally corresponded to later end times and higher maximum SPLs (Table 2). This pattern, along with later chorus start times at the beginning and end of the season, was responsible for the low  $r^2$  from the regression with time of sunset for the two longer time series. Connaughton and Taylor (1995) discovered a similar pattern of high intensity calling earlier in the day that lasted later into the evening

<sup>2</sup> MDNR (Maryland Department of Natural Resources), www.eyesonthebay.net, accessed Dec. 2009.

during the peak spawning season of weakfish. They noted physiological indicators of reproductive readiness in weakfish, including increased plasma androgen levels and hypertrophy of sonic muscle in males, were evident during the seasonal period of maximal sound production and spawning. This pattern has also been documented for spotted seatrout (Brown-Peterson, 2003) and toadfish (Fine and Pennymaker, 1986). It is likely that similar conditions exist in black drum and contribute to earlier and increased sound production during the peak seasonal reproductive period.

For each time series the ascending slope was significantly greater than the descending slope of choruses. The more gradual changes associated with the descending slope of the chorus event may be due to fewer individuals calling. This may be a consequence of sonic muscle fatigue, but it may also be related to fluctuations in hormone levels, as demonstrated on a seasonal time frame for weakfish. Monthly mean values of time of maximum SPL were not highly variable despite the relatively high variability in chorus start and end times. Rates of SPL change during chorus events are not available in the literature, although in cases where sufficient diel time series data have been collected authors have observed a relatively rapid onset of calling and substantial increase in SPL over moderately short time periods (Breder, 1968; Connaughton and Taylor 1995; Locascio and Mann, 2008; Mann et al., 2008). One mechanism for this increase in SPL may be that an individual's calls elicit responses from other individuals and result in rapidly increased SPL as calling activity spreads throughout the network of fish. This mechanism has been proposed to serve as a means of aggregating individuals for spawning while creating the opportunity among (male) individuals to compete acoustically for a chance at reproduction. Some evidence indicates that calling rates of individuals are not highly variable (Connaughton and Taylor, 1995; Locascio, 2010) and therefore increased SPL and calling rates of a group may be due to more individuals calling, as opposed to individuals calling more (Connaughton and Taylor, 1995). More data are needed to understand how frequencies and sound levels and calling rates vary among individuals of a species. Variation in fundamental frequencies of black drum calls with body size has been shown by Tellechea et al. (2010).

## Conclusions

This study revealed that the timing and amplitude of black drum sound production is strongly correlated with the seasonal spawning period described in the literature. Long-term acoustic recording systems can therefore be used to complement traditional methods for defining the spawning season, are much less expensive, and produce high-resolution time series data. These recording systems are an especially useful and cost-effective tool for exploring new and remote locations where the

formation of spawning aggregations is suspected or for monitoring the recovery of historical spawning sites. Inferences about habitat quality can also be made from acoustic data because spawning site selection should place early life history stages in habitats beneficial for growth and survival (Peebles and Tolley, 1988). In order to advance the use of passive acoustic methods future studies must focus on establishing quantitative relationships between sound production and spawning, the number and biomass of spawning individuals, and environmental parameters. Also required is a more detailed understanding of the behavior associated with sound production and the identification of currently unidentified sound-producing species.

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