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Seasonal Dynamics and Environmental Drivers of Goliath Grouper (*Epinephelus itajara*) Sound Production

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Abstract: The Goliath groupers are known to produce characteristic low frequency vocalizations (“calls”) during spawning aggregations and as part of territorial behavior. Acoustic monitoring for Goliath grouper calls around Florida has historically occurred between July and December to capture the spawning season, with a particular focus on August–November. Because of the unique waveform of the Goliath grouper call, we implemented a noise adaptive matched filter to automatically detect Goliath grouper calls from year-round passive acoustic recordings at two wrecks off Florida’s Gulf of Mexico coast. We investigated diel, temporal and environmental factors that could influence call rates throughout the year. Call rates peaked in August, around 0300 EST and just after the full moon. The Goliath groupers were more vocal when background noise was between 70 and 110 dB re 1 μ Pa. An additional smaller peak in call rates was identified in May, outside of the typical recording period, suggesting there may be other stimuli besides spawning that are eliciting high sound production in this species. Goliath grouper sound production was present year-round, indicative of consistent communication between individuals outside the spawning season.



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Keywords: passive acoustics; fish acoustics; soniferous; match filter; lunar cycle

Key Contribution: Goliath grouper sound production peaks during the spawning season (August–October), but occurs year-round with some increased sound production in May. Sound production has a diel pattern and is influenced by background noise.

1. Introduction

Sustained observations of reef fish and their behavior have historically presented challenges to researchers due to logistical constraints of sampling in their naturally complex and dynamic habitats (reefs, ledges, banks, etc.). Although video-based approaches are minimally invasive and can sample the behavior of a wide variety of species, these are primarily limited to diurnal observations and are susceptible to currents and turbidity [1,2]. Conversely, sound travels effectively underwater [3], and more than 900 species of fish are known to intentionally produce sound when engaged in reproductive activity (e.g., courtship and spawning), competitive feeding, social organization or territorial defense, with sound production being particularly prevalent in demersal and reef-associated species [4].

Passive acoustic monitoring entails using a hydrophone to listen to underwater sounds, including those produced by soniferous fishes [5]. This approach provides a continuous and non-invasive method for monitoring species biodiversity [6], and has been used to estimate the abundance of soniferous fishes [7]. Passive acoustic monitoring systems are relatively cost-effective and can be used in adverse conditions, such as storms and harmful

algal blooms [8–11]. Passive acoustics has been used for over 60 years in fish biology and fisheries surveys (see [12,13] for review), and are being routinely used to determine habitat use, delineate and monitor spawning areas, and study the behavior of fishes [14,15]. This technique has also revealed that ecosystem-level (e.g., coral reef) sounds vary based on diel, lunar, and seasonal or celestial cycles. For example, in Australian waters, the combined vocal activity of fishes and crustaceans is most intense at dusk, with an increase of 20 dB above the mean ambient noise level [16,17]. However, the biotic noise signature can also vary over longer temporal scales due to interspecific differences in vocal behavior, with the vocal activity of some marine organisms increasing during certain seasons [18,19], while that of others appears to remain consistent throughout the year [20–22].

The Atlantic Goliath groupers (*Epinephelus itajara*; herein, referred to as Goliath grouper), are subtropical to tropical soniferous reef fish ranging from North Carolina to Brazil and throughout the Gulf of Mexico [23]. Goliath groupers are the largest species of grouper in the Atlantic, reaching up to 2.5 m and exceeding 400 kg [23,24]. Like many large fish, Goliath groupers exhibit life history strategies that include long lifespans (37 years), slow maturity, and the formation of spawning aggregations [25,26], which make the species susceptible to population decline from overfishing.

In the late 1980s, the species approached extinction due to severe fishing pressure, and a complete moratorium was enacted in U.S. state and federal waters in 1990 [27,28]. While populations of Goliath groupers beyond Florida remain depleted [29,30], along Florida's coastlines, populations have been recovering [31] and more historical, northward spawning sites have recently been established [32]. However, in 2023, in an effort to increase the biomass of more commercially valuable groupers and snappers—argued to be predated upon by Goliath grouper—a highly regulated limited fishery called the Goliath Harvest Program was opened, although scientific studies of the distribution, abundance, and diet of Goliath groupers have not supported these claims [26]. With the Goliath Harvest Program newly opened, it is crucial to understand the factors influencing the behavior of these fish for which data is severely lacking, particularly outside of the spawning season [28].

Goliath groupers are known to form aggregations at natural and artificial reefs and exhibit site fidelity [9,33]. Goliath groupers produce sounds that are acoustically distinct from other species of groupers in response to a variety of circumstances, most notably during spawning, courtship, or as an antagonistic response (e.g., when approached by divers) [9,13]. Acoustic monitoring for Goliath grouper sounds around Florida has historically occurred between July and December [9] to capture the spawning season, with a particular focus on August–November [34]. During the described Goliath grouper spawning season that occurs during new moon phases in August, September, and October, large aggregations of fish can be found on shipwrecks and reefs [24,34], where single-pulse, narrow band, loud (up to 150.9 dB re 1 μ Pa), low frequency (below 100 Hz) sounds (hereafter, referred to as “calls”) have been recorded [9]. Sound production during the spawning season was related to diel and lunar phase with calls climaxing between 01:00 and 03:00 h local time and reduced numbers of calls recorded around the full moon [9]. Although calls have been documented during the spawning season, data are lacking to understand call dynamics over longer temporal scales, including outside of the spawning season. The aim of this study was to investigate patterns of Goliath grouper calls from long-term passive acoustic recordings at two nearby wrecks off Florida's Gulf of Mexico coast and assess the influence of temporal and environmental factors on Goliath grouper sound production.

2. Materials and Methods

2.1. Acoustic Data Collection

Digital SpectroGram (DSG) and LS1 acoustic recorders (Loggerhead Instruments, Inc., Sarasota, FL, USA) were used to record passive acoustic data, including the Goliath grouper calls. DSG recorders were programmed to record 11 or 21 s of marine sound every five or ten min using a 10 kHz sample rate. The difference in programmable settings used depended on the planned duration of deployment. LS1 recorders, which have greater data

storage capacity, were programmed to record 40 s every four min using a 48 kHz sample rate. Both recorder settings were capable of recording the Goliath grouper calls because the sample rates are well above the frequencies used by fish in general.

A recorder was deployed at two artificial reef sites in the Gulf of Mexico: (1) MD1 ($27^{\circ} 09.691' N$, $82^{\circ} 53.062' W$), a 24 m concrete hopper barge with 3 m relief, and (2) “Crane”, an approximately 6×3 m construction excavator devoid of a crane surrounded by other scattered debris ($27^{\circ} 9.054' N$, $82^{\circ} 55.140' W$), with approximately 4 m relief. These two sites were situated at 24 and 25 m depths, respectively, with the coordinates of the former being publicly known. The two sites were approximately 3.6 km from one another (Figure 1). Data were collected sporadically between April 2019 and June 2021.

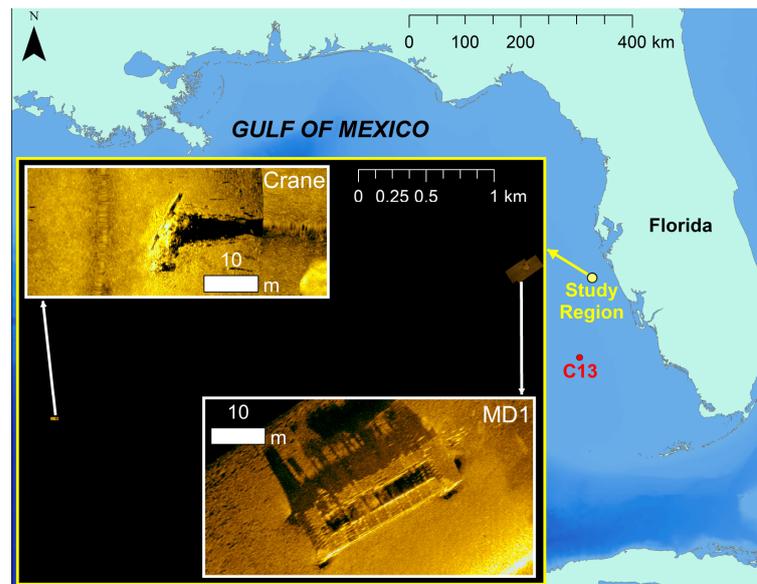


Figure 1. Overview map of the study region (yellow point) off the west coast of Florida in the Gulf of Mexico, relative to the C13 data buoy (red point). Land is shown in green. Inset map shows a zoomed in version of the study region and the two sampling sites, MD1 and Crane, along with accompanying sidescan imagery of the sites.

2.2. Call Detection

Because the characteristic waveform of fish sound is unique, the detection of known structure in an audio signal can be used to identify the sounds of different species. One of the best documented problems in communications [35], pattern recognition [36], and image processing [37] is the ability to detect an object or pattern in a known deterministic signal in the additive Gaussian noise. Using matched filtering is the simplest and most effective technique [35]. With a maximized signal-to-noise ratio and minimized detection error probability, the matched filter (MF) is optimal when the noise is white (or the spectral density is known) and synchronized (i.e., the signal arrival time is likewise known). The Goliath grouper calls were initially labelled manually by generating spectrograms of the acoustic data files and visually and audibly identifying the calls. This step was used to identify the call templates used in the MF, where the input signal is convolved with the template to detect the desired signal. The manually labeled calls also served to evaluate the MF detection skills.

The mathematical derivation of the MF is provided and follows Elm (2019) [38]. The optimal characteristic of a MF lies in the property of the filter impulse response $h(n)$, which corresponds to a time-reversed version of the target signal $h(n) = x(-n)$ Equation (1). The output $y(n)$ is the summation of the convolutions between the impulse response $h(n)$, the received finite-length L , and the discrete-time input signal $s(n)$. However, since the replica

signal is a time-reversed version of the target signal, the MF output is the summation of the correlations between $s(k) * x(-k)$, as follows:

$$y(n) = s(n) * h(n) = \sum s(k)h(n - k). \quad (1)$$

Increased signal-to-noise ratio can significantly affect the performance of the MF. To mitigate this effect, we implemented an adaptive threshold matched filtering. The adaptive MF uses two templates, one for the Goliath grouper call and another one for the background noise, both extracted from the dataset analyzed (Figure 2). The threshold value is calculated by convolving the noise template with the input signal. The mean of the latter convolution is multiplied by a gain factor (Kd), with which a decision is made on whether the input is a desired call or not. This gain is set to give the maximum number of true detections and reduce the number of false positives, and is unique to each dataset. Further details on this call detector can be found in Altaher et al. (2023) [39].

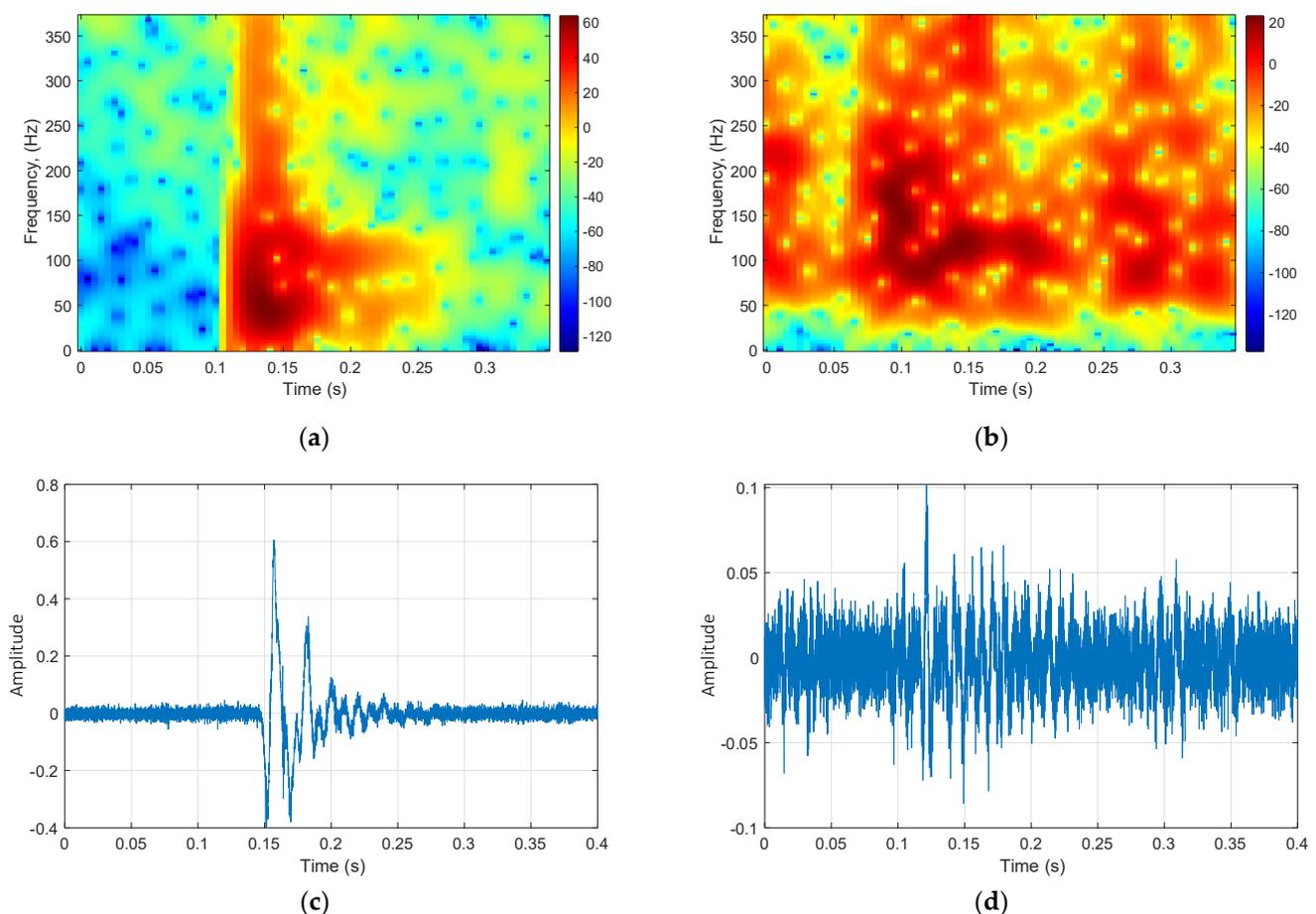


Figure 2. (a) Goliath grouper call spectrogram (dB). (b) Other pulse-like sounds spectrogram in the background noise (dB). (c) Amplitude envelope of the Goliath grouper call in (a). (d) Amplitude envelope of other pulse-like sounds in (b). The signal amplitude is used in the matched filter to detect the Goliath grouper calls.

The performance of the MF was determined by calculating the following metrics: sensitivity, precision, and F score. These metrics require computation of the true positive (TP), false positive (FP), and false negative (FN). Sensitivity determines the proportion of events that were correctly classified, and can be computed using the following formula:

$$Sensitivity = \frac{TP}{TP + FN} \quad (2)$$

Precision represents the fraction of correctly identified calls, and is calculated as follows:

$$Precision = \frac{TP}{TP + FP} \quad (3)$$

F-measure is the harmonic mean of precision and sensitivity, and is calculated using the formula described below:

$$F = \frac{2TP}{(2TP + FN + FP)} \quad (4)$$

2.3. Call Modeling

Different sampling regimes were used on the recorders throughout the study duration. To account for this, we modeled the number of Goliath grouper calls detected per second (i.e., call rate) and assessed the effect of environmental, celestial, and temporal variables on these (Table 1). A generalized additive model (GAM) was built using a Tweedie distribution with a log-link function using the ‘mgcv’ package in R (version 4.0.2). GAMs are particularly useful in ecological data where the relationships between covariates and the response variable are rarely linear.

Table 1. Covariates investigated for the call model.

Variable	Description	Range in Dataset
Wind speed (m/s)	Wind speed averaged over an eight-min period	0.3–15.8
Water temperature (°C)	Sea surface temperature	17.5–29.0
Atmospheric pressure (hPa)	Sea level pressure	1003.6–1024.4
Moon phase	Obtained using the longitude and latitude of MD1 and the ‘suncalc’ package. Treated as a circular smoother.	0–1 0: New Moon Waxing Crescent 0.25: First Quarter Waxing Gibbous 0.5: Full Moon Waning Gibbous 0.75: Last Quarter Waning Crescent
Hour of the day	Treated as a circular smoother. In UTC.	0–23
Month	Month of the year. Treated as a circular smoother.	1–12
Background noise (dB re 1 µPa)	Mean sound pressure level in the 100–200 Hz frequency band	50–140
Site	Location that the data was collected at. Treated as a factor.	MD1, Crane

Environmental data were obtained from an offshore buoy (Station 42023 C13; 26.010° N 83.086° W), which was 123.0 km and 121.4 km from MD1 and Crane, respectively. Several environmental covariates were considered as predictor variables (Table 1). Weather buoy measurements, typically recorded every 30 min, were matched with the date time stamps from the audio files. All data were kept in Coordinated Universal Time (UTC). To assess whether the Goliath grouper exhibits a diel pattern in call production, hour of the day was included. Peak sensitivity for Goliath grouper hearing occurs around 120 Hz (Locascio unpubl. data), so we considered background noise (dB) in the 100–200 Hz mean pressure band, measured as the average sound pressure level of the file. Full data exploration was

conducted prior to model building to avoid common statistical problems [40]. This included checks for outliers, interactions and collinearity between covariates. Collinearity can obscure which covariates are driving the response variable and leads to type II errors (i.e., failure to reject the null hypothesis when it is false) [40]. Model selection was conducted using the Akaike Information Criterion (AIC) [41].

3. Results

A total of 298 and 564 days of data were collected at the Crane and MD1, respectively, between April 2019 and June 2021 (Figure 3).

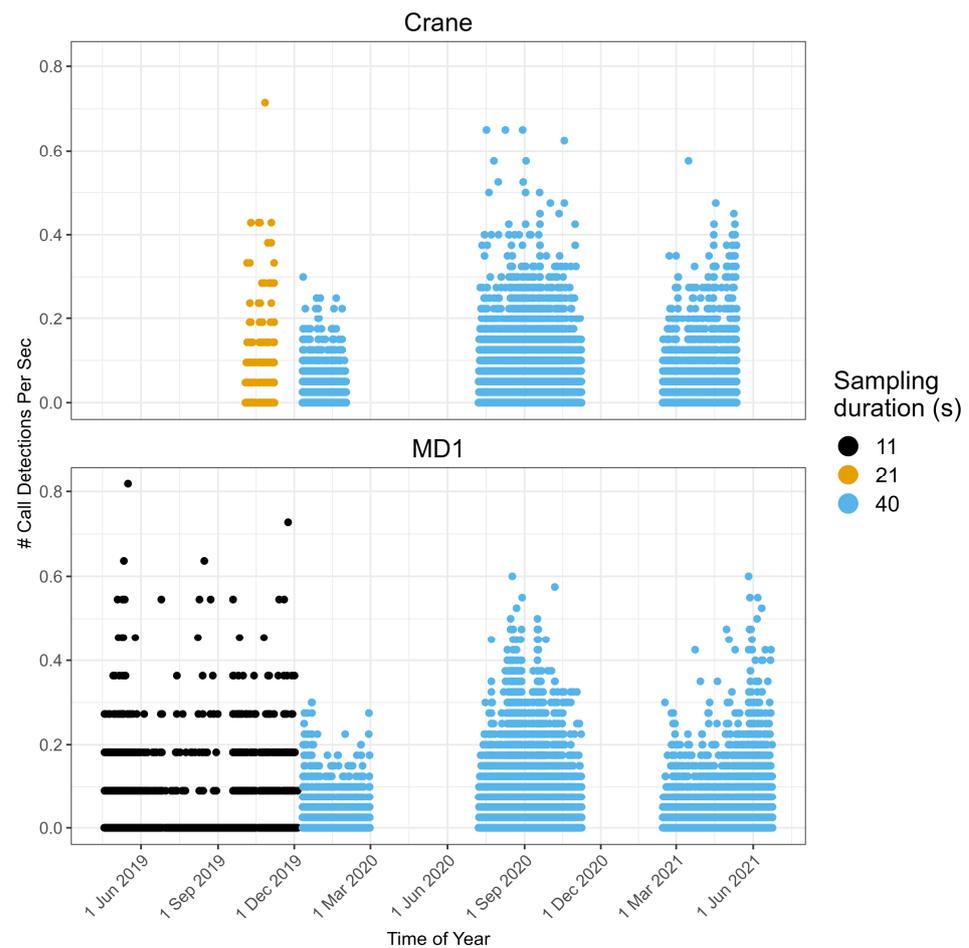


Figure 3. Timeseries of calls detected by the adaptive matched filter at the two sites, Crane and MD1.

3.1. Call Detection

Goliath grouper calls were detected in 23.5% of recordings, totaling 17,461 calls. The performance metrics of the detector are shown in Table 2. The detection skills of the Goliath grouper call detector were similarly high at the two sampling locations.

Table 2. Results of the three metrics used to test the performance of the adaptive matched filter. The performance metrics are shown for both sampling sites: Crane and MD1.

Site	Sensitivity	Precision	F
Crane	0.9749	0.9164	0.9448
MD1	0.9757	0.9380	0.9565

3.2. Call Model

Data exploration for the GAM revealed water temperature, day length, and month to be collinear, and so only month (which reflects day length and water temperature) was considered in model development. The equation for the optimal model is as follows:

$$\begin{aligned} \# \text{ Calls Per Second} = & s(\text{hour, bs} = \text{"cc"}) + s(\text{month, bs} = \text{"cc"}) + s(\text{moon phase, bs} = \text{"cc"}) \\ & + s(\text{atmospheric pressure}) + s(\text{wind speed}) + s(\text{background noise}) + \text{site, } Tw_p(\mu, \sigma^2) \end{aligned} \quad (5)$$

The Goliath grouper call rates were higher between 12 and 4:30 am EST (i.e., 5–9:30 am UTC), peaking at ~3 am EST, and just after the full and third quarter phases of the lunar cycle (Figure 4). The call rates were higher at the Crane site than at MD1. Neither sites are formally identified spawning locations but call production was higher in July–September, peaking in August. Outside of these months, the call rate was variable, with a small peak from the end of April to the end of May, and a decrease in call production during the winter months (November–March) (Figure 4b). The trends between call rate and atmospheric pressure and wind speeds were less clear, but there is some indication of higher call rates at lower atmospheric pressures (1010–1015 hPa) and windspeeds (<5 m/s). The Goliath grouper call rates were lower when background noise in the 100–200 Hz frequency band was <~70 dB re 1 μ Pa, but increased between ~70 and 110 dB re 1 μ Pa. There is some evidence to suggest Goliath grouper sound production decreased when noise increased above 110 dB re 1 μ Pa, but data beyond this sound pressure level were sparse. All model covariates were significant (Table 3) but hour of the day, month, and background noise were the most important model covariates, appearing in each of the top five most suitable models as determined by AIC (Table 4).

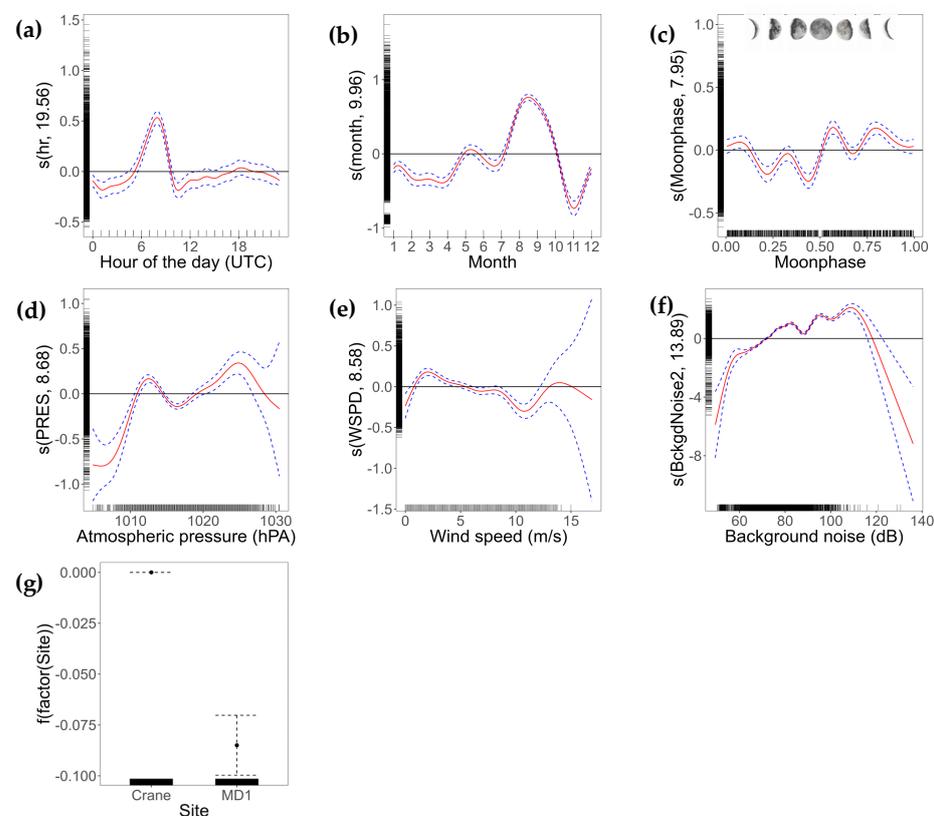


Figure 4. Estimated smoothers for each covariate in the optimal model: (a) Hour of the day (UTC); (b) month of the year; (c) moon phase (0 = new moon, 0.5 = full moon); (d) atmospheric pressure; (e) wind speed; (f) background noise (dB re 1 μ Pa) in the 100–200 Hz frequency band; (g) recorder location. The solid red line represents the smoother. The blue dashed lines represent 95% confidence intervals.

Table 3. Results of the optimal generalized additive model used to describe the trends in Goliath grouper call rates. Edf = estimated degrees of freedom. Ref.df = reference degrees of freedom.

Covariate	edf	Ref.df	F	p-value	R ² (adj.)	Deviance Explained (%)
Hour	19.558	22.000	145.72	<0.05		
Month	9.960	10.000	1077.14	<0.05		
Moon phase	7.953	8.000	132.23	<0.05		
Atmospheric pressure	8.681	8.959	149.29	<0.05		
Windspeed	8.583	8.929	79.72	<0.05	0.165	20.7
Background noise	13.888	13.996	1875.77	<0.05		

	Level	Coefficient	SE	t value	
Site	Crane	−4.707782	0.006428	−732.4	
	MD1	−0.084985	0.007523	−11.3	<0.05

Table 4. Top five most suitable generalized additive models for describing the trends in Goliath grouper call rates. The bolded model indicates the optimal model selected by the Akaike Information Criterion (AIC).

Model	Log-Likelihood	AIC	ΔAIC
<i>s</i>(hour) + <i>s</i>(month) + <i>s</i>(moon phase) + <i>s</i>(atmospheric pressure) + <i>s</i>(wind speed) + <i>s</i>(background noise) + factor(site)	6008.532	−11,870.9	0
<i>s</i> (hour) + <i>s</i> (month) + <i>s</i> (moon phase) + <i>s</i> (atmospheric pressure) + <i>s</i> (wind speed) + <i>s</i> (background noise)	5944.768	−11,745.4	125.52
<i>s</i> (hour) + <i>s</i> (month) + <i>s</i> (moon phase) + <i>s</i> (atmospheric pressure) + <i>s</i> (background noise) + factor(site)	5650.363	−11,172.1	698.82
<i>s</i> (hour) + <i>s</i> (month) + <i>s</i> (moon phase) + <i>s</i> (atmospheric pressure) + <i>s</i> (background noise)	5587.614	−11,048.6	822.31
<i>s</i> (hour) + <i>s</i> (month) + <i>s</i> (atmospheric pressure) + <i>s</i> (wind speed) + <i>s</i> (background noise) + factor(site)	5474.450	−10,818.6	1052.34

4. Discussion

The identification of spawning sites for Goliath groupers is of paramount importance given the recent changes in species' management in Florida state waters. Although current harvest efforts target limited numbers of juveniles in nearshore areas (i.e., <9 NM of shore along the Gulf of Mexico), these may influence offshore dynamics of adults as these individuals mature and eventually recruit to these deeper habitats. Our data suggest that fish at artificial reef sites off Sarasota exhibit temporal patterns in sound production congruent with those of established spawning sites elsewhere in the Gulf of Mexico and the Atlantic coast of Florida [32,34]. Fish captured from these sites for other projects in early fall have exhibited physical signs of spawning readiness, such as milting (M.J. Ajemian, pers. obs); however, systematic sampling of spawner tissues and plankton (i.e., eggs and larvae) is still required to confirm spawning activity. Given the high probability of these behaviors, the sites examined herein can be prioritized for confirmation of spawning aggregations.

This study identified more Goliath grouper calls at night than during the day, which is congruent with findings from previous studies that focused on the spawning season and found that sound production is highest in the darkest conditions (i.e., at night, around the new moon) [9,34]. This may be to facilitate orientation of spawning partners to one

another and to reduce egg predation by planktivorous fishes, although one study at a more northerly Florida spawning site found similar sound production levels between the new and full moons [32]. In this study, more calls were detected shortly after the full moon and last quarter of the lunar cycle, perhaps indicating the importance of sound production unrelated to spawning activity i.e., as part of agonistic/territorial behavior towards conspecifics and other organisms or other behaviors such as alert calls.

Other grouper species, such as red hind (*Epinephelus guttatus*), Nassau grouper (*Epinephelus striatus*), and yellowfin grouper (*Mycteroperca venenosa*) are also known to cue their spawning activity based on the lunar cycle. Their spawning activities are associated with notable diel and lunar patterns in courtship associated sounds [8,42]. During spawning periods, red hind abundance increases leading up to the full moon [43,44] at fish spawning aggregation sites in the US Virgin Islands. At other locations, such as Puerto Rico or the Cayman Islands, the timing of the aggregation- and the courtship-associated sounds peak relative to the full moon would be different [8,45]. However, unlike these smaller grouper species, our data shows that Goliath grouper sound production is not limited to spawning season. It is present year-round, suggesting that these fish constantly communicate.

Background noise measured in the 100–200 Hz range also impacted call rates, which were lower when sound pressure levels were <70 (and >110 dB). The 100–200 Hz frequency range is above the peak frequency of the Goliath grouper call, which is known to be 60 Hz [9]. Although Goliath grouper call activity during spawning aggregations have been reflected in the sound pressure level variation of the 0–100 Hz [9] and also in the 100–200 Hz frequency band (A. Ibrahim, pers. Obs), the long-term noise timeseries herein is relatively independent of the Goliath grouper call. A maximum of nine calls were detected in the 11 s files (15 and 26 calls in 21 and 40 s files, respectively; Figure 3), and knowing that a call lasts ~110 ms, the cumulative call duration accounts for <10% of the file duration. Thus, we can conservatively assume that at least 90% of the file duration from which background noise is calculated contains only non-grouper sound sources (although it depends on the relative amplitude of the calls over the background noise). Based on this assumption, the model shows an increased call rate when the sound pressure level in the 100–200 Hz band is between 70 and 110 dB re 1 μ Pa. The call rates were lower when sound pressure levels were <70 dB. This observed pattern may be related to the hearing threshold for this species. Wild yellow grouper (*Epinephelus awoara*) are most sensitive to sounds at 200 Hz, and were found to have an auditory threshold of 90 dB re 1 μ Pa [46]. Similarly, call rates appear to decline when sound pressure levels exceed 110 dB re 1 μ Pa, though such levels occurred infrequently in our dataset. This may indicate that Goliath grouper calls and/or sounds that elicit calls are masked when background noise is louder, which is caused by storms and anthropogenic sounds (e.g., boat noise). However, both sound sources may interfere with fish communication and, in fact, cause a reduction in call activity [47]. Further studies that investigate the hearing capabilities and sensitivity of the Goliath grouper might provide insight into the pattern of call rates relating to background noise.

We included other environmental parameters readily available to us from the C13 weather buoy, including wind speed and atmospheric pressure. Wind speed and current direction can impact larval transport and fish recruitment, and are known to correlate with the timing of spawning for broadcast spawning reef fish, including the Goliath grouper [32]. Peak call rates were associated with relatively lower atmospheric pressures and windspeeds, conditions that typify summertime weather patterns in the Gulf of Mexico. These conditions may be conducive to support and retain the Goliath grouper larvae prior to shoreward transport and settlement in mangroves and estuaries of southwest Florida; however, oceanographic modeling of this process has not yet been performed from these sites.

Collins et al. (2015) [48] reported that Goliath grouper abundance was positively correlated with vertical relief and structure volume of artificial reefs. It would thus stand to reason that higher call rates would be expected at MD1 over the Crane site, based on the dimensions of the sites alone. However, we found significantly higher call rates at

the Crane site than MD1, which could be attributed to several factors including increased abundance at the Crane, increased noise from anthropogenic activity at MD1 impacting call detection, or increased individual sound production. Sporadic video surveys at each site during the spawning season indicate higher abundance at the Crane (Chérubin et al. unpubl. data), but as a smaller structure with considerably less interstitial spaces for large Goliath groupers to occupy, we suspect that groupers would be easier to see at this site and that the site layout alone may have facilitated greater competition, and thus elicited more calls. It is also possible that less protection at the Crane yields more communication between individuals toward potential threats.

To date, most efforts to quantify sound production in the Goliath grouper have focused on spawning seasons (with recordings occurring between July and December). This study found that Goliath grouper sound production occurred year-round at both study sites. Our modeled data support previous findings of high levels of production in August, but also suggest slightly elevated sound production in spring (from the end of April to the end of May) for reasons unknown. It is not clear whether these observations simply represent a period during which migratory fish arrived at the sites and are increasing sound production due to elevated interactions with conspecifics (e.g., resident fish) or whether this is an expansion of the spawning season into earlier months of the year than previously reported. Indeed, because of climate change, several species of fishes are experiencing northward expansion of spawning grounds [49], including the Goliath grouper [32], and in some cases extended spawning periods are also observed [49]. Unfortunately, due to logistics, we were unable to maintain continuous year-round monitoring systems at both sites simultaneously, limiting our ability to speculate on the reasoning behind this observation. We thus recommend future studies implement continuous, sustained acoustic recordings to facilitate this knowledge, along with systematic sampling of fish reproductive tissues as stated above.

Detecting and classifying fish sounds from long-term datasets is time consuming, necessitating the development of automatic detection methods [39,50–52]. We found improved detection capabilities of a matched filter that used both a Goliath grouper call and a background noise template rather than just a call template alone. Using a noise template from the analyzed dataset allows for a more accurate estimation of the threshold value as the templates can be chosen to match the expected characteristics of the signal and noise. It improves the discrimination capability between the signal to be detected and noise. This can be particularly important in cases where a call is weak and/or the noise is non-stationary or varies over time. This detection algorithm provides the opportunity to efficiently detect Goliath grouper calls from long-term passive acoustic monitoring datasets. This type of automatic call detection can be coupled with localization algorithms in the case of an acoustic array and provide high resolution fish call distribution, which can be used to study the small-scale fish movement around their habitat [39].

A limitation of using passive acoustics is the inability to approximate how many fish are contributing to sound production. Animal-borne bio-logging tags, particularly those that incorporate an accelerometer and/or hydrophone, provide a means to quantify sound production and fine-scale behavior at the individual level, and can complement passive acoustic monitoring [53]. Further, these tags can also be fitted with other sensors, such as video cameras, which can help provide an environmental context with each call and discern whether there is behavioral call variation [54–56]. We therefore suggest researchers consider this approach in the future as it may foster a stronger understanding of the role of various external stimuli in Goliath grouper call dynamics.

5. Conclusions

While incredibly useful at advancing science and management, large-scale long-term, passive acoustic analyses present an immense analytical challenge: how does one mine terabytes of raw recording data to enumerate species-specific sounds? Only in recent years, automatic fish sound signal detection methods have been developed and remain few. In

this study, we developed an automatic Goliath grouper call detector that maximizes the call signal-to-noise ratio during the detection process by accounting for the background noise in the recordings. The skill of the detector provides great confidence in the detected calls, which can be used to study the dynamics of Goliath grouper sound production.

Previous studies, focused on Goliath grouper spawning season, have revealed the timing of peak sound production and its relationship to spawning activity. In the study herein, we collected 862 days of acoustic records throughout all seasons. By developing a model to evaluate the influence of environmental and celestial variables, we showed that Goliath grouper sound production was not limited to the spawning season. Goliath grouper calls were present year-round and exhibited temporal variability that was observed in all seasons with a decrease in mean call rates during the boreal winter months. In addition, we showed that sound production was tied to the lunar cycle in general and to background noise as well. The reasons behind sound production outside the spawning season are unknown and invites further research into the communication behavior of this species. Such information could be used to understand how the Goliath groupers use their environment, and thus help resource managers track habitat quality for this vulnerable species.

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