JASA ARTICLE

The oyster toadfish (*Opsanus tau*) alters active and diurnal calling amid vessel noise in New York City

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ABSTRACT:

While many studies have demonstrated the negative impacts of anthropogenic noise on aquatic animals, few studies have examined its effect on species that inhabit major ports. New York City provides habitat for the oyster toadfish (*Opsanus tau*), a species in which females must hear the male advertisement call to reproduce. This study had two equally important goals. First, vessel noise in the waters of New York City was characterized: An analysis of 480 vessel noise events revealed that noise incidence varied widely, while amplitude varied less. Second, toadfish calling behavior was quantified under noisy and quiet conditions. Toadfish called over twice as much in quiet samples, which occurred in the early morning, than in samples with noise. This early morning peak in calling behavior differs from those of non-urban populations and is evidence of diurnal call suppression. Furthermore, in samples with noise, toadfish actively called less when noise duration was longer, amplitude was greater, and the dominant frequency of noise overlapped the fundamental frequency of calls. Finally, toadfish did not change call amplitude, frequency or duration during noise. These results provide evidence that fishes living in vessel-heavy urban environments adjust their reproductive-related acoustic communication behavior to cope with noise.

 https://doi.org/10.1121/10.0044262

(Received 3 March 2026; revised 9 June 2026; accepted 11 June 2026; published online 2 July 2026)

[Editor: Shane Guan] Pages: 233–244

I. INTRODUCTION

Many studies have demonstrated the negative impacts of anthropogenic noise on animals, and our understanding of these effects on behavior, physiology, and mortality is growing (Slabbekoorn *et al.*, 2018). In the marine environment, most research has focused on the impact of anthropogenic noise in oceans (Duarte *et al.*, 2021), but bays and estuaries are critical habitat, especially for early life-stage teleost fishes (Arevalo *et al.*, 2023). Fewer studies have examined the effects of noise on teleost fish in these areas. Also, it is becoming increasingly clear that many teleosts produce sound. Evolutionary relationships suggest that over 20 000 species of teleosts might be sound producers (Looby *et al.*, 2023). Being able to detect an important acoustic signal, like an advertisement call, in murky estuarine waters might be critical for reproductive success. Surprisingly, very few studies have examined the effect of anthropogenic noise on the advertisement calling behavior of soniferous fishes, *in situ* and in detail, in a major global port.

The Bureau of Labor Statistics ranks the combined Port of Newark and New York as the second busiest port in the US, measured by vessel passages (Bureau of Transportation Statistics, 2025). Automatic Identification System (AIS) data for a rectangle of approximately 10 miles^2 in Upper New York Harbor reported hundreds of unique vessels and over 8000 identification transmissions from moving vessels on June 1, 2023, alone (NOAA Office for Coastal Management, 2025). No study to date has described, in detail, the characteristics of vessel noise in the various coastal habitats of New York City. The first aim of this study is to fill that gap.

Despite high vessel traffic, New York City provides reproductive habitat for the soniferous oyster toadfish (*Opsanus tau*) (Anderson *et al.*, 2008; Hom *et al.*, 2024). Male toadfish produce advertisement calls, with fundamental frequencies around 200 Hz, to attract females to nests (Fish, 1954; Gray and Winn, 1961; Winn, 1972). Vessel noise is a large component of anthropogenic noise in this spectral range (Shabangu *et al.*, 2022). Importantly, since females provide no parental care (Clapp, 1899; Gudger, 1910), the ability of the female to detect, localize, and evaluate advertisement calls, even in noise, is critical to toadfish reproductive success.

Few studies have examined the impact of *in situ* vessel noise on male toadfish calling behavior. In Woods Hole,

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MA, Mackiewicz *et al.* (2021) compared the number of toadfish calls before and after vessel noise events and found a decrease in calls immediately after noise. Conversely, in the Chesapeake Bay, Colbert *et al.* (2023) found no effect of individual noise events on numbers of toadfish calls, but did find a significant effect over a 30-day period, where toadfish called less as noise gradually increased. Most recently, Hom *et al.* (2024) compared toadfish at Pier 40 in Manhattan, on the Hudson River, to toadfish in Woods Hole, MA, and found that diurnal calling behavior differed: Numbers of calls at Pier 40 peaked from midnight to 6:00 a.m., the quietest time of the day, while numbers of calls at Woods Hole peaked in the evening around sunset. Woods Hole was found to be less noisy than Pier 40. While these studies all relate the presence of noise to the number of toadfish calls, they do not clearly distinguish between active behavior and diurnal behavior, and they do not examine other important characteristics of both noise and calls. The second aim of this study was to address these gaps by examining several parameters of vessel noise (incidence, amplitude, dominant frequency, duration, and periodicity) and how these relate to numbers of calls. Also, we investigated several parameters of calls (number, amplitude, fundamental frequency, duration, and periodicity) and related them to incidence of vessel noise. Finally, we tested specifically for evidence of active vs diurnal patterns in call suppression related to noise.

II. METHODS

A. Passive acoustic monitoring and sampling

Hydromoth hydrophones (Open Acoustic Devices, Eastleigh, UK) were used to record sound. Hydromoths have been demonstrated to be adequate for recording sound below 20 kHz (Lamont *et al.*, 2022), which includes the hearing range of toadfish. The hydrophones were calibrated by deploying the Hydromoths with a reference hydrophone in Sheepshead Bay, Brooklyn, in early spring. A SoundTrap 300 STD hydrophone (Ocean Instruments, Auckland, New Zealand) with a manufacturer reported error of ±3 dB was used as the reference hydrophone. Hydromoths have been reported to match the frequency response of SoundTraps below 15 kHz (Lamont *et al.*, 2022). Computer-generated pure tones at 200, 400, 600, 800, and 1000 Hz were played underwater, and recordings were made on the Hydromoths and SoundTrap, which were arranged in an array. The recorded amplitudes were averaged over the five tone frequencies to arrive at a calibration factor for each Hydromoth. The derived sensitivity of the Hydromoths varied from –166.9 to –169.5 dB re 1 V/μPa, and the sampling rate was set to 48 kHz.

After calibration, several Hydromoths were deployed for 24 h at 13 sites in New York City in April and May, 2023, to detect the presence of toadfish (Fig. 1 and Table I). Four locations, Valentino Pier ("val," Brooklyn), Pier 40 ("p40", Manhattan), Sheepshead Bay ("shb," Brooklyn) and Shirley Chisholm State Park ("csp," Brooklyn) were chosen for extended acoustic monitoring. Hydrophones were deployed at these locations for 11 weeks from May 8 to July 24, 2023, except for csp, where they were deployed for 7 weeks from June 4 to July 20, 2023. Hydromoths were deployed in their waterproof housing, which was attached to a brick. The assembly was lowered to the seafloor with nylon sinking line.

Toadfish calling peaked on different days at each location, so the 4 days with the most calls were selected for analysis at each location. Toadfish activity varies throughout the day, so both peak and non-peak hours were included. To count advertisement calls, characterize vessel noise, and assess the impact of vessel noise parameters on call counts, 4-min samples were examined every 30 min during these days.

B. Noise characterization

Vessel noise events were manually identified using RAVEN PRO v1.6.5 (Cornell University, Ithaca, NY) based on spectrographic content and sound. Non-vessel sound, including sound from docks, aircraft, waves, and rain, was not quantified. A trainer spent several months in the field recording vessel noise and identifying the sources, both with simultaneous sound and video and also using a handheld hydrophone and log. The trainer then determined the protocol for identifying noise events. An annotation started at the first point in an audio file when both visual and audio evidence of noise was encountered and ended when both were no longer detectable. No attempt was made to distinguish individual vessels, so a noise event could include more than one vessel. The trainer then trained the annotator to apply the protocol. After several training sessions, the annotator traced noise events in the recordings. The trainer reviewed all traced events and, out of 480 events, modified fewer than 10, either by adjusting the length of the trace or adding a trace that was missed. Once noise events were identified, several parameters of noise were measured. Duration of vessel noise for the analysis was defined as the number of seconds in a 4-min sample that included noise. Ten-second subsamples at peak amplitude of noise were used to quantify vessel noise amplitude and dominant frequency. Noise amplitude and dominant frequency were calculated in R using the packages SEEWAVE (Sueur *et al.*, 2008), TUNER (Borg, 2016), and SOUNDGEN (Anikin, 2019). Unless otherwise noted, all amplitudes were calculated between 25 and 800 Hz, the approximate hearing range of toadfish (Fish and Offutt, 1972; Rogers *et al.*, 2020; Yan *et al.*, 2000).

One-time surveys using cameras and hydrophones were conducted at each location to identify vessel types and match those types with spectrograms. Video and sound were recorded simultaneously for 1 h at each site. Video was recorded from a camera placed on the dock or pier immediately above the submerged hydrophone. Recordings were made on 2 separate days in August between 9:00 and 11:00 a.m. Vessel type is reported but was not used in our analysis of calling behavior.

https://doi.org/10.1121/10.0044262

FIG. 1. Location map. White dots indicate short-duration (24 h) sampling sites where toadfish advertisement calls were detected (solid) or not (black X). Colored dots with toadfish icons indicate sites where advertisement calls were detected and extended acoustic monitoring was conducted. The base map was made using MAPCREATOR.IO.

TABLE I. Location details.

Parameter	val	p40	shb	csp
Location name	Valentino Pier, Brooklyn, NY	Pier 40, New York, NY	Sheepshead Bay, Brooklyn, NY	Shirley Chisholm State Park, Brooklyn, NY
Location GPS coordinates	40.678267, −74.018401	40.728272, −74.011956	40.583017, −73.936247	40.638069, −73.868471
Location type	Fixed pier	Floating dock	Floating dock	Fixed pier
Distance from hydrophone to nearest vessel channel, m	115.8	261.2	3.0	58.8
Hydrophone mean depth, m	2.5	4.3	1.9	2.1
Proximity to USDOT urban area	Within	Within	Within	Surrounded by
Total no. of 4-min samples	192	192	190	190
Sampling dates used in analysis	6/7/23–6/10/23	6/10/23–6/14/23	5/28/23–6/1/23	6/20/23–6/23/23
Average water temperature during sampling, °C	18.7	19.0	19.4	21.0

We use the term "urban area" for locations adjacent to land with a US 2020 Census population density greater than 10 000 people/mile^2 (3474/km^2). We use "non-urban" for locations adjacent to land with a US 2020 Census population density less than 2000 people per square mile (772 per square kilometer).

C. Advertisement call characterization

Automated call detection for teleost fish allows analysis of calls quickly in large datasets [e.g., Chérubin *et al.* (2025)]. However, detection of animal signals in masking noise requires care, and several steps were taken to ensure accuracy of the analysis. Toadfish calls were identified using the template detector from the R package OHUN (Araya-Salas *et al.*, 2023). To examine calls during noise, actual calls were used as templates for the detector, but only high amplitude calls—i.e., those that would not be masked during noise—were used as templates. The detector, therefore, ignored distant calls whether or not they occurred in noise. A subset of 16 4-min samples (4 at each location) was randomly selected and true-positive, true-negative, false-positive, and false-negative detections were manually identified. The detector's overall precision was 90% in quiet and 98% in noise, and these rates did not differ between quiet and noise when calculated individually for each test sample [$t(22.8) = -1.371$, $p = 0.184$]. Overall recall was 78% in quiet and 86% in noise, and these rates did not differ between quiet and noise [$t(23.0) = -1.050$, $p = 0.305$]. Finally, the false-positive rate was 7% in quiet and 3% in noise, and these rates did not differ between quiet and noise [$t(8.1) = -0.424$, $p = 0.683$]. The signal-to-noise ratio (SNR) was calculated using true-positive and false-negative detections in the validation set. SNR was calculated individually for each of the first three harmonic bands of each call and is reported for quiet and noise and, in noise, for the harmonic bands with maximum and minimum SNRs. Importantly, if vessel noise, geophony, or biological noise (e.g., cusk eel choruses) clearly masked advertisement calls, those samples were removed from any analysis of the impact of vessel noise on calls. In total, 54 of 768 samples were removed from these analyses.

To characterize call amplitude and duration, and to assess the impact of vessel noise presence on these parameters, 20-min samples were examined. These samples were randomly selected but not used if all or none of the sample included vessel noise, which would preclude the comparison of behavior before, during, and after noise. Call amplitudes were adjusted to remove the amplitude of background noise (Brumm and Zollinger, 2011). All reported amplitudes are received amplitudes, not amplitudes measured at 1 m, since the exact distance to the toadfish and the vessels was unknown. We made no attempt to account for changes in sound propagation conditions, e.g., changing salinity. For this analysis, 19 samples containing 899 calls were examined.

To characterize call fundamental frequency, waveforms for individual calls were examined at 1/10-s intervals and wave peaks were manually counted. These frequencies were then visually compared to spectrograms and reused for animals that presented the same spectrographic characteristics. If the best identifiable frequency was a second, third or, rarely, fourth harmonic, its value was converted to a fundamental frequency before comparison in analysis. Because the detector ignored low amplitude calls, and toadfish calls include several harmonics, vessel noise did not impede manual counts of peaks.

Finally, in an attempt to identify how individual animals behave in noise, spectrograms were used to manually identify individuals based on the shape, amplitude, and duration of the call (Van Wert and Mensinger, 2019). For this analysis, 17 samples containing 40 total calls of 20 purported individuals were examined.

D. Statistical analysis

Data were analyzed using linear models in R with the packages LME4 (Bates *et al.*, 2015), EMMEANS (Lenth, 2016), CAR (Fox and Weisberg, 2018), MASS (Venables and Ripley, 2002), and RMISC (Hope, 2012). Fixed factors were evaluated using type III analyses of variance (ANOVAs), and *post hoc* tests used Bonferroni corrections. Table II provides details on the structure of important models, and Appendix s2 in the supplementary material includes model output and the results of *post hoc* tests associated with Fig. 4. Data were visualized using GGPLOT2 (Wickham, 2011) or PRISM v10.5.0 (GraphPad Software, Boston, MA).

To determine if the dominant frequency of vessel noise overlapped the harmonics of toadfish calls, the average first and second harmonic of calls in a sample were compared to the dominant frequency of noise in the hearing range for that sample. These harmonic ranges are identified by boxes f_1 and f_2 in Fig. 4. If the dominant frequency was within 2

TABLE II. Select linear models.

Question	Model
Do noise detections vary by location?	model = glm(noise_detected_boolean ~ location, family = binomial, data = all_samples)
Does advertisement call number vary by location?	model = glm(call_count ~ location + period_of_day, family = "poisson", data = all_samples)
How do noise parameters affect the number of calls?	model = glm(call_count ~ vessel_amplitude_db + vessel_duration_sec + fundamental_frequency_overlap_boolean + 2nd_harmonic_overlap_boolean + location + period_of_day, family = "poisson", data = samples_with_noise)
Does call amplitude change during or after noise?	model = lmer(incremental_amplitude_db ~ location + before_during_after + (1 | noise_event), data = subset_of_samples_with_noise)
Does call fundamental frequency change with temperature?	model = lm(fundamental_frequency_hz ~ temperature_c, data = all_samples)

https://doi.org/10.1121/10.0044262

standard deviations (i.e., approximately 95% of values) of a harmonic, it was labelled as overlapped by the harmonic.

III. RESULTS

A. Vessel noise

Vessel noise was detected at all 13 initial sites. Vessel noise was characterized at the four acoustic monitoring locations (Fig. 2 and Table III). Each location had significantly different numbers of samples with noise [$X^2(3,\ n=764) = 146.35,\ p<0.001$)] [Fig. 2(a)]. Pairwise comparisons using estimated marginal means indicated each location was different from the others (e.g., p40 vs val, $p<0.001$; shb vs csp, $p=0.048$). On the other hand, when vessel noise was present, the amplitude [$F(3,\ 323)=29.39,\ p<0.001$] (Fig. 2(b)] and dominant frequency [$F(3,\ 323)=8.96,\ p<0.001$] [Fig. 2(c)] of that noise differed, but only at p40, where it was lower in both cases. For example, vessel noise amplitude was lower at p40 compared to val ($p<0.001$) and vessel noise dominant frequency was lower at p40 compared to val ($p<0.001$). The duration of vessel noise did not differ among locations [$F(3,\ 36)=1.48,\ p=0.237$] [Fig. 2(d)]. Vessel noise incidence (seconds of noise per sample) varied by the period of the day [Fig. 2(e)]. At val and p40, night had the least incidence of noise (e.g., night vs afternoon at val, $p=0.012$). At shb and csp, night was among the periods with the least incidence of noise (e.g., night vs afternoon at shb, $p<0.001$). Val had significantly greater incidence of noise than the other locations in all periods except the afternoon (e.g., night at val vs night at shb, $p<0.012$).

B. Toadfish advertisement calls

Toadfish advertisement calls were detected at 11 of 13 initial sites. At the four acoustic monitoring locations, a total of 29 868 advertisement calls were identified over the 4-day sampling period (Table IV). Other toadfish vocalizations (e.g., grunts and growls) and other types of biological sound were observed but not detected by our template detector and

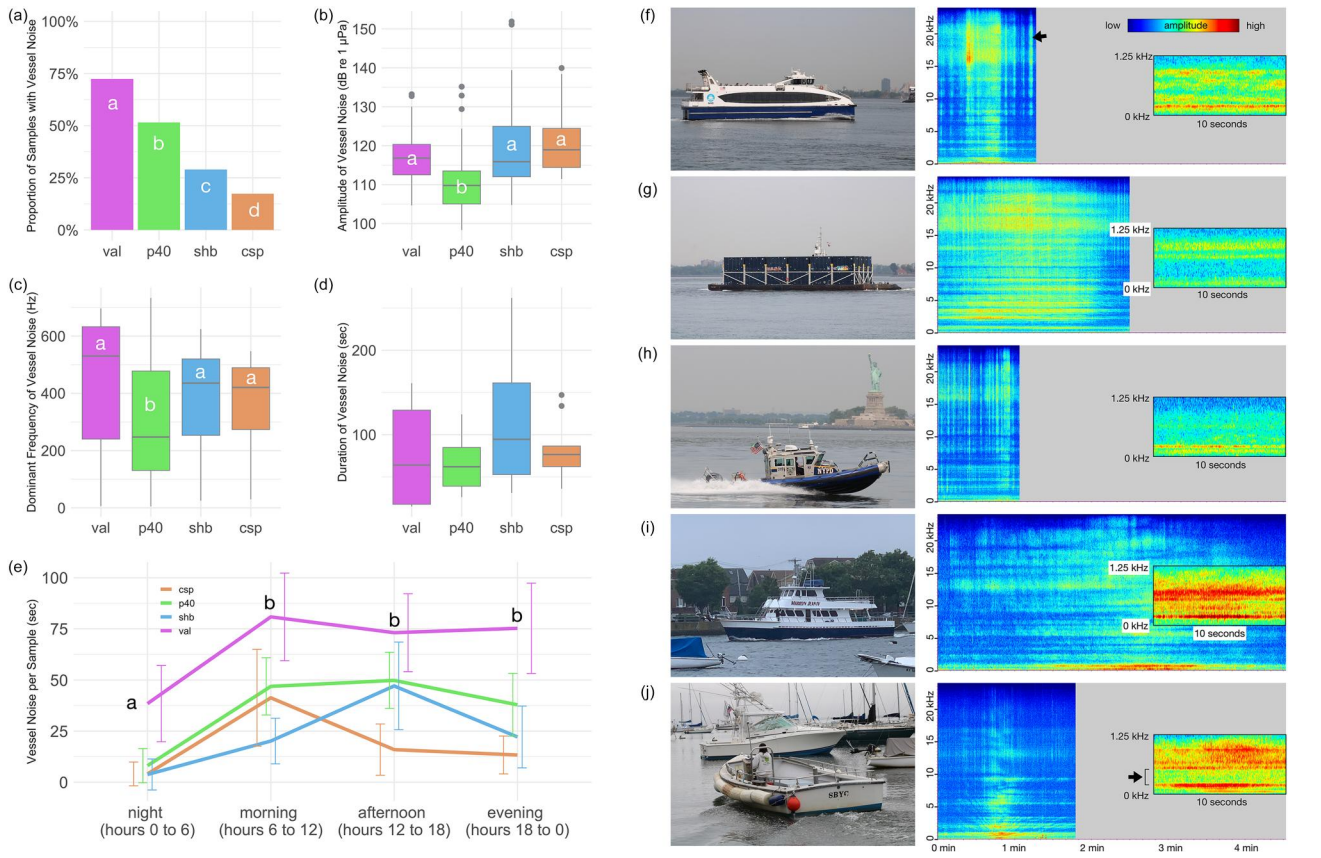

FIG. 2. Vessel noise measurements, vessel examples, and spectrograms. Unless otherwise noted, letters indicate significance groups based on *post hoc* tests, boxes are second and third quartiles, whiskers extend 1.5× beyond the interquartile range, and dots are outliers beyond that range. (Left panels) Vessel noise measurements calculated in the hearing range of toadfish. (a) The number of 4-min samples with noise. (b) Peak vessel noise amplitude. (c) Vessel noise dominant frequency. (d) Vessel noise duration. (e) Average seconds of noise per 4-min sample by period and location. Whiskers in panel (e) are 95% confidence intervals, and significance is only displayed for period comparisons at val. (Right panel) Images and associated spectrograms of common vessel types. Large spectrograms are 4 min 30 s in length and 0–24 kHz in range. Inset spectrograms are 10-s segments at peak amplitude in the approximate hearing range of toadfish (0–1.25 kHz). The vessels shown are (f) a New York City high speed ferry, (g) a tugboat with trash barge, (h) a police outboard vessel, which uses the same engine type as most recreational motorboats, (i) a charter fishing boat (also known as a party or head boat), and (j) a Sheepshead Bay launch, which uses the same engine type as many recreational sailboats. The black arrow in panel (f) indicates breaking waves (thin, uniform vertical bands between 7.5 and 24 kHz), and the black arrow in panel (j) indicates a band of relatively low amplitude noise (225–500 Hz) that is found in many types of vessel noise. The spectrograms in panels (f) through (h) were recorded at val, while those in panels (i) and (j) were recorded at shb. Photos were taken during sound recording, so photos match spectrograms.

TABLE III. Summary of vessel noise over 4 days.

Parameter	val	p40	shb	csp
No. of samples with vessel noise present (% of total samples)	139 (72%)	99 (52%)	55 (29%)	33 (17%)
No. of discrete noise events recorded	196	165	85	34
Estimated no. of h of noise/24 h	6.7	3.4	2.3	1.7
Average peak amplitude of noise, dB	116.7	110.1	119.4	120.2
Average dominant frequency of noise, Hz	330	180	315	326
Average length of a noise event (in a subset of 20-min samples, $n = 40$), s	76.6	65.5	115.5	80.9
Average amplitude of ambient sound, dB	106.1	101.7	105.5	104.0
List of top 3 vessel types observed at each location	Ferry, tug, fire/police	Ferry, tug, fire/police	Recreational motor, recreational sail, head	Recreational motor

were, therefore, not analyzed. Because the number of toadfish at each location and the exact distance from the hydrophone to the fish were both unknown, the differences in both call number [$X^2(3, n = 764) = 13\,821.3$, $p < 0.001$] [Fig. 3(a)] and call amplitude [$F(3, 15.01) = 17.99$, $p < 0.001$] [Fig. 3(b)] cannot be interpreted. It is worth noting, however, that the mean received incremental amplitude of calls, at all locations combined, was 117.2 dB, while the maximum received incremental amplitude was 141.6 dB.

The fundamental frequency of calls varied among locations [$F(3, 15.01) = 82.15$, $p < 0.001$] [Fig. 3(c)], with val lower than p40 ($p = 0.006$) and csp ($p < 0.001$) but not different from shb ($p = 0.061$). The duration of calls also varied among locations [$F(3, 15.01) = 4.74$, $p = 0.016$] [Fig. 3(d)], with p40 showing a significantly longer duration compared to val ($p = 0.018$). The proportion of each day's calls per period of the day differed at some locations [$F(3, 700) = 4.60$, $p = 0.003$] [Fig. 3(e)]. Call proportions at val and p40 did not differ during any period of the day (p values between 0.29 and 0.99). Call proportions at csp and shb differed from each other in the morning ($p < 0.001$, csp higher) and the afternoon ($p = 0.002$, shb higher). Importantly, at csp, the location with the lowest number of noise events, calls peaked in the evening and were significantly higher than those at val ($p = 0.002$) and p40 ($p = 0.004$). Also, at night, calls at csp were significantly lower than those at val ($p < 0.001$) or p40 ($p = 0.001$). The peak calling period for csp, therefore, was in the evening. The peak for shb was evening and night. The peak for val and p40 was night.

C. Effect of vessel noise on numbers of calls

Among all locations, toadfish called more frequently in samples without noise compared to either the quiet-filled ($p < 0.001$) or noise-filled ($p < 0.001$) portion of samples with noise [$F(2, 2127) = 80.97$, $p < 0.001$] [Fig. 4(a)]. In samples where noise was present, increased noise amplitude resulted in significantly fewer calls ($z = -9.002$, $p < 0.001$) [Fig. 4(b)]. Also, increased duration of noise also resulted in significantly fewer calls ($z = -2.369$, $p = 0.017$) [Fig. 4(c)]. When the dominant frequency of noise overlapped the fundamental frequency of calls, calls were significantly lower ($z = -4.747$, $p < 0.001$) [Fig. 4(d), box f_1], whereas noise that overlapped the second harmonic of calls had no effect ($z = 1.899$, $p = 0.062$) [Fig. 4(d), box f_2]. More noise events overlapped call fundamental frequency than overlapped the second harmonic [Fig. 4(e)].

D. Effect of noise presence on call amplitude, frequency, and duration

Advertisement call amplitude, fundamental frequency, and duration were compared immediately before, during, and immediately after discrete vessel noise events [Figs. 4(f)–4(h), left column, "Chorus Behavior"). Also, using spectrograms to attempt to identify individual fish, the same three call parameters were measured for the purported individuals before and during noise events [Figs. 4(f)–4(h), right column, "Individual Behavior"]. The amplitude of toadfish advertisement calls in the chorus decreased during noise by approximately 1 dB [$F(2, 878.98) = 5.06$, $p = 0.007$] [Fig. 4(fi)], while the amplitude of purported individuals did not change [$F(1, 22) = 1.37$, $p = 0.254$] [Fig. 4(fii)]. Note: Fig. 4(fii) is the closest estimate of the Lombard effect provided by the data. The fundamental frequency of calls did not vary for either the chorus [$F(2, 879.86) = 0.49$, $p = 0.611$] [Fig. 4(gi)] or for purported individuals [$F(1, 22) = 0.18$, $p = 0.676$] [Fig. 4(gii)]. Likewise, the

TABLE IV. Summary of toadfish advertisement calls over 4 days.

Parameter	val	p40	shb	csp
No. of calls detected over 4 days	4764	1968	15 590	7546
Average no. of calls/min	6.3	2.4	21.0	10.1
Average incremental amplitude of calls (i.e., with background noise subtracted), dB	116.4	100.4	127.3	115.9
Average fundamental frequency of calls, Hz	154	163	160	187
Average duration of calls, ms	406	518	475	495

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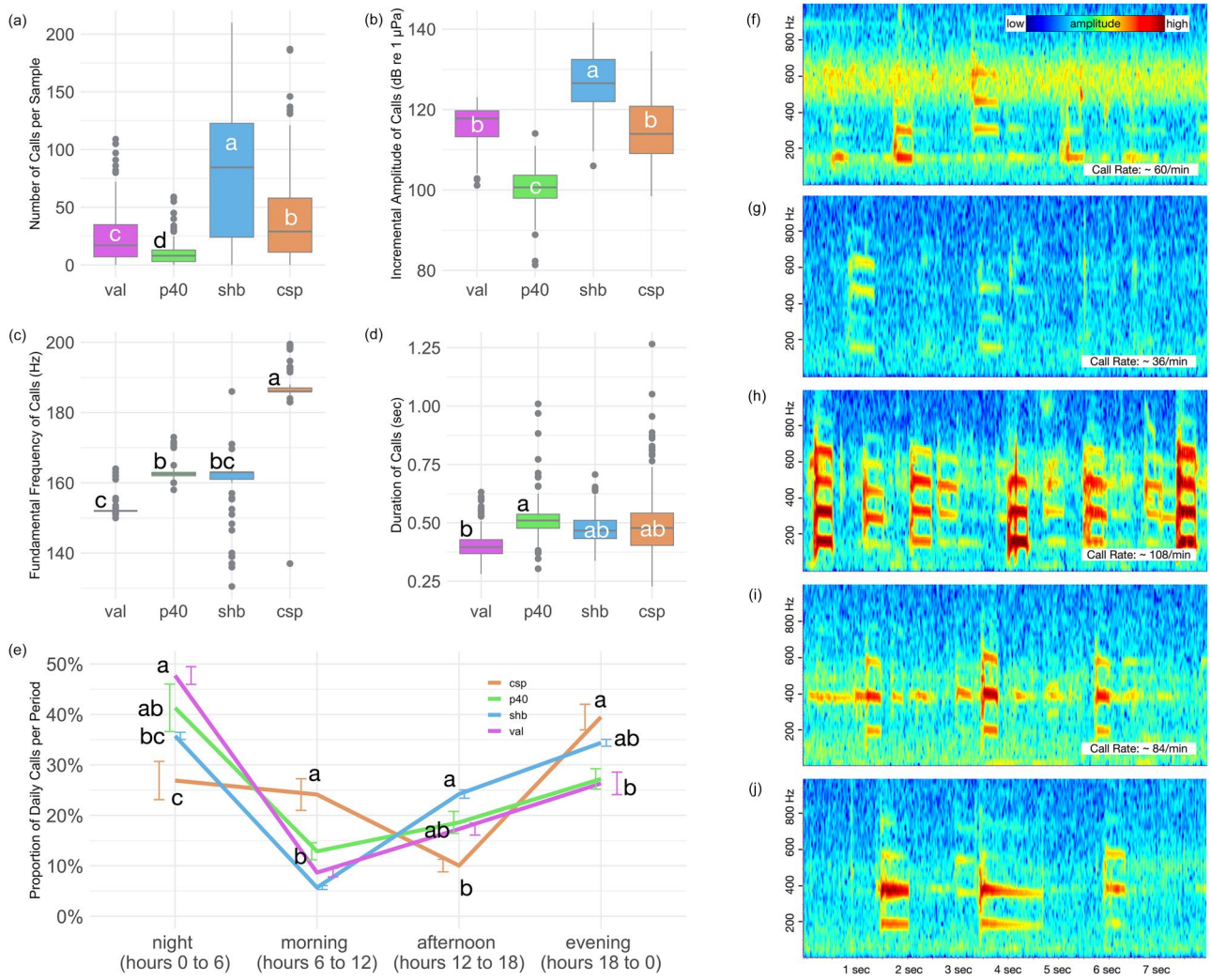

FIG. 3. Toadfish advertisement call measures and spectrograms. Unless otherwise noted, letters indicate significance groups based on *post hoc* tests, boxes are second and third quartiles, whiskers extend 1.5× beyond the interquartile range, and dots are outliers beyond that range. (Left panels) (a) The number of calls detected at each location per 4-min sample, (b) the incremental amplitude of calls at each location, (c) the fundamental frequency of calls, (d) the duration of calls, and (e) the proportion of each day's calls per period of the day. (Right panels) Toadfish calls recorded during local peak calling at (f) val, (g) p40, (h) shb, and (i) csp. (j) Calls of varying duration at csp. The call in the center is approximately 2× the duration of the call on the left and nearly 3× the duration of the call on the right, despite their temporal proximity. All spectrograms are approximately 8-s segments in the range of 0–1 kHz.

duration of calls did not vary for either the chorus [$F(2, 881.11) = 0.14$, $p = 0.859$] [Fig. 4(hi)] or for purported individuals [$F(1, 22) = 0.40$, $p = 0.532$] [Fig. 4(hii)].

E. Effect of temperature on call frequency and duration

Average fundamental frequencies of calls were highly correlated with temperature [$r^2 = 0.73$, $F(1, 643) = 1703.8$, $p < 0.001$]. The coefficient for temperature indicated an increase in 11.3 Hz for each degree Celsius of temperature. Average duration of calls did not vary significantly with average temperature [$r^2 = 0.00$, $F(1, 643) = 0.002$, $p = 0.963$].

F. SNR

The average maximum SNR was 17.3 dB in quiet and 10.5 dB in noise, and these groups differed significantly [$t(453.61) = 9.229$, $p < 0.001$]. Among calls in noise, the maximum SNR harmonic band and the minimum SNR harmonic band were also compared in a paired test. The average maximum SNR was 10.5 dB (as described above), and the average minimum SNR was 4.7 dB, and these groups differed significantly [$t(149) = 22.2$, $p < 0.001$].

IV. DISCUSSION

This study used passive acoustic monitoring to closely examine the behavior of a soniferous fish in one of the busiest marine environments in the US (Bureau of Transportation Statistics, 2025). Several points emerge for discussion.

A. Noise incidence varies by location, and noise is periodic

New York City soundscapes had significantly different incidence of vessel noise. Each location had different numbers of samples with noise [Fig. 2(a)]. Val and p40, the locations

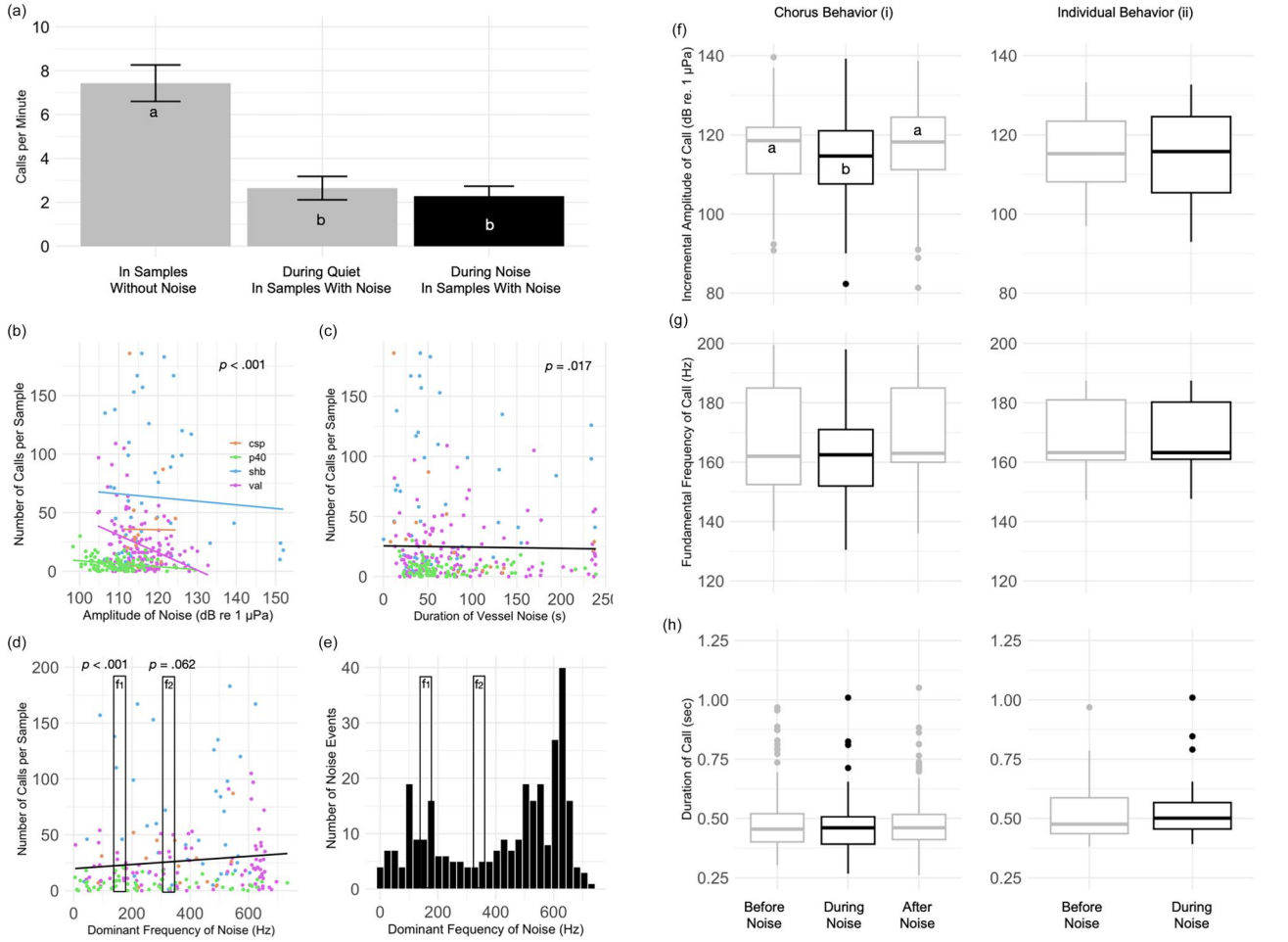

FIG. 4. Effect of vessel noise on toadfish calls. Letters indicate significance groups based on *post hoc* tests, and *p* values are taken from the linear model for the factor of interest, i.e., the *y* axis variable. (Left panels) (a) Calls per minute in quiet (gray columns) and noise (black column). The right two columns are the quiet and noisy portions, respectively, of samples with noise. In samples with noise, scatterplots of numbers of calls vs amplitude (b), duration (c), and dominant frequency (d) of noise are shown. In panel (d), box f1 shows where the dominant frequency of vessel noise overlapped the first harmonic of calls (143 Hz–185 Hz) and box f2 shows the same for the second harmonic (308 Hz–351 Hz). *p* values above boxes are for the effect of noise in the box on call number. (e) Histogram of dominant frequency of noise events, with advertisement call harmonics overlaid. In all graphs, straight lines are linear regressions, black refers to all locations as a group, and colors indicate individual locations. (Right panels) Boxes are second and third quartiles, whiskers extend 1.5× beyond the interquartile range, and dots are outliers beyond that range. Shown are the amplitude (f), fundamental frequency (g), and duration (h) of advertisement calls measured for a chorus of toadfish before, during, and after calls (i) and for purported individuals before and during calls (ii).

with the highest incidence of noise, are close to high-traffic commercial and ferry routes (Hom *et al.*, 2024). Shb and csp, the locations with lower incidence of noise, have no ferry traffic and virtually no commercial traffic. This heterogeneity indicates that, even in a city, diverse soundscape habitats are present. Interestingly, there was little variation in the amplitude of noise among locations [Fig. 2(b)]. Amplitude at p40 was lower than at other locations, which is likely because the p40 hydrophone was farthest from the shipping channel (Table I). The dominant frequency of noise was also significantly lower at p40 compared to other locations [Fig. 2(c)]. This difference is also likely due to the distance to the shipping channel because, in general, lower frequency sound propagates further than higher frequency sound (Delsasso, 1957). There was no difference in the duration of noise events among locations [Fig. 2(d)]. Importantly, noise was periodic and the quietest time of day at all locations was between midnight and 6:00 a.m. [Fig. 2(e)]. In summary, the major difference among locations was noise incidence.

B. Toadfish calling shows weak periodicity

At all locations, the least calling occurred during morning or afternoon while the most calling occurred during evening or night [Fig. 3(e)]. Peak calling varied among locations. Val and p40 calls peaked at night (midnight to 6:00 a.m). Shb had two equal peaks at evening (6:00 p.m. to midnight) and night. Csp calls peaked in the evening. Periodicity of calling in toadfish populations has been reported. At p40, toadfish were reported to call most from midnight to 6:00 a.m. (Hom *et al.*, 2024). In Woods Hole, MA (Van Wert and Mensinger, 2019; Hom *et al.*, 2024), and in the Chesapeake Bay (Ricci *et al.*, 2017), toadfish peak calling occurred at sunset. In eastern Long Island, toadfish call detections peaked during the day, not at night (Wirth and Warren, 2020), and in his original assessment of calling patterns, Fine (1977) found no periodicity at all. Given this considerable variability, it is possible that peak calling is a behavior that can be altered by a local population of fish, perhaps to cope with noise.

C. Call rate suggests numerous, clustered individuals

Individual toadfish have been observed calling at a rate of less than 10 calls/h to as many as 7.2 calls/min (Van Wert and Mensinger, 2019) and even increasing to approximately 25 calls/min when a female is close to a nest (Fish, 1972). All the spectrograms in Fig. 3 show much higher call rates, so it seems likely that there is more than one animal calling. Indeed, the spectrogram of calls from shb [Fig. 3(h)] suggests perhaps four to seven animals are in close range of the hydrophone. Clustering of individually identified oyster toadfish has been reported (Putland *et al.*, 2018), and nest aggregations have been described in other toadfish species (Amorim *et al.*, 2010; McIver *et al.*, 2014), but it is unclear if vessel noise impacts aggregation behavior in toadfishes.

D. Toadfish cope with noise diurnally and actively

Toadfish called over twice as much in samples without vessel noise than in either the quiet or noisy portions of samples with noise [Fig. 4(a)]. Samples without noise tended to occur from midnight to 6:00 a.m. [Fig. 2(e)]. The increase in calling during this period occurred in three of four locations and suggests a discreet diurnal behavior because, if call suppression in noise was only active, the quiet portions of noisy samples would have the same call rate as the completely quiet samples [i.e., the first and second columns in Fig. 4(a) would be the same].

Peak calling at csp occurred not at night but in the evening, resembling non-urban locations like Woods Hole (Hom *et al.*, 2024; Van Wert and Mensinger, 2019). Csp was also the location with the lowest incidence of noise. It is noteworthy that, even in New York City, locations exist that resemble quiet, non-urban locations.

In samples with noise, toadfish called less when the duration of noise was longer [Fig. 4(c)]. This is evidence of active call suppression and is similar to behavior of the Lusitanian toadfish (Alves *et al.*, 2021). However, it possibly contradicts evidence that toadfish in the Chesapeake Bay do not call less in response to single vessel passages, although duration of vessel passage was not specifically tested in that study (Colbert *et al.*, 2023). Finally, there is evidence that toadfish also suppress calling over weeks-long time scales (Colbert *et al.*, 2023), but the days-long analysis presented here precludes direct comparison with that finding.

E. Toadfish call less when noise frequency overlaps call frequency

Toadfish called less when the dominant frequency of noise overlapped the fundamental frequency of their calls [Fig. 4(d)]. This behavior indicates that toadfish may discriminate noise frequency. Toadfish did not alter calling behavior, however, when the dominant frequency of noise overlapped the second harmonic [Fig. 4(d)]. In *Porichthys notatus*, the plainfin midshipman fish, a familial toadfish, hearing sensitivity increases during the reproductive season (Sisneros and Bass, 2003), allowing females to better encode the second harmonic of the male hum. Whether or not female toadfish undergo reproductive state changes in hearing sensitivity is unknown, but male toadfish called even when their second harmonic was masked by noise. Importantly, there were relatively few noise events that overlapped the second harmonic compared to the first [Fig. 4(e)]. In fact, the frequency range of 225–500 Hz may act as a noise frequency refuge since even during noise it is relatively quiet [e.g., Fig. 2(j), inset], and, therefore, toadfish may not need to suppress calls for noise in this band.

Note that most noise events had a dominant frequency over 600 Hz, and the slope of the line in Fig. 4(d) is positive, indicating that calls increase with noise dominant frequency. Toadfish hearing sensitivity declines precipitously above 300 Hz (Rogers *et al.*, 2020), so, at the average amplitude of noise in this study, noise frequencies above 600 Hz are unlikely to be perceived by toadfish. Therefore, it is unlikely that higher frequency noise stimulates calls, but, instead, such noise is probably not perceived, allowing animals to behave as if there was no noise.

Vessel noise events are characterized by bands of varying amplitude [Figs. 2(f)–2(j)]. Toadfish calls are harmonic, also with bands of amplitude [Figs. 3(f)–3(j)]. In the noise portion of the validation set, the high-SNR harmonic was significantly greater than the low-SNR harmonic, demonstrating that even if one harmonic is masked by a particular noise event, another harmonic might convey signal. In the plainfin midshipman, primary afferent response to a stimulus with a harmonic was greater than to a stimulus without a harmonic (McKibben and Bass, 2001). Also, in the green tree frog (*Hyla cinerea*), detection thresholds of a signal in masking noise were lower if the signal included a harmonic (Simmons, 1988). Harmonic calling may be well-suited for signal detection in environments with banded masking noise, like that from vessels.

F. Toadfish call less when noise is louder, but do not call louder in noise

Toadfish called less when the amplitude of noise was greater [Fig. 4(b)]. The benefit of this behavior is that toadfish do not waste energy producing a call that is likely to be masked. This behavior is also reflected in Fig. 4(f), where the amplitude of the chorus, but not of purported individuals, decreased during noise. Since calling males are stationary, and the loudest fish are the ones closest to the hydrophone, a decrease in chorus amplitude suggests that, during noise, the fish closest to the hydrophone are calling relatively less than fish further from the hydrophone, who, because of their distance, may have already experienced the noise peak or are yet to experience it. As a result, chorus amplitude appears lower in noise. This effect highlights the importance of hydrophone placement. A hydrophone placed at some distance from both the calling animals and the source of noise can lead to erroneous assessments of the impact of noise on behavior.

The Lombard effect is strictly defined as an increase in the amplitude of an individual's vocalization during noise

(Brumm and Zollinger, 2011). Figure 4(fii) is the best estimate of the Lombard effect that our data (2 calls each from 40 purported individuals) allow, but it suggests that toadfish do not increase call amplitude during noise at these noise levels. The Lombard effect has been experimentally demonstrated in oyster toadfish (Luczkovich *et al.*, 2016), but the stimulus amplitudes in that study seem greater than the noise levels measured in New York City, so this behavior might not be relevant for toadfish in the local habitat.

G. Noise does not impact frequency or duration of calls

Neither the toadfish chorus, nor purported individuals, changed the fundamental frequency of calls during noise [Fig. 4(g)]. In the plainfin midshipman fish, a significant increase in the peak frequency of a chorus's "hum" was found during boat noise at dawn, but not during boat noise at dusk (Ogurek *et al.*, 2024). There are no other studies that assess fundamental frequency in noise for toadfishes. Neither the toadfish chorus, nor purported individuals, changed the duration of calls in noise [Fig. 4(h)].

H. Ambient sound levels

Mean ambient sound ranged from 101.7 dB at p40 to 106.1 dB at val (Table III). This range agrees with other measures in New York Harbor (Rosenbaum *et al.*, 2021). This range is greater than that reported offshore along the US East Coast (Rice *et al.*, 2014). The influence of ambient sound levels on behavior was not assessed in the current study.

I. Other differences between locations

Very different numbers of calls were recorded at each location [Fig. 3(a) and Table IV]. This difference could be due to different numbers of animals or to the randomness of hydrophone placement. Unfortunately, our methods do not allow us to differentiate between the two.

The amplitude of calls [Fig. 3(b)] differed widely among locations. This difference could be due to hydrophone placement or to animals calling at different amplitudes. At all locations taken together, the mean received incremental amplitude of calls was 117.2 dB, while the maximum received incremental amplitude was 141.6 dB. Fish (1954) reports the maximum amplitude of a grunt (not an advertisement call) as 118.06 dB above 0.0002 dyn/cm^2 (144.1 dB re 1 μPa) at a distance of 2 ft. Assuming spherical spreading, this results in 139.8 dB re 1 μPa at 1 m, close to 141.6 dB, even though the call types differ. Tavolga (1971) reports an approximate sound pressure level (it is unclear if this is an average or a maximum) of the advertisement call as 40 dB above 1 dyn/cm^2 (140 dB re 1 μPa) but gives no other data. No recent paper has provided comprehensive data on the amplitude of advertisement calls in dB re 1 μPa at 1 m. However, the amplitude of the advertisement call of the related Bocon toadfish (*Amphichthys cryptocentrus*) was reported as 147.49 dB (re 1 μPa) (Staaterman *et al.*, 2018). The amplitudes reported in the current study are, therefore, in line with existing data.

The fundamental frequency of calls varied among locations [Fig. 3(c)], and this variation was highly correlated to temperature, with an increase in 11.3 Hz for each degree Celsius. This same effect has been previously reported for toadfish at longer time scales (weeks) in Woods Hole, MA (Van Wert and Mensinger, 2019), and the Chesapeake Bay (Ricci *et al.*, 2017). A strong linear relationship between fundamental frequency and temperature has also been demonstrated in plainfin midshipman fish (Bass and McKibben, 2003; Brantley and Bass, 1994).

Fish (1954) reported the fundamental frequency of Rhode Island toadfish as 325 Hz and the second harmonic as 625 Hz. Four years later, Tavolga (1958) reported a much lower fundamental frequency, 250 Hz, among Florida oyster toadfish, and he noted the difference compared to Rhode Island. The mean fundamental frequency of toadfish advertisement calls in the current study ranged from 154 Hz (val) to 187 Hz (csp). At Woods Hole, MA, during a recent weeks-long study, toadfish advertisement call frequency similarly ranged from 132 to 223 Hz (Van Wert and Mensinger, 2019). Today's Northeast US toadfish, therefore, resemble historical animals from Florida, not Rhode Island. It is worth noting that at 625 Hz, the second harmonic of Rhode Island toadfish would be heavily masked by contemporary noise [Fig. 4(e)], suggesting the possibility that vessel noise has acted as a selective pressure on call frequency.

Call duration varied slightly among locations [Fig. 3(d)], but there was no correlation between duration and temperature alone, as reported in longer-term studies (Van Wert and Mensinger, 2019). Calls of varying duration are often observed in the same recording [e.g., Fig. 3(j)]. The location-based differences in call duration, therefore, might be caused by differences in chorus composition. It is unknown if individual toadfish can dynamically change call duration or if duration is correlated to size or some other factor.

Surprisingly, at p40 in downtown Manhattan, both vessel noise and ambient amplitudes were lower than at other locations. The structure of Manhattan's West Side, with long piers that force shipping hundreds of meters offshore, may provide quiet shoreline habitat that is ideal for the soniferous toadfish.

V. CONCLUSION

This study used passive acoustic monitoring to characterize vessel noise and examine the calling behavior of a soniferous fish in a major global port. The most variable characteristic of vessel noise was incidence, which was significantly different among sampling locations. Noise amplitude was less variable. Toadfish appear to alter behavior diurnally by calling much more during the quietest times of the day. They also actively suppress calls in the presence of noise. During noise, toadfish do not seem to alter other call

parameters, such as amplitude, duration, or fundamental frequency (i.e., no evidence for the Lombard effect), but their harmonic calls seem well-suited for finding areas of high SNR in banded vessel noise. These results provide evidence that fishes living in vessel-heavy urban environments adjust their reproductive-related acoustic communication behavior to cope with noise.

SUPPLEMENTARY MATERIAL

See the supplementary material for an example of call detection in noise and for linear model output and the results of *post hoc* tests associated with Fig. 4.

ACKNOWLEDGMENTS

The authors would like to thank the staff of the Hudson River Project and, in particular, Siddhartha Hayes, Toland Kister, Michaela Mincone, and Carrie Roble. We are also indebted to Robert McGann and the members of the Sheepshead Bay Yacht Club, and Ciara Scully, Andrew Williams, and Jessica Steve at New York State Parks. T.D.Q. would like to thank Stephen Gosnell for guidance on statistics, Kelsey Hom for instruction in bioacoustics, and Lucy Quigley for the toadfish icons in Fig. 1. This work was supported by grants from Sigma Xi and the City University of New York.

AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

DATA AVAILABILITY

The data that support the findings of this study are openly available in Dryad at https://doi.org/10.5061/dryad.xgxd254v2.

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