Vocal behavior of the endangered splendid toadfish and potential masking by anthropogenic noise

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Abstract

Vessel-related noise is a potential stressor for coral reef fauna. The Parque Nacional Arrecifes de Cozumel (PNAC) is a Mexican Marine Protected Area that is exposed to pervasive vessel traffic. PNAC is also the primary range of splendid toadfish (Sanopus splendidus, family Batrachoididae), an IUCN red-listed soniferous fish for which vessel noise may represent a threat. We conducted a passive acoustic monitoring survey during summer of 2017 at Paraiso Reef in PNAC and obtained the first scientific recordings from splendid toadfish, enabling a vocal characterization of the species. We simultaneously collected data on sound levels of vessels passing near the reef. High noise levels of cruise ship and small motorboat traffic caused elevated anthropogenic sound pressure levels for up to 15 hr per day in the same bandwidth as toadfish vocalizations. A single cruise ship added up to 4 dB above nighttime ambient levels while small motorboat traffic added up to 7 dB. The overlap of toadfish vocalizations and vessel-related noise highlights the susceptibility of splendid toadfish to acoustic masking and reduction in communication space throughout the day, warranting further study. Because acoustic communication is critical to toadfish reproductive success, noise from cruise ships and small motorboats may threaten splendid toadfish individuals or population viability.

Keywords

acoustic masking, coral reef, passive acoustic monitoring, soundscape, toadfish

1 INTRODUCTION

Cozumel, Mexico has been a popular tourist destination for several decades, with diving, recreational fishing, and cruise travel comprising most of the island's economy. Continued tourism to Cozumel is dependent on a healthy and biologically diverse reef ecosystem. However, reefs worldwide, including those in Cozumel, are experiencing declines in condition and function from cumulative stressors including coral disease, overfishing, tourism, marine pollution, sedimentation, and climate change (Hughes et al., 2017; Lapointe, Brewton, Herren, Porter, & Hu, 2019; Suchley & Alvarez-Filip, 2018).

An additional stressor to reef fauna is anthropogenic noise pollution. Several reviews have summarized the potential effect of vessel noise on fishes (e.g., de Jong...
et al., 2020; Mickle & Higgs, 2017; Popper & Hawkins, 2019; Radford, Kerridge, & Simpson, 2014; Slabbe Koorn et al., 2010) with some empirical studies focusing specifically on the impact of noise on reef fishes (e.g., Holles, Simpson, Radford, Berten, & Lecchini, 2013; Holmes, McWilliam, Ferrari, & McCormick, 2017; Kaplan & Mooney, 2015; McCormick, Allan, Harding, & Simpson, 2018; Nedelec et al., 2017; Staaterman et al., 2020; Velasquez Jimenez, Fakan, & McCormick, 2020). The results of these studies of reef fishes’ response to sound exposure from vessel noise are highly variable.

While the principle concerns of anthropogenic noise impacts to fishes include altered perception and production of sounds (Popper & Hawkins, 2019), such as masking (Putland, Merchant, Farcas, & Radford, 2018; Vasconcelos, Amorim, & Ladich, 2007), an emerging body of the literature has recently demonstrated responses to noise outside of direct auditory or communicative contexts, including developmental changes (Fakan & McCormick, 2019), increased stress, altered foraging (Magnhagen, Johansson, & Sigray, 2017), disrupted schooling (Sarà et al., 2007), and increased susceptibility to predation (Simpson et al., 2016; Simpson, Purser, & Radford, 2015). The diversity of possible vessel noise effects on fishes suggests that more urgent study is needed to understand the consequences of high vessel traffic on coral reefs and their associated fauna.

1.1 Monitoring the health of Cozumel’s coral reefs

Recent years have seen an increase in the number of cruise ships visiting Cozumel island, particularly after the completion of a third cruise ship terminal in 2015, which made Cozumel the second busiest cruise port in the world (Caribbean Journal staff, 2014; Mexico News Daily, 2019; OECD, 2017). In the 2017/2018 cruise year, Cozumel received over a thousand cruise ships with an estimated 4.1 million passengers, and up to eight ships per day, an increase of approximately 40% from 2014 to 2015 (Business Research and Economic Advisors, 2018; CONANP, 2016; Port Administration of Quintana Roo APIQROO, 2017; Secretaría de Medio Ambiente y Recursos Naturales, 2016; Secretaría de Turismo, 2015). Data related to dive tourism are more difficult to find and quantify, but internet searches resulted in the identification of hundreds of companies offering SCUBA dive trips in Cozumel. In September 2019 there were 243 boats, each carrying a maximum number of 60 passengers, with permits from the National Commission of Natural Protected Areas Mexico (CONANP) to enter the Cozumel Reefs National Park (Parque Nacional Arrecifes de Cozumel [PNAC]) (CONANP and SEMARNAT, 2019). Cozumel reefs have already suffered from intense fishing activities and are under increasing pressure from this tourism. In just 27 years (1984–2011) live coral cover off Cozumel declined by 13% due to impacts from tourists, small motorboat pollution, and other anthropogenic threats compared to an average coral cover decrease of 11% on the Mesoamerican Barrier Reef (Jackson, Donovan, Cramer, & Lam, 2014; Wilkinson, 2008; Wilkinson & Souter, 2008).

Regular baseline monitoring of the health of Cozumel’s extensive reefs is currently led by locally based CONANP staff. Since 2004, scientists have conducted monthly physicochemical monitoring at 11 reef sites and traditional photo-transect monitoring every 6 months at six reef locations to measure the percentage of coral cover and to count and photo identify fish and benthic species present at each site (CONANP, 2020; Garcia Salgado et al., 2008; Gress, Arroyo-Gerez, Wright, & Andradi-Brown, 2018). Additional site-specific photogrammetry studies documenting coral assemblages were conducted in 2018 in PNAC (Hernández-Landa, Barrera-Falcon, & Rioja-Nieto, 2020). These types of surveys are time and labor intensive, limited to depths accessible to human divers, and rarely conducted at night. Diver surveys focused on marine fauna frequently overlook cryptic or nocturnally active species such as toadfish, and species that may be correlated with reef health such as snapping shrimp (Sale, 1997; Willis, 2001). Diver surveys can also introduce sampling error and bias associated with behavioral responses of marine fauna to human presence (Pais & Cabral, 2018). While providing a basic understanding of reef health, visual surveys do not account for all potential impact producing factors, specifically noise, on marine fauna.

An alternative method to visual surveys for monitoring specific species, and overall coral reef health while also measuring anthropogenic noise pollution, is noninvasive, passive acoustic monitoring (PAM) of the reef soundscape (e.g., Bertucci et al., 2020; Lindseth & Lobel, 2018; McWilliam, McCauley, Erbe, & Parsons, 2017; Mooney et al., 2020; Nedelec et al., 2015; Staaterman, Rice, Mann, & Paris, 2013). PAM enables access to a greater range of habitats than traditional diversity sampling methods, is less labor intensive, provides more extensive temporal resolution, and is more easily conducted over large spatial and temporal scales (Sueur, Pavoine, Hamerlynck, & Duvail, 2008). Several studies conducted at various locations (e.g., Australia, New Zealand, French Polynesia, and the U.S. Virgin Islands) in the past decade have focused on reef-generated sound as an indicator of reef health (summarized in
Mooney et al., 2020). Some of these studies have used ecoacoustic (soundscape) indices with mixed success (e.g., Bertucci, Parmentier, Lecellier, Hawkins, & Lecchini, 2016; Kaplan, Mooney, Partan, & Solow, 2015; Kennedy, Holderied, Mair, Guzman, & Simpson, 2010). A small subset of acoustic-focused reef biodiversity studies have also assessed the potential impact of anthropogenic sound (e.g., Kaplan & Mooney, 2015).

1.2 Study objectives and focal species

Prior to this study, no PAM had been conducted within PNAC. Initially, the research team was focused on obtaining the first scientific recording of vocalizations from one of the most iconic Cozumel reef species, the splendid toadfish (*Sanopus splendidus*, Family Batrachoididae)(Figure 1). Consultation with CONANP suggested that local conservation managers were concerned about the potential effect of cruise ship noise on reef fishes, including *S. splendidus*. To address this concern, the study objectives were expanded to include an analysis of cruise ship and small motorboat noise to determine if there were potential effects of the anthropogenic noise levels on *S. splendidus*. Autonomous acoustic recorder data were processed and analyzed to identify noise sources and determine the frequency overlap of vessel noise and *S. splendidus* vocalizations. Based on that information, CONANP staff could assess the risk that increasing vessel noise may pose to *S. splendidus*. This work may be more broadly extrapolated to other vulnerable or data deficient species that communicate in the same frequency band.

*Sanopus splendidus* was originally described as an endemic species to Cozumel (Collette, 1974), and is currently categorized as an endangered species by the International Union for the Conservation of Nature (IUCN) (Collette, Aiken, & Polanco Fernandez, 2015). The splendid toadfish’s endangered status is based on an estimated area of occupancy that is less than 500 km² (IUCN estimates it as ~109 km²) and is severely fragmented or limited to less than five geographic locations within that area (Collette et al., 2015). The habitat fragmentation is assumed to result in increased extinction risks to the taxon since most of its individuals are found in small and relatively isolated subpopulations. In addition, the ranking also assumes the population’s continuing decline, poor habitat quality, and loss of mature, reproducing individuals (Collette et al., 2015; Hawkins, Roberts, & Clark, 2000; IUCN Standards and Petitions Committee, 2019).

A recent analysis of recreational diver records suggests that the splendid toadfish population may have a broader distribution than described by IUCN, with observations as far north as Isla Mujeres, Mexico and as far south as the Sapodilla Cayes, Belize, a distance of nearly 600 km (Moreno Mendoza & Barrientos Medina, 2019). The species’ full habitat range and the connectedness of this range remain unknown. A lack of information on the species’ population size, distribution and trends, baseline life history or ecological data leads to uncertainty in the conservation status.

There is little published about the ecology and life history of *S. splendidus* (Collette, 1974; Moreno Mendoza & Barrientos Medina, 2019), and Caribbean toadfishes more broadly (Hoffman & Robertson, 1983). Much is inferred from the extensive amount of information on other toadfish species (e.g., Amorim et al., 2010; Barimo, Serafy, Frezza, & Walsh, 2007; Gill, 1907; Gray & Winn, 1961; Mosharo & Lobel, 2012; Newman, Gruber, & Handy, 2004; Rice & Bass, 2009; Serafy, Hopkins, & Walsh, 1997; Staaterman et al., 2018; Wilson, Dean, & Radtke, 1982). Toadfishes are relatively sedentary benthic species with limited home ranges (Greenfield, Winterbottom, & Collette, 2008; Gudger, 1908; Isaacson, 1964) that feed on fishes and benthic invertebrates (Gosline, 1996; Gudger, 1908; Hoffman & Robertson, 1983). Male toadfishes often create dens or burrows in caves or substrate-associated refugia where females will lay eggs that the males fertilize and then guard until the direct-developing larvae hatch and eventually disperse from the den (Arora, 1948; Brantley & Bass, 1994; Breder Jr., 1941; Hoffman & Robertson, 1983; McIver, Marchaterre, Rice, & Bass, 2014). Field observations suggest that individual fish exhibit strong fidelity to a particular den (Hoffman & Robertson, 1983; Staaterman et al., 2018), though some toadfish will occupy more than one den (Hoffman & Robertson, 1983). Males spend multiple months guarding eggs serially deposited by different females (Hoffman &

**Figure 1** Splendid toadfish (*Sanopus splendidus*) of Cozumel. Photo credit: Steve Rosenberg (Rosenberg, 2019)
Robertson, 1983; McIver et al., 2014). Toadfishes depend on conspecific sounds for mate attraction and territorial defense (e.g., Gray & Winn, 1961; Maruska & Mensinger, 2009), and male calling behavior is directly related to reproductive success (Gray & Winn, 1961; Vasconcelos et al., 2012). Eleven species of toadfishes have been documented as sound producing (Chiu et al., 2013; Mosharo & Lobel, 2012; Staaterman et al., 2018). Previously described courtship calls produced by Caribbean toadfishes (Amphichthys, Batrachoides, and Sanopus) are relatively short (~0.5–1 s duration) and frequency modulated (Mosharo & Lobel, 2012; Staaterman et al., 2018). Both the peak frequencies of toadfish courtship calls and their primary auditory sensitivity are between 100 and 1,000 Hz (e.g., Cohen & Winn, 1967; Fish & Offutt, 1972; Sisneros, 2007), which overlaps with the frequency of noise from ships (Luczkovich, Krahforst, Hoppe, & Sprague, 2016; Vasconcelos et al., 2007).

### 2 | MATERIALS AND METHODS

#### 2.1 | Survey location and design

The study area was located on Paraiso Reef in PNAC. *S. splendidus* have officially been observed at 24 sites on the leeward site of Cozumel (Moreno Mendoza & Barrientos Medina, 2019), but they are reliably sighted at Paraiso Reef so there was a high likelihood of species presence for acoustic recordings. Indeed, multiple den sites were visually observed with vocalizing occupants during both pre-deployment surveys and during the equipment deployment and retrieval. This site was also chosen in consultation with CONANP staff because it is the closest dive site (<400 m) to the Puerta Maya Pier cruise ship terminal on Cozumel (Figure 2). Cruise ships following a transit corridor into the terminal must pass within a few hundred meters of Paraiso Reef, and it was hypothesized that sound pressure levels (SPLs) from the cruise ships might be negatively affecting marine fauna.

In addition to cruise ships transiting in and out of Puerta Maya within 300–400 m of the study site, nearly all dive boats pass directly over Paraiso Reef enroute to other dive sites. It is also frequented by large groups of cruise ship snorkelers and beginner SCUBA divers because of its ease of access, shallow water depths (maximum 17 m) and proximity to shore (~180 m). Submarine excursions visit the southern end of the reef up to three times daily. It is also one of the reef sites most frequented by night divers. This combination of human use results in high intensity and extended exposures of Paraiso Reef fauna to vessel noise, light, and people, relative to other reef locations on the island.

#### 2.2 | Data collection

JASCO Applied Sciences (JASCO) and CONANP scientific divers deployed an Autonomous Multichannel Acoustic Recorder Generation 3 (AMAR-G3) with four M36-V35-100 omnidirectional hydrophones (Geospectrum Technologies Inc., −165 ± 3 dB re 1 V/μPa sensitivity) set 1 m above the sea floor and protected by hydrophone cages. The cages were covered with shrouds to minimize noise artifacts from water flow. The AMAR was placed in a sandy site in 11 m water depth (20.472568°N, 86.98093°W) among sparsely distributed coral outcrops and rocky overhangs that provided habitat for several *S. splendidus* dens (Figures 3 and 4). Prior to the placement of hydrophones, divers visually confirmed at least three occupied den locations within <10 m from the AMAR to ensure that recorded vocalizations could be attributed to the splendid toadfish.

![FIGURE 2](a) The study site location (Paraiso Reef denoted with a yellow circle) in Cozumel, with other identified dive sites (black and white dive flag) around the island, and (b) satellite photo showing the proximity of the recording location (yellow circle), to known dive sites (dive flags), Marina Fonatur port (“marina”) and cruise ship terminals, Puerta Maya and SSA Mexico.
The AMAR operated on a duty cycle alternating between 14 min at 32,000 Hz and 60 s at 375,000 Hz. The intermittent high-frequency sampling at 375,000 Hz was performed to capture marine mammal vocalizations, if present, but none were acoustically detected. The recordings occurred continuously over 50-days from July 14 to September 3, 2017.

### 2.3 Data analysis

Acoustical terminology is from ISO 18405 (ISO, 2017). Reference values used are 1 μPa for SPL and 1 μPa²/Hz for power spectral density (PSD).

#### 2.4 Toadfish vocalization detections

Though there are many toadfish species with specific acoustic differences within the family, toadfish advertisement sounds are typically about 0.5–1 s in duration, have a fundamental frequency ($f_0$) between 75 and 300 Hz, and have rich harmonic content. A previous study of the closely related *Sanopus astrifer* (Mosharo & Lobel, 2012) showed that vocalizations from this genus are frequency modulated with an increase in frequency over the call. The general properties of the related *S. astrifer* vocalization (Mosharo & Lobel, 2012) were used to infer the presence of toadfishes at the study site. While *S. astrifer* does not occur in Cozumel (Collette, 2002), there are two sympatric species of *Sanopus* documented in Cozumel, *S. splendidus* and *S. johnsoni* (Collette, 1974); neither of which has previously been recorded. *S. splendidus* specimens have been collected from around the island and surrounding area (Collette, 1974; Collette, 2002; Moreno Mendoza & Barrientos Medina, 2019), while *S. johnsoni* is only known from the location where it was discovered at the southern end of Cozumel at Palancar Reef (Collette, 1974).

Using 12, high signal to noise ratio (SNR) putative toadfish calls manually identified in the recordings, a template-based detection algorithm was trained in Raven 2.0 Sound Analysis Software (Bioacoustics Research Program, 2017). The template detector was used to identify the temporal occurrence of toadfish calls on hydrophones 2 and 4. Hydrophones 1 and 3 were deployed for redundancy and had overlapping detection ranges with hydrophones 2 and 4, respectively, and contain the same detections.

Recall of the detector (TP/TP + FN) was 71.4% and Precision (TP/TP + FP) was 33.3%, where TP = true positive detections, FN = false negative detections, FP = false positive detections. Hours with no true positive
detections were manually reviewed to identify false negative detections. All detection events were visually reviewed to discard false positive detections, and false negative events were included with true positives in call occurrence analyses.

The spectral and temporal properties of toadfish calls were determined using Raven 2.0 processing discrete Fourier transform on 8,192 samples and a Hann window with 75% overlap, yielding a 3.91 Hz, 0.016 s resolution.

2.5 | Ambient sound levels and time series analysis

Ambient sound analysis provides a quantitative description of the underwater soundscape and changes over time. Data were analyzed for ambient sound levels and included an estimation of the contribution of vessel sound energy to the total measured soundscape. The results were combined and presented in five ways: (1) spectrogram for the entire deployment duration (Figure 7); (2) exceedance percentiles of the decicade-band SPL (ISO 18,405) (top Figure 8); (3) exceedance of the limits of prevailing noise (Wenz, 1962) percentiles of the PSD levels (bottom Figure 8); (4) minute SPL_{1-min} for various frequency bands as functions of time (Figure 9), and (5) daily SPL_{24h}, computed for the total received sound pressure (Figure 11).

Ambient sound level spectrograms were created using the JASCO software PAMLab, an acoustic inspection tool software program, a Hamming-windowed fast Fourier transform (FFT) with 1 Hz resolution and 50% window overlap. The 32,768-point FFT performed with these settings were averaged to yield 1 min averaged spectra. The 50th percentile (median of 1 min spectral averages) were compared to the Wenz ambient noise curves (Wenz, 1962), which show the variability of ambient spectral levels off the U.S. Pacific coast as a function of frequency for a range of weather, vessel traffic, and geologic conditions.

3 | RESULTS

3.1 | Toadfish vocalizations characterization

An initial visual inspection of spectrograms of the audio data immediately revealed a variety of biological sounds, including harmonic, frequency modulated signals closely resembling previously described toadfish vocalizations (Figure 5). Unfortunately, most biological sounds recorded on Paraiso Reef could not be identified to a species level. We used two lines of evidence to support the hypothesis for the identity of the putative *S. splendidus* calls: (1) we assumed that these calls would have similar acoustic properties of other toadfish calls (duration, frequency, modulation), and (2) hydrophones were deliberately placed adjacent to visually confirmed *S. splendidus* dens, and therefore it was predicted that the calls with the highest received levels were produced by *S. splendidus* and not by other toadfish species.

**FIGURE 5** Representative focal *Sanopus splendidus* calls with many short duration (~1 s) harmonic sounds and \( f_0 = 75 \) Hz. Panels (a), (c), (e), (g) show a filtered waveform of the signal (bandpass filtered 0–1,000 Hz), and panels (b), (d), (f), (h) show the corresponding spectrograms (spectrogram settings: Hann window, dFT = 8,192, 75% overlap, 3.61 Hz and 0.64 s resolution). Both amplitude and power are shown as calibrated received levels based on the known sensitivity of the AMAR
Recorded vocalizations were frequency modulated with a slightly concaved frequency contour, a mean (±SE) 0.82 ± 0.03 s duration, and a frequency increase of 90.9 ± 8.9 Hz (Figure 5). The initial call was occasionally followed by 1–3 shorter notes with the same frequency but different frequency contours (Figure 5).

Toadfish vocalizations were detected across multiple hours every day of the survey from July 14 to September 3, 2017 on hydrophones 2 and 4, with a significant increase at night (Figure 6, Table 1). Even though there were no obvious habitat differences between the hydrophone positions, there were more *S. sanopus* calls detected on hydrophone 2 than hydrophone 4 (Figure 6(a)).

### 3.2 Ambient and anthropogenic sound levels

The broadband hourly SPL\textsubscript{1h} averaged over the 50-day recording period was 120 dB re 1 μPa. The data showed a clear and repeated daily pattern of human activity beginning with the arrival of cruise ships at dawn and ending with recreational dives on the reef after dusk. Long-term spectral averages along with median band-level series provide an overview of frequency over time in the soundscape. Over the 50-day recording period, broadband vessel sounds dominate the soundscape. The full study period spectrogram showed a continuous and repetitive pattern of higher SPLs during daylight and lower sound levels during nighttime, with small motorboat noise being the main contributor to the local soundscape during daylight (Figure 7).

Interesting features of the soundscape during the study period included tropical storm Franklin, which was a clearly detected event on August 8; sound level peaks from the daily cruise ship arrivals and departures; and in at least one instance, an active acoustic echosounder operating the entire time a cruise ship was at port (Martin, Morris, Bröker, & O’Neill, 2019).

Sound level statistics quantify the observed distribution of recorded sound levels (e.g., Wenz, 1962) (Figure 8). The different percentile levels ($L_{5}$, $L_{25}$, $L_{50}$, etc.) are the sound level exceeded by $n\%$ of the data. $L_{\text{max}}$ is the maximum recorded sound level. $L_{\text{mean}}$ is the linear arithmetic mean of the sound power. Decadecade-band distribution (Figure 8(a)) and PSD (Figure 8(b)) plots were directly compared to a Wenz plot (Wenz, 1962), providing a detailed spectral distribution. Vessel noise was the primary sound source that exceeded the limits of prevailing noise in the PSD $L_{\text{mean}}$ percentile with frequency band of 40–1,000 Hz (Figure 8(b)). Cruise ships increased sound levels the most in the 40–100 Hz band, while small motorboats increased sound levels in the 100–1,000 Hz band (Figure 8(b)). The increase of all percentiles above 1,000 Hz was likely due to reef biological sounds (Figure 8(b)).

### 3.3 Vessel noise in the soundscape

The ambient soundscape included anthropogenic sound from cruise ships and small motorboats ferrying tourists and recreational divers to and over Paraiso Reef. On a typical busy-day (Table 2) several anthropogenic sound sources were detected.

Figure 9 shows the recorded median minute SPL\textsubscript{1-min} including all vessel (cruise ships and small motorboats) sounds that were broadband (20–10,000 Hz) with low-frequency components (blue [10–100 Hz] and red [100–1,000 Hz] lines) that overlap with fish vocalization frequencies (75–300 Hz). The peaks (exceeding 120 dB SPL\textsubscript{1}.}
**TABLE 1**  Total *Sanopus splendidus* calls detected each day, during daylight hours and nighttime hours over the course of the passive acoustic survey.

| Date       | Total *S. splendidus* calls detected | Daylight *S. splendidus* calls detected (06:00 a.m. – 7:00 p.m. EST) | Nighttime *S. splendidus* calls detected (7:00 p.m. – 06:00 a.m. EST) |
|------------|--------------------------------------|--------------------------------------------------------------|---------------------------------------------------------------|
| July 14, 2017 | 56                                   | 9                                                         | 47                                                          |
| July 15, 2017 | 66                                   | 3                                                         | 63                                                          |
| July 16, 2017 | 77                                   | 0                                                         | 77                                                          |
| July 17, 2017 | 13                                   | 0                                                         | 13                                                          |
| July 18, 2017 | 61                                   | 11                                                        | 50                                                          |
| July 19, 2017 | 63                                   | 7                                                         | 56                                                          |
| July 20, 2017 | 19                                   | 0                                                         | 19                                                          |
| July 21, 2017 | 24                                   | 8                                                         | 16                                                          |
| July 22, 2017 | 6                                    | 1                                                         | 5                                                           |
| July 23, 2017 | 15                                   | 12                                                        | 3                                                           |
| July 24, 2017 | 102                                  | 40                                                        | 62                                                          |
| July 25, 2017 | 37                                   | 9                                                         | 28                                                          |
| July 26, 2017 | 24                                   | 2                                                         | 22                                                          |
| July 27, 2017 | 35                                   | 0                                                         | 35                                                          |
| July 28, 2017 | 32                                   | 0                                                         | 32                                                          |
| July 29, 2017 | 29                                   | 0                                                         | 29                                                          |
| July 30, 2017 | 6                                    | 2                                                         | 4                                                           |
| August 3, 2017 | 9                                   | 2                                                         | 7                                                           |
| August 4, 2017 | 4                                   | 1                                                         | 3                                                           |
| August 5, 2017 | 1                                   | 1                                                         | 0                                                           |
| August 6, 2017 | 4                                   | 3                                                         | 1                                                           |
| August 7, 2017 | 19                                   | 0                                                         | 19                                                          |
| August 8, 2017 | 39                                   | 1                                                         | 38                                                          |
| August 9, 2017 | 4                                   | 3                                                         | 1                                                           |
| August 10, 2017 | 8                                   | 0                                                         | 8                                                           |
| August 11, 2017 | 4                                   | 0                                                         | 4                                                           |
| August 12, 2017 | 8                                   | 0                                                         | 8                                                           |
| August 13, 2017 | 1                                   | 0                                                         | 1                                                           |
| August 14, 2017 | 6                                   | 3                                                         | 3                                                           |
| August 15, 2017 | 4                                   | 1                                                         | 3                                                           |
| August 16, 2017 | 27                                  | 2                                                         | 25                                                          |
| August 17, 2017 | 9                                    | 0                                                         | 9                                                           |
| August 18, 2017 | 14                                   | 0                                                         | 14                                                          |
| August 19, 2017 | 36                                   | 1                                                         | 35                                                          |
| August 20, 2017 | 18                                   | 1                                                         | 17                                                          |
| August 21, 2017 | 6                                    | 2                                                         | 4                                                           |
| August 22, 2017 | 11                                   | 2                                                         | 9                                                           |
| August 23, 2017 | 7                                    | 0                                                         | 7                                                           |
| August 24, 2017 | 11                                   | 0                                                         | 11                                                          |
| August 25, 2017 | 23                                   | 1                                                         | 22                                                          |
| August 26, 2017 | 7                                    | 2                                                         | 5                                                           |

**TABLE 1**  (Continued)

| Date       | Total *S. splendidus* calls detected | Daylight *S. splendidus* calls detected (06:00 a.m. – 7:00 p.m. EST) | Nighttime *S. splendidus* calls detected (7:00 p.m. – 06:00 a.m. EST) |
|------------|--------------------------------------|--------------------------------------------------------------|---------------------------------------------------------------|
| August 27, 2017 | 19                                   | 5                                                         | 14                                                          |
| August 28, 2017 | 8                                    | 4                                                         | 4                                                           |
| August 29, 2017 | 19                                   | 5                                                         | 14                                                          |
| August 30, 2017 | 56                                   | 9                                                         | 47                                                          |
| Total       | 1,047                                | 153                                                       | 894                                                         |

**FIGURE 7**  Spectrogram of underwater sounds for the 50-day recording period showing a clear diel pattern. The quiet period on August 8 occurred during tropical storm Franklin.

**FIGURE 8**  (a) Exceedance percentiles and mean of decidecade SPL$_{1\text{min}}$ averaged over the 50-day recording period and (b) exceedance percentiles and probability density (greyscale) of 1-min PSD levels compared to the limits of prevailing noise (Wenz, 1962).
The arrival and departure of cruise ships at Puerta Maya and the SSA Mexico terminals is a significant contributor to the Paraiso Reef soundscape. Figure 10 shows the number of cruise ship Port-of-Cozumel calls during the study period. The number above each bar indicates the number of cruise ships present each day at Puerta Maya and SSA Mexico terminals closest to Paraiso Reef. There were no cruise ship port calls to Cozumel on Sundays. While the typical busy-day (July 28) used in sound level comparisons included the arrival and departure of three cruise ships, it is important to note that there are many days throughout the year when cruise ship numbers are higher.

On August 8, Tropical storm Franklin passed over Cozumel island. This event was clearly recorded in the acoustic data. The Carnival Breeze cruise ship was diverted to a different port of call that day, reducing the cruise ship arrivals at Puerto Maya to one and Cozumel ports were closed to all small motorboats. This natural event significantly decreased the daily SPL 24h on this day (Figure 11).

This natural event provided an unexpected opportunity to compare the daily sound levels between a “busy” activity day with significant small motorboat traffic and three cruise ships passing near the AMAR (July 28); the day during tropical storm Franklin (“storm” day), where small motorboat traffic was limited, but one cruise ship made its usual port of call (August 8); and a “Sunday” activity day (August 20) with no cruise ships, but typical small motorboat traffic (Figure 12). This is in comparison to the measured soundscape levels at “night” (after dusk and before dawn) without anthropogenic sound inputs, which registered a SPL9h of 112 dB (Table 2).

The comparison of these days that reflect varying anthropogenic activity levels suggests that on average, the arrival of one single cruise ship to the pier nearest Paraiso Reef adds up to 4 dB (1.6 times) to the ambient soundscape levels during the daylight hours. The small motorboat traffic without cruise ship arrivals on Sunday can add up to 7 dB (2.2 times). The arrival of several cruise ships (three or more) together with the presence of small motorboat traffic around the study area adds up to

### Table 2
Comparison of sound pressure levels for different scenarios: “busy,” “Sunday,” “storm,” and “night.” The ΔSPL (dB) column represents the absolute difference between the sound pressure level (SPL) (dB re 1 μPa) at “night” and those scenarios measured during daylight.

| Scenarios | T (hrs) | SPL_T | ΔSPL_T | Description |
|-----------|--------|-------|--------|-------------|
| “Busy”    | 15     | 124   | 12     | Typical (multiple) small motorboats, three cruise ships |
| “Sunday”  | 15     | 119   | 7      | Typical small motorboat traffic, no cruise ships |
| “Storm”   | 15     | 116   | 4      | Limited small motorboat traffic, one cruise ship |
| “Night”   | 9      | 112   | 0      | Without any anthropogenic noise |

The arrival and departure of cruise ships at Puerta Maya and the SSA Mexico terminals is a significant contributor to the Paraiso Reef soundscape. Figure 10 shows the number of cruise ship Port-of-Cozumel calls during the study period. The number above each bar indicates the number of cruise ships present each day at Puerta Maya and SSA Mexico terminals closest to Paraiso Reef. There were no cruise ship port calls to Cozumel on Sundays. While the typical busy-day (July 28) used in sound level comparisons included the arrival and departure of three cruise ships, it is important to note that there are many days throughout the year when cruise ship numbers are higher.

On August 8, Tropical storm Franklin passed over Cozumel island. This event was clearly recorded in the acoustic data. The Carnival Breeze cruise ship was diverted to a different port of call that day, reducing the cruise ship arrivals at Puerto Maya to one and Cozumel ports were closed to all small motorboats. This natural event significantly decreased the daily SPL24h on this day (Figure 11).

This natural event provided an unexpected opportunity to compare the daily sound levels between a “busy” activity day with significant small motorboat traffic and three cruise ships passing near the AMAR (July 28); the day during tropical storm Franklin (“storm” day), where small motorboat traffic was limited, but one cruise ship made its usual port of call (August 8); and a “Sunday” activity day (August 20) with no cruise ships, but typical small motorboat traffic (Figure 12). This is in comparison to the measured soundscape levels at “night” (after dusk and before dawn) without anthropogenic sound inputs, which registered a SPL9h of 112 dB (Table 2).

The comparison of these days that reflect varying anthropogenic activity levels suggests that on average, the arrival of one single cruise ship to the pier nearest Paraiso Reef adds up to 4 dB (1.6 times) to the ambient soundscape levels during the daylight hours. The small motorboat traffic without cruise ship arrivals on Sunday can add up to 7 dB (2.2 times). The arrival of several cruise ships (three or more) together with the presence of small motorboat traffic around the study area adds up to
12 dB (four times). It is thus apparent that both cruise ships and small motorboats are meaningful contributors to the soundscape, but that small motorboats are the largest contributor of anthropogenic noise to the soundscape because of the duration of the activity, which averaged approximately 15 hr per day, relative to ephemeral cruise ship arrivals and departures (Table 2).

4 | DISCUSSION

The Cozumel Paraiso Reef study focused on the splendid toadfish, demonstrated the value of PAM survey data as a tool for understanding vulnerable species and habitats that may lead to conservation initiatives. We present the first description of acoustic recordings of *S. splendidus* vocalizations that can be effectively used by scientists and managers to determine the species’ occurrence, habitat range, and behavior and ecology, including mating and spawning (sensu Bertucci, Lejeune, Payrot, & Parmentier, 2015; Caiger et al., 2020; Luczko, Pullinger, Johnson, & Sprague, 2008; Wall et al., 2014). Recent quantitative approaches allow for estimating population density and abundance based on calling patterns (Marques et al., 2013), and these approaches could also be applied to *S. splendidus*.

In addition to *S. splendidus*, there are other toadfish found in Cozumel; *S. johnsoni* was also described as a Cozumel endemic (Collette, 1974). This species is less colorful than the *S. splendidus* and is highly cryptic with limited field observations. Few specimens have been deposited in museum collections, and it is considered data deficient by the IUCN. *Opsanus dichrostomous* and *S. reticulatus* have also been collected on the Yucatán Peninsula (Collette, 1974, 2001; Collette, 2002). Only *S. splendidus* was observed during deployment and hydrophones were placed near occupied toadfish dens. Therefore, it is most likely that the focal, high SNR toadfish sounds recorded belonged to our targeted species, *S. splendidus*. Given the similar characteristics of all toadfish vocalizations, information from this initial survey can be used in future efforts to improve management and conservation outcomes for other toadfish species and Caribbean coral reefs in general.

4.1 | Potential impacts of noise exposure on *S. splendidus*

There is a lack of quantitative information on the impacts of anthropogenic noise on fishes, turtles and other reef fauna, but preliminary recommendations for acoustic thresholds for these species suggest that sound levels must be quite high to cause injury (Popper et al., 2014). The swim bladder of toadfish is not thought to be involved in their hearing (Bass, Bodnar, & Marchatterre, 1999; Coffin et al., 2014; Fay & Simmons, 1999) so toadfish are not as susceptible to noise-induced hearing loss as fish whose swim bladder transmits sound pressure to the ears (Popper et al., 2014). While hearing damage is not expected at the noise levels recorded in this study (see Popper et al., 2014), fish do listen for changes in background sounds to detect approaching predators, to find prey, and to locate mates for breeding (Ladich, 2019; Popper & Hawkins, 2019; Slabbekoorn...
et al., 2010), and therefore behavioral effects are biologically relevant. Female toadfish are guided by acoustic cues to reach vocalizing males for mating (McKibben & Bass, 1998; Zeddies, Fay, Alderks, Acob, & Sisneros, 2010). Thus, it is highly likely that acoustic communication plays an important role in the social and reproductive behaviors of *S. splendidus* and masking of advertisement vocalizations by vessel noise could impair the reproductive success of these batrachoidids.

This study found that the soundscape of Paraiso Reef during daylight is mainly comprised of anthropogenic sounds from vessel activity. The recorded vessel noise in this study is in the frequency bands (50–500 Hz) that overlap in frequency with previously described toadfish vocalizations (Vasconcelos et al., 2007) and those collected in this study.

Sound levels recorded at the study location were 4–12 dB (1.6–4 times) higher during daylight when both cruise ships and small motorboats were active versus nighttime when there was little or no human activity except for night dive boats. Daylight peak traffic times were 07:00–10:00 a.m., 2:00–3:00 p.m., and 6:00–7:00 p.m., with SPL_{1_min} exceeding 120 dB for several minutes. Sound level measurements from the activity of only small motorboats near Paraiso Reef increase noise levels by at least 4–7 dB above ambient for sustained periods of time. Vessel noise levels recorded were broadband (20–10,000 Hz) with a percentile $L_{mean}$ exceeding the limits of the Wenz ambient noise curves from 40 to 1,000 Hz.

The study results suggest that the anthropogenic noise produced by small motorboats starting at dawn and extending into the nighttime, is equivalent to, or possibly more impactful than that produced by cruise ships, particularly from a temporal perspective. This is similar to findings in other studies (Picciulin, Codarin, & Spoto, 2008; Scholik & Yan, 2002). The pervasive occurrence of vessel noise increases acoustic masking of advertising toadfish and decreases the area over which fish can acoustically communicate (Putland et al., 2018) in this study for 12–15 hr of the day. The diel nature of the species’ vocalization may mitigate the effects of masking to some extent, but the impact of this extended period of masking on individuals and the population is unknown.

In addition to communication masking, other possible behavioral effects that could result from the SPLs recorded at the study site include greater depredation (Simpson et al., 2015; Simpson et al., 2016) and increased levels of cortisol (stress hormone) leading to immunosuppression. The cumulative effect of these kinds of behavioral disturbance could have population consequences, particularly when combined with other reef stressors.

Examples of management and noise mitigation that could be implemented to reduce potential impacts in the Cozumel tourist zone include the creation of exclusion zones for certain types of boats; offering financial incentives such as lower harbor fees to quieter ships and small motorboats; and establishing navigation routes that direct transiting vessels outside the reef areas. Vessel speed reductions have been shown to decrease vessel noise, with 10%–15% speed reductions equating to 1 dB attenuation (Wladichuk, Hannay, MacGillivray, Li, & Thornton, 2019). Designating slow speed zones for small
motorboats may be required to alleviate noise pollution in already degraded habitats. Ocean users and resource managers are required to work cooperatively to design policy that leads to success by developing achievable and enforceable measures to avoid, minimize and mitigate the possible significant adverse impacts of anthropogenic underwater noise.

To increase the understanding of healthy versus degraded reef soundscapes and potential impact of anthropogenic noise, it is necessary to continue monitoring other barrier reef locations at different times of the year. Additional research is also needed to better understand the habitat distribution, abundance, and possible threats to species communications, which is essential to reproduction and dispersion. Future deployments along the Mesoamerican Barrier Reef would provide insight into the answers to these questions.

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**CONFLICTS OF INTEREST**

The authors declare no conflicts of interest.

**AUTHORS’ CONTRIBUTIONS**

Cynthia Pyć and Aaron Rice conceptualized the research. David Zeddies and Sam Denes designed the study. Jonathan Vallarta and Cynthia Pyć were part of the data collection team. Aaron Rice, Jonathan Vallarta and Emily Maxner completed the acoustic analyses. Cynthia Pyć, Jonathan Vallarta and Aaron Rice wrote the manuscript with contributions from David Zeddies and Sam Denes.

**ETHICS STATEMENT**

No ethics approval was required for this research.

**DATA ACCESSIBILITY STATEMENT**

Underlying data can be shared upon request to the corresponding author for collaborative research.

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