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NOTE

Soundscapes from a Tropical Eastern Pacific reef and a Caribbean Sea reef

E. Staaterman · A. N. Rice · D. A. Mann · C. B. Paris

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Abstract Underwater soundscapes vary due to the abiotic and biological components of the habitat. We quantitatively characterized the acoustic environments of two coral reef habitats, one in the Tropical Eastern Pacific (Panama) and one in the Caribbean (Florida Keys), over 2-day recording durations in July 2011. We examined the frequency distribution, temporal variability, and biological patterns of sound production and found clear differences. The Pacific reef exhibited clear biological patterns and high temporal variability, such as the onset of snapping shrimp noise at night, as well as a 400-Hz daytime band likely produced by damselfish. In contrast, the Caribbean reef had high sound levels in the lowest frequencies, but lacked clear temporal patterns. We suggest that acoustic measures are an important element to include in reef monitoring programs, as the acoustic environment plays an important role in the ecology of reef organisms at multiple life-history stages.

Keywords Acoustic ecology · Coral reef · Tropical Eastern Pacific · Caribbean · Damselfish · Passive acoustic monitoring

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E. Staaterman (✉) · C. B. Paris
Applied Marine Physics and Marine Biology and Fisheries,
Rosenstiel School of Marine and Atmospheric Science,
University of Miami, Miami, FL, USA
e-mail: estaaterman@rsmas.miami.edu

A. N. Rice
Bioacoustics Research Program, Cornell Laboratory
of Ornithology, Cornell University, Ithaca, NY, USA

D. A. Mann
Loggerhead Instruments, Sarasota, FL, USA

Introduction

The “soundscape,” or acoustic environment of a given habitat, includes the sounds produced by abiotic factors such as wind, waves, and rain as well as the sounds produced by soniferous organisms (Urick 1983). The interaction between the soundscape of a habitat and the organisms living within it is often referred to as “acoustic ecology” (Schafer 1977). Because many marine organisms are able to perceive and produce sound, and because sound travels five times faster in water than it does in air, sound is a fundamental component of the life history of many marine organisms, and consequently, acoustic ecology should be a central component of marine ecology. However, the majority of studies on underwater sounds have focused on the physical properties of sound propagation in deep water, while the acoustic ecology of shallow-water coastal environments, where much of the marine biota resides, is poorly understood (Urick 1983; Hildebrand 2009).

Many marine animals produce and listen to sounds to navigate, seek mates, find food, or deter predators (e.g., Myrberg and Fuiman 2002). In coastal habitats with high biodiversity, these sounds typically vary on daily, monthly, and seasonal time scales (Cato and McCauley 2002; Lobel et al. 2010). Recent studies have demonstrated that different types of marine habitats with distinct structural or biological composition have unique soundscapes (Radford et al. 2010; Huijbers et al. 2012). However, few studies have examined site-specific and temporal variations within coral reef habitats (Lammers et al. 2008; Kennedy et al. 2010). Between reefs within the same archipelago, Kennedy et al. (2010) found differences in the soundscapes, some of which were correlated with biological measures such as percent coral cover. Yet before evaluating environmental correlates driving differences in reef soundscapes, the first objective, and the focus of this paper, is to evaluate how acoustic profiles differ. This initial comparison between two specific locations demonstrates differences in spectral and temporal patterns. In terms of acoustic ecology, we should consider that the resident animals in each of these locations may be accustomed to their local soundscape and could use this information to form an "acoustic image" of their environment (Fay 2009).

Methods

To our knowledge, an examination of soundscapes from coral reefs in different geographic regions has not been conducted. We characterized a reef soundscape in the Caribbean Sea (the upper Florida Keys) as well as one from the Tropical Eastern Pacific (the Pacific side of Panama) for a 2-day period in July 2011. These two regions share many genera due to the recent closure of the Isthmus of Panama ~3 million years ago (Coates and Obando 1996), but we acknowledge that there is a limit to the comparative nature of this study due to the divergent fauna present as well as differing oceanographic conditions. Reefs in the Florida Keys are largely comprised of *Acropora palmata* rubble, covered in turf algae. Dominant live corals include *Montastraea* spp. as well as *Porites*, *Siderastrea*, *Millepora*, *Gorgonia*, and *Palythoa* spp. (Ruzicka et al. 2009). The most frequently observed fish families in Florida are Scaridae, Haemulidae, Acanthuridae, Labridae, Pomacentridae, Lutjanidae, and Pomacanthidae (Kellison et al. 2012). In Panama, reefs are dominated by *Pocillopora damicornis* and *P. elegans* (Guzman et al. 2008), and the primary fish families are Labridae and Pomacentridae (Benfield et al. 2008). In terms of percent live coral cover, the two reefs were representative of their respective geographic regions (Florida coral cover: 20.2 % regional, 23 % local; Ruzicka et al. 2009; Panama coral cover: 61.2 % regional, 38–56 % local; Guzman et al. 2008; Enochs et al. 2011). Although the acoustic measurements presented here are merely "snapshots" in time, they can still reveal patterns in the acoustic environment of these reefs from different regions.

Florida

The Florida recordings are part of a longer-term study on the temporal and spatial patterns of Caribbean reef soundscapes. A passive acoustic recorder called the DSG (Loggerhead Instruments, Sarasota, FL, USA), which is a calibrated autonomous recording unit containing an HTI-96 hydrophone (sensitivity: −169.7 dBV μPa^{-1}, High-Tech Inc., Gulfport Mississippi) and a 16-bit computer board, was deployed at Sand Island Reef (25° 0′ 38.16″ N, 80°13′ 13.656″ W) in the Florida Keys Reef Tract from July 7 to 9, 2011, 15:20 h to 12:50 h local time. It was mounted to a wire suspended between an anchor and a buoy, so the hydrophone was 1.5 m off the substrate. The mean water depth was 7 m, and tidal flux was less than 1 m; sunrise occurred at 06:35 h, sunset at 20:16 h. Daily wind speeds ranged from 4.7 to 5.7 ms^{-1} (NOAA-NOMADS Live Access Server).

The DSG recorded 12 s every 5 min at a sampling rate of 20 kHz (providing a range of 0–10 kHz for frequency analysis). Acoustic data were processed in custom-made scripts in Matlab (The Mathworks, Inc., Natick, MA, USA). A series of fast Fourier transforms (FFT size: 800 samples; resulting in 25-Hz frequency resolution) was performed, and FFTs were averaged for each 12-s clip. Using the sensitivity of the hydrophone and the known calibration of the recording device, we report the distribution of acoustic power across the frequency range of 1–10 kHz as Power Spectral Density in dB re: 1 μPa^2 Hz^{-1}. To compare the distribution of acoustic energy throughout time and between the two sites, spectral data were compiled into 100-Hz bins, but the 0–25 Hz bin was excluded from the analysis to avoid effects of tidal and/or turbulent flow as well as distant shipping traffic (Urick 1983; Hildebrand 2009).

Panama

A portable audio recorder called the Microtrack II (M-Audio, Irwindale, CA, USA) was set inside of a small waterproof housing that connected to an HTI-96 hydrophone (sensitivity: −170 dbV μPa^{-1}). It was deployed off of Isla Contadora in Las Perlas Archipelago, on the Pacific side of Panama (8°38′ 9.168″ N, 79°1′ 53.680″ W) for the same time period as the Florida recording. It was anchored directly to the substrate using a small weight belt; the mean water depth was 4.5 m, but it ranged from 2 to 6.5 m due to large tidal fluxes. Sunrise occurred at 06:04 h, sunset at 18:42 h local time. Daily wind speeds ranged from 2.9 to 4.9 ms^{-1} (NOAA-NOMADS Live Access Server).

The Microtrack recorded continuously at 44.1 kHz, with brief interruptions (<30 min) for battery changes. Acoustic data were then sub-sampled to match the rate of the Florida recordings (12 s every 5 min), and the same calculations were made for all Panama data as described above for the Florida data. The Microtrack was calibrated in the lab using signals of known voltage. A local average was used to interpolate missing data during battery changes.

Comparison between sites

Power spectral density measurements of the entire sampling period were compared for each 100-Hz bin from

0 to 10 kHz for the two sites using Kruskal–Wallis tests, with significance set at the $\alpha = 0.05$ level. Spectrograms were visually and aurally scrutinized to identify biological sounds from the two locations (Raven Pro 1.4, Cornell Lab of Ornithology, Ithaca, NY, USA).

Results and discussion

The temporal patterns seen at the reef in Panama are indicative of bioacoustic activity. At sunset, there were significant increases in acoustic energy in frequencies greater than 1,000 Hz, which lasted until just before sunrise (Fig. 1a). We attribute this peak to snapping shrimp, which tend to dominate reef soundscapes at frequencies above 1,000 Hz and are active at night in other marine habitats (Radford et al. 2010; Au et al. 2012). There was a clear 400-Hz band with the opposite temporal pattern; it peaked in the afternoon when the other frequencies were generally quieter. These sounds were most likely produced by a damselfish, potentially the common *Stegastes acapulcoensis* (Benfield et al. 2008), as the waveform and spectrogram are similar to other published damselfish recordings (Fig. 2a, e.g., Mann and Lobel 1997; Myrberg 1980).

In contrast, the only temporal pattern evident at the reef in Florida was a small increase in energy at high frequencies during dawn and dusk (Fig. 1b). Throughout all times of day, however, sound levels were higher than in Panama in the range of 25–200 Hz. This can be partially explained by the slightly higher wind speeds, which tends to elevate noise levels in the lowest frequencies (Urick 1983), but the other sound source in this frequency band was a prevalent frequency-modulated “growl” of ~1 s duration and with dominant frequencies ~30 Hz and harmonics up to ~200 Hz (Fig. 2b), which may be produced by a fish. Overall, the presence of elevated sound levels within distinct frequency bands is indicative of biological activity from a variety of animals (McCauley and Cato 2000), which occurred in diurnal choruses at the reef in Panama, but tended to be more regularly distributed throughout time at the reef in Florida.

When averaged across time, the two habitats revealed markedly different soundscapes. Acoustic energy was generally higher at the Panama site than in Florida; Kruskal–Wallis tests revealed significantly higher power spectral density for all frequency bands except for <200 Hz, where Florida had significantly higher levels than Panama ($p < 0.05$, Fig. 2c). There was greater variance in the Panama soundscape over time compared to the Florida soundscape (i.e., error bars in Fig. 2c) with the highest sound levels occurring at dusk and at night (Fig. 1a).

The implications of the patterns we observed depend upon the point-of-view of the listener. For example, recent studies have shown that larval fish can use reef sounds as an orientation cue (Simpson et al. 2005; Montgomery et al. 2006). Larvae may have evolved the ability to locate specific habitats based on differences in their soundscapes (e.g., Radford et al. 2011; Huijbers et al. 2012). The distance at which this behavior takes place is still largely

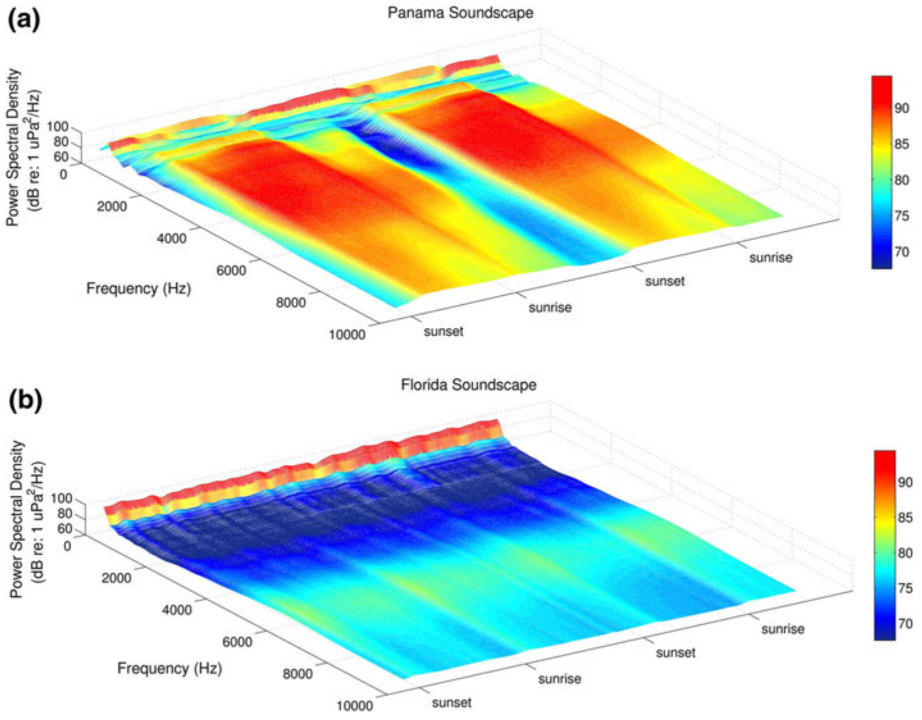

Fig. 1 The power spectral density of 100-Hz bands is plotted across the duration of the recording for both locations; the *color bar* also indicates power spectral density. On the reef in Panama **a**, on both nights, there was a substantial increase in acoustic energy at frequencies >1,000 Hz, which lasted until sunrise. The quietest time of the day was in the afternoon, except for a peak of acoustic activity in the 400 Hz bandwidth, which was not evident at night. In contrast, the only temporal pattern observed at the Florida reef **b** was a small increase in acoustic energy >4,000 Hz at sunrise and sunset on both days

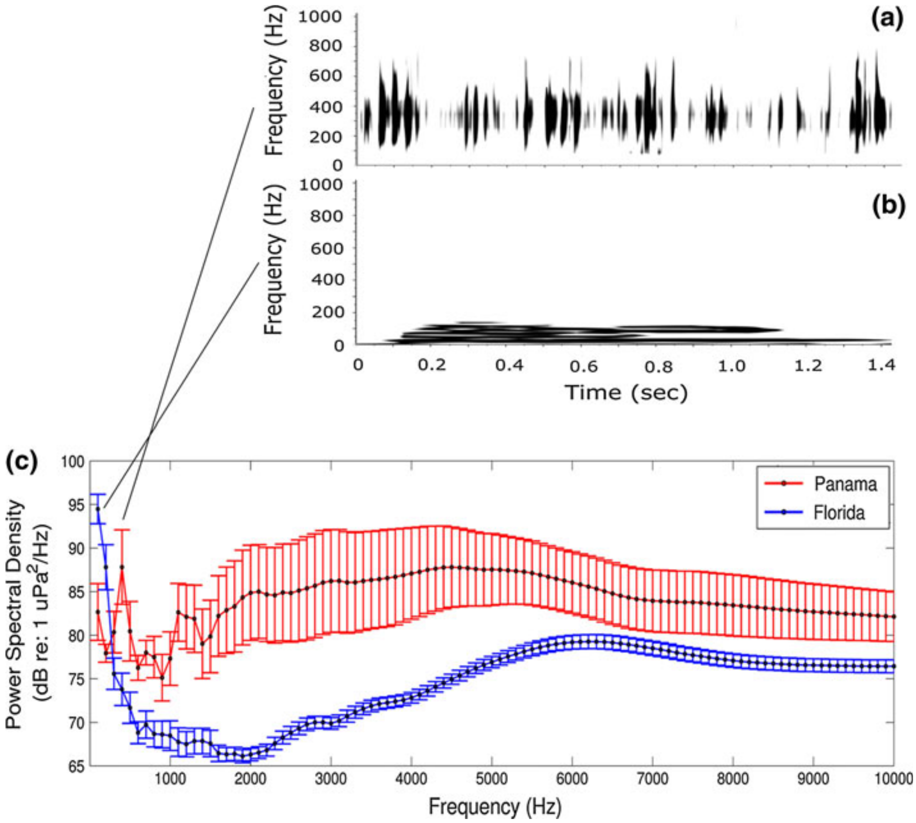

Fig. 2 Average power spectral density and specific spectrograms for Panama and Florida. **a** At the reef in Panama, high daytime sound levels at 400 Hz were attributable to a sound that was most likely produced by a damselfish (Spectrogram parameters: DFT size: 512, window size: 386). **b** On the reef in Florida, a prevalent "growl" sound was responsible for higher sound levels <200 Hz (Spectrogram parameters: DFT size: 4096, window size: 3,053). Both examples above were band-pass filtered (1–1,000 Hz). **c** Average ± SD power spectral density measurements for each 100-Hz band. Levels on the reef in Panama were significantly higher than on the reef in Florida, except in the 25–200 Hz band. There was also higher temporal variability in Panama than in Florida

unknown and will be location specific. For soniferous adults living on the reef, ambient reef sounds are the *noise* that individuals have to compete with in order to successfully send or receive a message; it is one of the factors that determines the size of their "acoustic space" (Clark et al. 2009). In Caribbean damselfish, it is estimated that a 20 dB signal-to-noise ratio is required for successful communication (Myrberg 1980), which limits the distance at which sounds are detectable (Mann and Lobel 1997) and may, in turn, determine the distance between animals' territories.

Reef soundscapes can reveal important information about the state of the reef. While we did find higher sound levels in the snapping shrimp band at the healthier Panamanian reef (38–56 % live coral, Enochs et al. 2011) compared to the more degraded Florida reef (23 % live coral cover, Ruzicka et al. 2009), we caution the use of these sounds as an ecological assessment tool (Lammers et al. 2008; Kennedy et al. 2010). Snapping shrimp live in great abundances in dead or fragmented reefs, rubble fields, or sponges (Hultgren and Duffy 2010; Enochs et al. 2011), making it difficult to link their sounds with the presence of live coral. On the other hand, the use of passive acoustics to measure the abundance of soniferous fishes holds great promise (e.g., Luczkovich et al. 2008). The results shown here, particularly for the 400-Hz band at the Panama reef and the 25–200 Hz band on the reef in Florida, suggest that it may be possible to detect presence/absence or abundance of fish species with known call types. Yet, further studies documenting and describing the sounds produced by soniferous fishes are critically needed.

In conclusion, rather than considering bioacoustic measurements as a replacement to traditional reef monitoring programs, we suggest that soundscape measurements should be an additional component, due to the importance of sound to the ecology of reef inhabitants of different life stages. These data show that there is a great deal of variability over space and time, thus adequate characterization may require large-scale recording efforts. The observations of reef soundscapes made here is a critical step toward understanding the acoustic ecology of coral reefs and its role in larval replenishment.

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