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Snap, crackle, and pop: Acoustic-based model estimation of snapping shrimp populations in healthy and degraded hard-bottom habitats

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ABSTRACT

Human use of the ocean and its ecosystems continues to degrade coastal habitats around the world. Assessing anthropogenic impacts on these environments can be costly and manpower-intensive; thus, the development of rapid, remote techniques to assess habitat quality is important. We employed autonomous hydrophone receivers to record the soundscapes of healthy, sponge-rich hard-bottom habitat in Florida Bay, Florida (USA) and hard-bottom areas impacted by sponge die-offs. We also recorded sounds emanating from individual sponges of three species that were isolated in underwater sound booths, and then enumerated the invertebrates (mostly snapping shrimp) dwelling within the canals of each sponge. From these recordings, a modified cylindrical sound propagation model was used to estimate distances to individual snapping shrimp snaps. Using the program *Distance*, we estimated snapping shrimp population density and abundance within both habitat types. More snapping shrimp snaps per unit time were recorded in healthy hard-bottom areas as compared to degraded hard-bottom areas. In addition, the average distance to a snap source was greater within degraded hard-bottom areas than within healthy hard-bottom areas. As a consequence, the estimated density and abundance of snapping shrimp were one to two orders of magnitude greater within healthy habitat than within degraded habitat. This study demonstrates the feasibility of using acoustic sampling and modeling to rapidly assess populations of soniferous benthic indicator species, whose vocalizations may yield indirect estimates of habitat quality.

1. Introduction

Humans rely upon ocean ecosystems for goods and services; unfortunately, extractive use of marine resources (e.g., fishing and mining,) and the indirect effects of human habitation (e.g., land-based run-off and climate change) have altered and degraded these ecosystems (Jackson et al., 2001; Halpern et al., 2008). Worldwide, marine ecosystems are declining (Suchanek 1994; Valiela et al., 2001; Waycott et al., 2009) and coastal ecosystems are particularly vulnerable to anthropogenic disturbances (Vitousek et al., 1997; Limburg 1999; Lotze and Milewski 2004), threatening their function (Solan et al., 2004; Worm et al., 2006; Diaz and Rosenberg 2008).

Habitat monitoring and assessment are key to understanding how ecological communities respond to habitat degradation (Kremen et al., 1994), yet monitoring presents many challenges. It is often time-consuming, expensive (Harris et al., 2015), and prone to human bias (Willis 2001); as when, for example, the avoidance of divers by fishes skews estimates of their biodiversity (Dickens et al., 2011). So the development of accurate and inexpensive monitoring techniques is becoming increasingly important as anthropogenic influences continue to buffet near-shore environments, including structurally complex coastal habitats that are so important as nurseries and foraging grounds (Airoldi et al., 2008).

One promising technique, based on the burgeoning science of soundscape ecology, relies on the measurement of sound to monitor ecosystems (Pijanowski et al., 2011). Although pioneered in terrestrial ecosystems, the study of soundscapes has been extended to the marine environment as a framework for environmental monitoring (Harris et al., 2015). Contrary to the public perception that the sea is a quiet realm – as implied, for example, in Jacques Cousteau's *Silent World* – the ocean is alive with sound.

Underwater sound, whose sources are physical, biological, and anthropogenic, has been studied for decades. Early studies by Tait (1962) and Cato (1976, 1980) were some of the first to describe variation in underwater noise from rock and coral reefs off New Zealand and Australia, respectively. Recent research has confirmed that many of those noises are of biological origin and exhibit diel,

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lunar, and seasonal variation (Radford et al., 2008a, 2008b). There is also spatial variability in the sounds that emanate from within and among habitats (Radford et al., 2008a, b, 2010; Lillis et al., 2014), but only a few studies have used acoustics to assess community structure or habitat characteristics in the marine environment. For example, Lammers et al. (2007) described how acoustic activity is correlated with the structural characteristics of habitats, whereas Kennedy et al. (2010) determined that acoustic variability was positively correlated with the density, biomass, and diversity of organisms on coral reefs.

Though many marine organisms produce sounds and contribute to the biological component of soundscapes (Myrberg, 1981; Versluis et al., 2000; Bouwma and Herrnkind, 2009; Schärer et al., 2014; Staaterman et al., 2014), few are as ubiquitous as snapping shrimps whose snaps contribute a significant portion of energy to the biological din (Au and Banks, 1998; Radford et al., 2008a, 2010; Bohnenstiehl et al., 2016). By rapidly closing the dactyl of its large chela, a snapping shrimp creates a cavitation bubble that produces a loud pop upon its collapse (Versluis et al., 2000). Snapping shrimps occur throughout temperate and tropical waters (Au and Banks, 1998; Cato and McCauley, 2002; Radford et al., 2010) and dwell in a variety of habitats, from estuaries to coral reefs (Au and Banks, 1998). One group, within the genus *Synalpheus* (a clade of ~100 species), all live within the canals of tropical sponges (Duffy and Macdonald, 1999; Duffy, 2002). Many species within this genus exhibit direct development in which eggs hatch directly into crawling juveniles (Duffy, 2002), which further reinforces the link between shrimps and their sponge home. Some species of *Synalpheus* live in colonies of several hundred shrimps within a single sponge, and a few species are eusocial – the only occurrence of this extreme form of social behavior known among marine animals.

Large sponges that harbor snapping shrimps are particularly abundant and important components of tropical hard-bottom communities, such as those found in the Florida Keys (USA). Hard-bottom habitat covers roughly 30% of the near-shore environment of the Florida Keys (Bertelsen et al., 2009) where dozens of sponge species dominate the benthic animal biomass with a mean density of >80,000/ha (Stevely et al., 2011). Many of those sponges, especially large sponges like the loggerhead sponge (*Spheciospongia vesparium*), provide shelter and habitat for fish and invertebrates (Butler et al., 1995), including those that are soniferous (i.e., "sound producers").

However, the Florida Keys have undergone drastic ecological change in recent decades. In 1991, 2007, and 2013 portions of the Florida Keys – especially Florida Bay, the bay lying between the Florida mainland and the islands of the Florida Keys – were subjected to prolonged thermal stress and a major shift in salinity due to anomalous and persistent weather conditions (Butler et al., 1995; Stevely et al., 2011). These physical stresses resulted in massive and widespread blooms of cyanobacteria whose radical increase in concentration precipitated the mass mortality of sponges within a 500-km^2 area of the bay (Butler et al., 1995). The widespread loss of sponges resulted in a significant reduction of structural complexity in affected areas, leaving barren expanses of open substrate where sponges were once numerous. The ecological effects of such a dramatic shift in the character of these systems are still being studied, among these being a significant change in the underwater acoustic signature of affected hard-bottom areas (Butler et al., 2016).

Because of the close association between snapping shrimps and sponges, a reduction in sponge density in places such as Florida Bay would also likely reduce snapping shrimp density and abundance. Thus, the present study aimed to: (1) evaluate the efficacy of using remote acoustic monitoring to estimate snapping shrimp density and abundance, (2) examine how sponge mortality might have affected the distribution of snapping shrimp populations in Florida Bay, and (3) examine the potential to use underwater sound to assess habitat quality.

2. Materials and methods

To evaluate the effect of loss of sponges on snapping shrimp populations, underwater soundscapes were recorded at six healthy hard-bottom sites in Florida Bay outside of the area impacted by the sponge die-offs and at five hard-bottom sites within the area affected by the sponge die-off (Fig. 1). Butler et al. (2016) determined that the number of snapping shrimp snaps produced in hard-bottom areas unaffected by sponge die-offs was greater than the number of snapping shrimp snaps produced in hard-bottom areas degraded by sponge die-offs. Therefore, acoustic recordings made outside the range of the sponge die-offs were used as a baseline to characterize the soundscapes indicative of healthy snapping shrimp populations to which recordings made within the die-off area were compared.

2.1. Acoustic analysis and number of snapping shrimp snaps

Habitat recordings were made using a submersible hydrophone (Fig. 2A). Each system consisted of a manufacturer-calibrated Aquarian Audio H2a omnidirectional hydrophone (Aquarian Audio Products: sensitivity −180 dB re 1 V/uPa) connected to a Roland R-05 solid-state WAV recorder (48 kHz, 16 bit) housed within a waterproof housing. The system was manually calibrated using pure sine signals from a signal generator, measured in line with an oscilloscope, and the recordings were analyzed in MATLAB 2014b software (Mathworks, Inc.) by code written specifically for the calibration of hydrophone systems.

Using the calibrated hydrophone system, fifteen-minute habitat recordings were made at noon during either the first quarter or last quarter moon phase at each site, and from these recordings five 10-s subsamples were extracted for further analysis. In previous research (Butler et al., 2016), we examined the soundscapes of hard-bottom sites in Florida Bay and found that the number of snapping shrimp snaps varies considerably with time of day and moon phase affect, but varies little within a given moon phase and time of day. Because of this, our recordings in this study were all made near noon during quarter moons so as to reduce variability in snap frequency.

All recordings were post-processed using MATLAB 2014b software (Mathworks, Inc.). Each 10-s subsample was processed through a MATLAB script written specifically for this study. First, the data were high-pass filtered to 100 Hz to remove extraneous low-frequency interference. The data were then plotted for visual inspection and to determine a snap count threshold level. The threshold is the level above which any transient spike in the data is considered a snapping shrimp "snap" and varies from recording to recording. This method of counting snaps has been used successfully in previous underwater soundscape studies (Radford et al., 2010; Butler et al., 2016). Using the threshold level, data for individual snaps within the recording were located, extracted, and stored. Once data for individual snaps within a given subsample were extracted, the peak-to-peak pressure level for each snap was calculated. Raw data were converted to absolute pressure levels, which were converted to decibels relative to 1 microPascal (dB re 1 μPa). These values were later used to calculate sound transmission loss, as described below.

2.2. Estimating snapping shrimp snap rate and snap source level

To determine the cue rate (i.e., snap rate) and to estimate the snap source level, 15 individual sponges of three sponge species (loggerhead sponge, *Spheciospongia vesparium*; sheepswool