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Monitoring spatial and temporal soundscape features within ecologically significant U.S. National Marine Sanctuaries

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Abstract

The U.S. National Oceanic and Atmospheric Administration's Office of National Marine Sanctuaries manages a system of marine protected areas encompassing more than 2,000,000 km^2. U.S. National Marine Sanctuaries (NMS) have been designated to provide protection for their conservation, recreational, ecological, historical, scientific, cultural, archaeological, educational, or aesthetic qualities. Due to the large variability of attributes among NMS, designing coordinated system-wide monitoring to support diverse resource protection goals can be challenging. Underwater sound monitoring is seeing increasing application to marine protected area management because it is able to support this wide variety of information needs. Passive acoustics are providing invaluable autonomous information regarding habitat associations, identifying species spatial and temporal use, and highlighting patterns in conditions that are otherwise difficult to survey. Using standardized equipment and analysis methods this study collected ambient underwater sound data and derived measurements to investigate temporal changes in sound pressure levels and power spectral density, identify presence of select species of importance and support within and among site comparison of ambient underwater sound among eight sites within four U.S. NMS. Broadband sound pressure levels of ambient sound (10 – 24,000 Hz) varied as much as 24 dB re 1µPa (max difference 100 to 124 dB re 1µPa) among the recording sites, sanctuaries, and seasons. Biotic signals, such as snapping shrimp snaps and vocalizations of fishes, exhibited distinct diel and seasonal patterns and showed variation among sites. Presence of anthropogenic signals, such as vessel passage, also varied substantially among sites, ranging from on average 1.6 h to 21.8 h per day. The study identified measurements that effectively summarized baseline soundscape attributes and

prioritized future opportunities for integrating non-acoustic and acoustic variables in order to inform area-specific management questions within four ecologically varying U.S. National Marine Sanctuaries.

Keywords
Bioacoustics, passive acoustic monitoring, underwater soundscapes, U.S. National Marine Sanctuaries.

1. Introduction

Over the past decade the field of ‘soundscape ecology’ has matured into a research discipline of its own, e.g., Pijanowski et al., 2011a, 2011b, Truax & Barret, 2011, Farina, 2014, Gasc et al. 2016. Terrestrial ecologists initially took the lead in describing and quantifying soundscapes, defining the term as the relationship between a landscape and the composition of its sound (Pijanowski et al. 2011b). Soundscapes are comprised of contributions from the organisms utilizing the space (biotic sound), human activities in and around the space (anthropogenic sound) and environmental processes occurring in the space (abiotic/geophysical sound) (e.g., Pijanowski et al. 2011a). These three components together determine the distinct sound signature at any given place, which depending on the source, can show recognizable spatio-temporal patterns at differing time scales, reflective of changes in biotic, anthropogenic or even abiotic activities (Farina et al. 2011, Pijanowski et al. 2011b, Staaterman et al. 2014). As recording effort continues to grow internationally, the field is challenged to develop analytical techniques and tools that both accurately describe and characterize this variation in soundscapes. As well as isolating relevant ecological indicators from these data that relate to targets of interest for marine science and management, such as biological diversity and ecosystem health.

Marine soundscape ecology is a relatively recent field, with most studies focused descriptively on improving understanding of the acoustic characteristics of different marine environments, and isolating contributions to their trends and status. Underwater acoustic monitoring has been successful in identifying species presence/absence, habitat associations, migration timing and pathways, spawning patterns and locations, environmental conditions, and largescale differences among underwater habitats e.g., McCauley & Cato 2000, Parsons et al. 2009, Bertucci et al. 2015, Erbe et al. 2015, Davis et al. 2017, Putland et al. 2017a, Rowell et al. 2017) . However, effectively deriving measurements from quantitative marine soundscape data that can support more holistic comparisons and status and trend assessments among marine soundscapes remains an area of active research focus. Due to factors including but not limited to the greater efficiencies of sound propagation underwater, the transference of tools to derive biodiversity indices from terrestrial soundscapes to marine settings has proven to be largely unsuccessful, as they do not appear to translate consistently across the marine realm. Existing analytical approaches have been further advanced and new methodologies continue to be developed to better characterize marine soundscapes and their drivers (Freeman and Freeman 2016, Staaterman 2017, Bohnenstiehl et al. 2018, Mooney et al. 2020).

Deriving more comprehensive measurements from long-term passive acoustic monitoring datasets is necessary to support protected area management interests (Hatch et al. 2009). Some U.S. National Parks have used long-term recordings to identify thresholds to guide visitor and wildlife noise exposure within park areas, leading to management techniques such as the use of shuttle buses to reduce car traffic and alignment of overflight patterns with roads to concentrate peak noise conditions. In Europe, the Baltic Sea Information on the Acoustic Soundscape (BIAS project) produced seasonal soundscape maps for the demersal, pelagic and surface zones, serving as a baseline for the development of monitoring and assessment of ambient noise in the Baltic Sea (Nikolopoulos et al. 2016). In the USA, large-scale comparative soundscape monitoring capacities have been steadily growing under support from multiple federal agencies (NOAA & U.S. Navy Sound Monitoring - https://sanctuaries.noaa.gov/science/monitoring/sound/, Gedamke et al. 2016, Haver et al. 2018).

This study investigated underwater soundscapes within four U.S. National Marine Sanctuaries spanning latitudes from 42° to 24° (Figure 1). The northern-most sanctuary, Stellwagen Bank National Marine Sanctuary (SBNMS), has a highly seasonal ecology with spring upwelling driving high summer productivity that attracts a variety of invertebrate schooling and predatory fish and high concentrations of feeding marine mammals. The mid-latitude site, Gray's Reef National Marine Sanctuary (GRNMS), is a temperate hard-bottom reef located off the coast of Georgia, with complex "live-bottom" and rocky ledges providing habitat for a wide range of invertebrates, fishes and turtles, as well as transient marine mammals. The southern-most locations, within Florida Keys National Marine Sanctuary (FKNMS), were placed within different zones of fishing and recreational use within the range of the coral reef habitat contained within this protected area. Finally, the locations within western Gulf of Mexico's Flower Garden

Banks National Marine Sanctuary (FGBNMS) monitored two protected coral reef caps that sit atop disparately placed salt domes and host diverse communities of invertebrates, fishes, and turtles, as well as transient mammals. Acoustic data were collected over a two year period in a standardized and coordinated manner, supporting: 1) investigation of temporal changes in sound pressure levels and power spectral density, 2) identification of the presence of select species of importance, 3) supporting within and among site comparison of ambient underwater sound among sanctuaries and 4) highlighting future opportunities for integrating non-acoustic and acoustic variables in order to inform area-specific management questions of interest.

2. Methods

2.1 Study sites and deployment schedule

The four sanctuaries that were monitored in this study vary in size (57 to 9947 km^2), are shallow to very shallow (14.5 – 68 m recording depths) and are positioned offshore on the U.S. continental shelf (4.8 – 185 km from shore, with the exception of FKNMS).

The eight passive acoustic listening stations included: Stellwagen Bank National Marine Sanctuary (SBNMS); Site 27 (Site 1) and Site 33 (Site 2), Gray's Reef National Marine Sanctuary (GRNMS); FS15 (Site 3) and Station 20 (Site 4), Florida Keys National Marine Sanctuary (FKNMS); Western Dry Rocks (Site 5) and Eastern Sambo (Site 6), and Flower Garden Banks National Marine Sanctuary (FGBNMS); Stetson Bank (Site 7) and East Flower Garden Bank (Site 8) (Figure 1, Appendix S1: Table S1). Within each sanctuary, using available data, sites were chosen to reflect areas likely to be exposed to variable acoustic influence from sound-producing species and human activities. Given the relatively localized sound propagation field around shallower sites, it was understood that two recording locations would not sufficiently describe soundscape conditions within site boundaries. Thus, emphasis was placed on locations where other information sources were available (including past acoustic information, diver surveys, other oceanographic sampling via personal communication with sanctuary staff and personal research experience), where acoustic signals of interest would likely be present (whether biotic or anthropogenic or both), and where overall acoustic signatures might differ when compared.

Deployments were planned to occur concurrently at all sites for at least one lunar phase during each season in 2016/17. However, due to the inaccessibility of some locations this was not always achieved. Therefore, seasons were defined among sites as follows; Summer: 28th June

– 13th September 2016, Fall: 19th October – 29th December 2016, Winter: 22 February – 13th April 2017, Spring: 26th April – 15th July 2017 and recording durations ranged from 37 – 174 days per sanctuary (Appendix S1: Table S2).

2.2 Instrumentation

2.2.1 Autonomous underwater acoustic recorders

All acoustic recordings were made using SoundTrap ST300s (ST300) with external battery packs (Self-noise less than sea-state 0 at 100 Hz – 2 kHz and <34 dB re 1µPa above 2 kHz, Ocean Instruments Inc., Auckland, New Zealand). At all recording sites, the ST300s continuously sampled at a rate of 48000 Hz with a flat full-scale frequency response between 20 – 60 kHz (± 3 dB). Each individual ST300 at each site was calibrated by the manufacture directly before deployment and each had unique end-to-end response sensitivity. Digitized recordings (.wav files) were directly downloaded to a computer using the SoundTrap host software.

2.2.2 Mooring configuration

At all sites with water depths of less than 30 m (GRNMS, FKNMS and FGBNMS) the acoustic recorders were deployed and retrieved by divers. In these instances, recorders were dived to the benthos at each site and fixed securely to a rigid and weighted benthic stand, with no surface or subsurface mooring lines or floats. The hydrophone element in these situations were approximately 1 m from the seafloor. We found this depth to be the optimal balance between reducing flow noise across the hydrophone element which can be heightened in the water column and reducing the noise created from sediment moving across the hydrophone element. At sites with water depths greater than 31 m (sites at SBNMS) the acoustic recorders were suspended approximately two meters off the seafloor via an acoustic release (VEMCO VR2AR) and held to the substrate by two 18 kg biodegradable sandbags. Both mooring types were specifically designed and engineered to reduce any extraneous noise from the moorings themselves.

2.3 Acoustic Analyses

2.3.1 Soundscape quantification

All acoustic data were analyzed using MATLAB software (version 2019b) and statistical tests were run in SigmaPlot 13 by Systat Software, Inc. (Build 13.0.0.83) and RStudio (version 1.1.456, R version 3.5.1). The low frequency limit of the analysis was 10 Hz, to partially remove potential low frequency surface motion noise or low frequency interference, 10 Hz was used to retain some portion of the energy from fin whale pulses as these signals may be of acoustic significance to the sites. ST300s have a built-in high pass filter set at 20 Hz to reduce any potential noise from mooring vibration and flow noise, therefore, there is a drop in sensitivity/response which would cause an approximate attenuation of 13 dB at 10 Hz. All times are standardized for local standard time at each site (daylight savings offset removed).

To quantify ambient sound levels at each recording site and variation with frequency and time scale, power spectral densities (PSD) and broadband (10 – 24,000 Hz) RMS, median and percentile sound pressure levels (BB SPLs) were obtained for all recordings. Power spectral densities were calculated using a discrete Fourier transformation with a Hann window resulting in 1 Hz, 60 s resolution with 50 % overlap. Spectrograms were produced with DFT length of 48000, using a Hanning window with 50% overlap for a 24-hour period ('sample day') at one site within each sanctuary to illustrate and identify peak daily patterns (specifically of intense acoustic biological or anthropogenic activity) for that season and day.

To determine if season effected the broadband ambient sound recorded at each recording site, broadband RMS SPLs were averaged in 60s and 60min lengths, to determine the robustness of the relationship at different sampling resolutions. Kruskal-Wallis or Mann-Whitney U statistical tests were subsequently used to test for differences. If such tests provided significant results, a Dunn's pairwise multiple comparison, with Bonferroni correction, was then used to isolate further differences. Non-parametric statistical methods were used to test for differences among seasons as the data had unequal variance among treatments and data had a non-normal distribution (Zar 1999). Broadband SPLs were also averaged, in 5 min bins, across each recording season, within each site, to produce an average diel trend plot for each site over each season.

Sound pressure levels or band levels were also calculated in octave bands with a 60 s resolution for all recordings. Diel trends in select octave frequency bands, centered on 62, 125, 251, 501, 1000, and 7943 Hz were plotted for three days around each moon phase for all sites over all seasons to illustrate the variation among the selected frequency bands, to visualize the varying contributions of each and to demonstrate any periodicity within octave band levels. A period of three days was selected to depict daily patterns while recognizing anomalies such as human activities i.e., vessel passages. Wavelet scalograms were used to detect the strength and persistence of the periodicity in SPLs in the above frequency bands across the sampling periods (Grinsted et al. 2004, MATLAB wavelet toolbox).

2.3.2 Vessel presence and contribution to the soundscape

During the Summer recording period one site within each sanctuary (SBNMS – Site 1, GRNMS – Site 4, FKNMS – Site 6, FGBNMS – Site 8) was visually and aurally inspected for vessel presence during the three days surrounding each lunar phase, totaling twelve days for each site. Using Raven Pro 1.5, times with both audible and visible vessels were tagged so to be separated from periods without the presence of vessel signals. Ninety-six 15-minute sound files were loaded into Raven in 90-second pages for each day and viewed as a spectrogram using a fast Fourier transform (FFT) value of 4096. After the vessel signals were identified, the hours of vessel noise/day were recorded. Sound Pressure Level in 1/3 octave frequency bands were analyzed for both times where vessel noise was present and absent at each site. The median and 90th percentile levels were plotted for each lunar phase separately as well as across the entire month at each site. These plots were then used to compare the power spectral density levels for presence and absence of vessel signal to determine the influence of vessel presence on the soundscape.

2.3.3 Detection and classification of vocalizers

Snapping shrimp

Data from all Sanctuaries with temperate and tropical reef conditions (GR, FK and FGBNMSs), were analyzed using a snap detection algorithm to quantify the acoustic activity of snapping shrimp, using methods and rationale for amplitude thresholds for detection from Bohnenstiehl, Lillis & Eggleston, 2016. Snap rates (number of snaps per 60s) were determined for the first 60 s of each 15 min sound file for the duration of the recording period at each site. The number of snaps that were detected during Dawn (site specific sunrise ± 90 min), Noon (noon ± 90 min), Dusk (site specific sunset ± 90 min) and Midnight (midnight ± 90 min) were also compared by calculating snap rate for these periods over a standardized segment of time, for each sampling day at each site during each recording season. Differences among snap rates were tested for statistical significance using the Friedman Test as data had a non-normal distribution. Following a significant Friedman test result, post-hoc multiple group comparisons were conducted using Tukey Tests. Simple linear regression methods were used to test if snap rate could be used to predict the values of SPL in the 2000 – 20,000 Hz during the different recording seasons. This method was used despite the fact there was a slight deviation from a normal distribution in the data. However, the sample size was large enough to be assumed to not impact results, and transformations of the data may lead to more severe bias (Schmidt and Finan 2018).

Atlantic cod

As the distribution of Atlantic cod (*Gadus morhua)* along the North American coast is from Cape Hatteras to Ungava Bay, identification of their calls was restricted to recordings from SBNMS. Acoustic data were processed using the Atlantic cod detection algorithm (Urazghildiiev and Van Parijs 2016) and all detections were manually verified visually and aurally for true calls (Stanley et al. 2017).

Low frequency vocalizing whales

Acoustic data from all recording sites were processed using the Low Frequency Detection and Classification System (LFDCS) (Baumgartner and Mussoline 2011) using methods from Davis *et al.,* 2017; 2020, utilizing detections from fin (*Balaenoptera physalus*), sei (*B. borealis*) and North Atlantic right whales (NARWs) (*Eubalaena glacialis*). For continuous data, a given day was marked as having a species present if certain criteria were met, with each species having different criteria due to the performance of the detectors and calling behavior (see Davis *et al.* 2020). These criteria were used to be conservative and confident in stating these species presence. Detector evaluation/missed detection rate was quantified using the same methods as Davis *et al.,* 2017; 2020.

2.4 Wind and Wave Data

Hourly wind speed and wave height data was collected from the nearest NOAA weather station to the recorders within each sanctuary (SBNMS: Station 44029, GRNMS: 41008, FKNMS: SANF1 and FGBNMS: TABS V) (https://www.ndbc.noaa.gov/). Wave height was not available for the sites in FKNMS and FGBNMS. Pearson Correlation tests were performed to assess the relationship between hourly broadband (10 – 24,000 Hz) SPL and select octave bands (63 Hz, 125 Hz, 251 Hz, 501 Hz center frequency) SPLs, and hourly wind speed (m/s) and wave height (m) within all sites to assess the contribution these environmental parameters have on these metrics.

3. Results

3.1 Stellwagen Bank National Marine Sanctuary

3.1.1 Patterns in broadband sound pressure levels and spectral composition

Broadband (10 – 24,000 Hz) SPLs (both median and RMS values) varied by as much as 10 dB among recording sites and recording seasons within SBNMS, (100.5 – 110 dB re 1µPa, Table 1), with both sites reflecting the same overall seasonal patterns. The highest median broadband SPLs occurred during the Winter recording period, followed by Fall, Spring and with lowest levels recorded in the Summer recording period for both sites. Season significantly affected broadband SPL at both sites when using 60 sec averaging (Kruskal-Wallis; $P = <0.001$, Mann-Whitney; $P = <0.001$, Table 1 and Appendix S1: S3). Conversely, when using 60 min averaging not all seasons showed significant differences.

Diel seasonal averages of broadband SPL (BB SPL) varied among recording sites (Figure 2). While Site 1 tended to show an increase in BB SPL towards midday during the Summer and Spring recordings periods, Site 2 did not show this increase during any seasonal recording period. However, during the Winter period Site 2 exhibited an increase in BB SPL during the nighttime hours (~6 dB increase), with the transition occurring around sunrise and sunset (Figure 2).

In relation to spectral composition, the two recording sites within SBNMS were relatively complex due to a variety of acoustic contributors, with both sites having similar overall frequency contributions with shared biotic and anthropogenic signals (Figure 3; panels 1 & 2, Figure 4a).

At both recording sites there was a general trend of higher SPLs at low frequencies (<200 Hz), decreasing into the higher frequencies throughout the recording seasons. This was largely due to the presence of large commercial ships (see section below). There were also large peaks in the spectra at both Site 1 and Site 2 centered around 20 Hz due to the pulse vocalization of fin whales (*Balaenoptera physalus*). This was most pronounced during the Fall and Winter recording periods, with a rise of up to 20 dB re 1 $\mu Pa^2 Hz^{-1}$ (Figure 3). Particularly at Site 2, there were also narrowband spikes in the spectra from 8 – 12 kHz during all seasons except Winter, due to the signals from acoustic devices used on commercial fishing nets to deter porpoises and other marine mammals. These devices increased these frequency-specific sound levels during those time periods by as much as 12 dB re 1$\mu Pa^2 Hz^{-1}$ (Figure 3).

Sites within SBNMS showed a large amount of variation in SPLs within the select octave bands (Appendix S1: Fig. S2a & b). During the Summer recording period, Site 1 had an increase

(12 – 28 dB re 1µPa RMS) in several octave bands (centered on 62, 125, 251, and 501 Hz) which peaked around midday, and likewise in the spring. This diel trend was not seen during other seasons or at Site 2. The Winter recording period was more consistent, however, episodic peaks (≤ 17 dB re 1µPa) in SPL were still occurring, although not in consistent diel trend and largely due to transiting vessels (Appendix S1: Fig. S2a & b).

There was no strong linear relationship ($r > -0.5$ or 0.5) between BB (10 – 24,000 Hz) SPL or select octave band levels and wind speed (m/s) or wave height (m) at either site, during any seasonal recording period. Winter and Spring recording periods had the highest correlation among these variables; however, this was found to be a relatively weak to moderate relationship, with r values in the 0.257 – 0.425 range for wind speed, and 0.205 – 0.394 for wave height and BB SPL. The octave band levels centered on 501 Hz had the strongest linear relationship with these factors. However, these were only moderate, with wind speed (Pearson Test; $r = 0.359$ & 0.437, Site 1 & Site 2 respectively) and wave height ($r = 0.263$ & 0.407, Site 1 & Site 2 respectively) during the Spring, and with wind speed ($r = 0.437$ & 0.422, Site 1 & Site 2 respectively) during the Winter recording periods.

3.1.2 Vessel presence and contribution to the soundscape

At Site 1, over the three days per moon phase during the Summer Recording period manually examined for vessel presence, there was the highest vessel occurrence within this study, with 90.6 % of the hours analyzed including vessel sound (261 of 288 h), and a daily average of 21.75 ± 0.4 h of presence per day (Appendix S1: Table S4). Due to the high proportion of total hours with vessel presence, SBNMS was excluded from the further detailed vessel analysis as there were too few hours available to compare times with vs. without vessel presence.

3.1.3 Detection and classification of biological vocalizers

Atlantic cod

The number of cod vocalizations varied greatly between the two sites in SBNMS and among seasonal recording periods. Winter and Spring periods had the fewest numbers of detected calls, with seven and one vocalization(s) respectively. During the Spring recording period the only vocalization was detected at Site 1 (Figure 5). The Summer period had an intermediate number of vocalizations detected at both Site 1 and Site 2, with 32 and 29 vocalizations respectively. The Fall recording period had the largest number of vocalizations detected, with a substantially higher number of calls at Site 1 compared to Site 2 (4903 and 32 respectively). The peak of the vocalizations was recorded on the 24th of November 2016, with 715 true calls, three days after the third quarter moon phase.

Low frequency vocalizing whales

True detections of vocalizations from fin, sei and North Atlantic right whales were identified in all seasonal recording periods. Fin whale vocalizations had the highest daily presence, these were present every day during the Summer, Fall and Winter recording seasons at Site 2 (Appendix S1: Fig. S1). These were also high in daily presence at Site 1 occurring in 62.2 %, 90 % and 90.2 % of days during the Summer, Fall and Winter recording periods respectively. There were no fin whale vocalizations detected at either site during the Spring recording period (Appendix S1: Fig. S1). Sei whale vocalizations were present at both sites during all seasonal recording periods. Vocalizations were present at Site 1 for 8.1 %, 20 %, 54.9 % and 44.1 % and at Site 33 for 29.7 %, 24 %, 74 % and 91.2 % of days in the Summer, Fall, Winter and Spring recording periods respectively. Vocalizations from North Atlantic right whales were present during all recording periods at Site 2 (Summer: 2.7 %, Fall: 20 %, Winter: 21.6 % and Spring: 29.4 %) and all with the exception of the Summer period for Site 27 (Fall: 4 %, Winter: 49 % and Spring: 11.8 %).

3.2 Gray's Reef National Marine Sanctuary

3.2.1 Patterns in broadband sound pressure levels and spectral composition

Broadband (10 – 24,000 Hz) SPLs (both median and RMS values) varied by as much as 10 dB among recording sites and seasons within GRNMS (110.6 – 123.9 dB re 1µPa, Table 1). Season significantly affected BB SPL at both sites when using both 60 s and 60 min averaging (Kruskal-Wallis; $P = <0.001$, Mann-Whitney; $P = <0.001$, Table 1 & Appendix S1: Table S3). The highest median BB SPLs occurred during the Summer recording period for both sites, followed by Spring and lastly the Fall recording period for both sites. No data were available for the Winter period. On average, Site 4 had consistently higher BB SPLs than Site 3 during all seasonal recording periods. Diel seasonal averages of BB SPL were relatively consistent between recording sites (Figure 2). Both sites showed a consistent rise in BB SPL around dawn and dusk, which followed temporal and seasonal patterns in sunrise and sunset times (length of day). Both sites tended to peak around sunrise and sunset for approximately 1.5 hours, with daytime hours (defined as post-dawn peak to pre-dusk peak) being lower than nighttime hours (defined as post-dusk peak to pre-dawn peak).

In terms of spectral composition, both sites within GRNMS had similar overall shapes/frequency contributions with shared biotic signals such as snapping shrimp and toadfish (Figure 3; panels 3 & 4). Both sites were largely dominated by the acoustic signals of snapping shrimp, these snaps produced a broadband rise in the spectra at both sites between ~2 – 17 kHz. which was consistent through all recording seasons sampled (Figure 3 & 4b). As the two sites were relatively shallow (~ 20 m ± 1 m), there was also low frequency signal (10 – 500 Hz) associated with the wind and waves acting on the water surface (Figure 3). Periods of high winds, at times, caused an increase in broadband SPL, however, these factors were only mildly statistically correlated at Site 4 during the Summer recording period (Pearson correlation; r (682) = 0.39, P = <0.001) (see below). There were two large spectral peaks in the mid frequencies (~230 Hz and again at ~460 Hz), which were most pronounced during the Spring recording periods, at both sites but with Site 4 being most evident (Figure 3 and 4b). These peaks were the fundamental and harmonics of the calls produced by a toadfish species, thought to be the oyster toadfish (*Opsanus tau*), and raised the 251 Hz octave band by as much as 15 dB re 1 μPa during the Spring recording period (Figure 3 & 6 [panels i, j, k, l]). Sites within GRNMS showed stable broadband SPLs and were generally most influenced by the increase in snaps from snapping shrimp at dawn and dusk. This increased broadband SPLs by as much as 6 dB re 1μPa at both sites during the Summer, and 8 dB and 6 dB re 1μPa at Site 4 and Site 3 respectively during the Spring recording period.

During the Summer recording period, infrequent and close vessel passage (e.g., Figure 6; panel b ~12:20 – 13:30), SCUBA diving activity (e.g., Appendix S1: Fig. S2c; panel d, ~12:00 25th & 26th July), intense periods of unidentified fish chorusing around dusk (e.g, Figure 6; panels a, b, c d), contact with the hydrophone stand, and times of heavy rain and/or thunder (e.g., Appendix S1: Fig. S2c; panel a, ~09:00 18th July) were also found to influence octave bands (63, 125, 251, 501, and 1000 Hz). During the Spring recording period, octave band sound pressure levels showed strong diel patterns, with Site 3 showing a distinctive peak around dusk in octave bands centered on 251, 501 and 1000 Hz, and 125 and to a lesser extent. This resulted in a 23 and 20 dB re 1μPa increase in the 501 & 1000 Hz octave band respectively for around 4.5 hours, which was more pronounced around the full moon phase (Appendix S1: Fig. S2c; panel k). At

Site 4, these peaks were not limited to dusk and SPLs in 251 and 501 Hz bands would peak around dusk and remain elevated through the dark hours and then drop off around dawn (approximately 10 hours). This pattern was most pronounced around the first quarter and full moon. These two bands would also show a lesser peak around noon then drop until dusk during some moon phases (Figure 6).

There were no strong linear relationships (r > -0.5 or 0.5) between BB SPL and wind speed (m/s) or wave height (m) at sites within GRNMS. Sites had weak to moderate correlations, with the Summer period exhibiting the strongest of all seasons (Pearson Test; wind: $r = 0.241$ & 0.368, wave: $r = 0.200$ & 0.321 at Site 3 and Site 4 respectively).

However, at Site 4 there were moderate relationships between the octave band levels centered on 501 Hz and both wind speed ($r > 0.484$) and wave height ($r > 0.317$) during the Summer recording period, and moderate relationships ($r = 0.349 – 0.381$) between bands 63 Hz, 125 Hz, 251 Hz, and 501 Hz and wind speed at Site 3 during the Spring Recording period. Fall had the strongest relationships ($r > 0.5$) between the octave band levels centered on 125 Hz and 251 Hz and both wind speed and wave height, and the 501 Hz band and wind speed at Site 3, as well as bands centered on 125 Hz, 251 Hz and 501 Hz and wind speed at Site 4.

3.2.2 Vessel presence and contribution to the soundscape

At Site 3 within GRNMS, over the three days per moon phase in the Summer recording period manually examined for vessel presence, there was a low occurrence of vessel presence in the recordings (6.6 % or 18.9 of 288 h). This site had a daily average of 1.58 ± 0.5 h of vessel presence per day (Appendix S1: Table S4) and was the lowest of the study.

Removing times with vessel presence reduced the median SPL in the lower 1/3 octave frequency bands (bands centered on 251.2 Hz and below) by up to 4 dB and up to 12.5 dB re 1μPa in the 90th percentile (Figure 7). However, the 1/3 octave bands centered on 316 Hz and above, the median and 90th percentile SPL slightly increased by up to 2.8 dB re 1μPa ± 0.1, as it removed biologically significant times of the day increase SPL in these bands.

3.2.3 Detection and classification of biological vocalizers

Snapping shrimp

Sound from the snaps of snapping shrimp were present in all recordings at both sites within GRNMS. Snap signals were quantified in terms of both snap detection rate (per 60 seconds) and the SPLs of the snap associated frequency band (2000 – 20,000 Hz) during all recording periods. In general, Site 4 had higher overall snap rates than Site 3 for every recording period (Table 2, Appendix S1: Fig. S3a). The Spring recording periods had the highest seasonal snap rates at Site 3 and Spring and Summer were equally high at Site 4.

At a 24-hour time scale, both sites exhibited typical, strong diel patterns in snap rate, with an increase around dawn, dusk and midnight time segments compared to noon rates (Table 2, Appendix S1: Fig. S3a). There were significant differences in snap rate among the time segments (Dawn, Noon, Dusk & Midnight) within each site (Friedman Test; P = <0.001), with the Noon time segment consistently lower snap rates that the other three segments. During the Summer both sites exhibited significantly higher snap rates during Dawn and Midnight (Table 2). During the Fall and Spring recording periods Site 3 showed significantly higher rates during Dawn, Dusk and Midnight, compared to Noon, whereas at Site 4 during the Fall and Spring, Dusk and Midnight were significantly higher compared to Dawn and then Noon.

Low frequency vocalizing whales

There were no validated detections of vocalizations from any baleen whale species in any seasonal recording periods within GRNMS.

3.3 Florida Keys National Marine Sanctuary

3.3.1 Patterns in broadband sound pressure levels and spectral composition

Broadband (10 – 24,000 Hz) SPL (both median and RMS values) in FKNMS had a high degree of seasonal consistency, only varying by as much as 1.9 dB (107.8 to 109.6 dB re 1 uPa Winter and Spring respectively, Table 1). Seasonal comparisons were only available at Site 6 as Site 5 only had useable data from the Summer recording period. Season statistically affected broadband SPL at Site 6 when using 60 s averaging (Kruskal-Wallis; P = <0.001, Table 1). However, when using 60 min averaging there was no significant difference between Summer and Spring recording periods (Appendix S1: Table S3). At Site 6 the Spring recording period had the highest median broadband SPL, followed by Summer, Fall and then Winter, but these differences among seasons (within 1.8 dB re 1 μPa, Table 1) were much lower than those observed at other sanctuaries. Diel seasonal averages of broadband SPL were also extremely stable among seasons and recording sites (Figure 2). Both sites exhibited a rise in SPL around dawn and dusk, which followed temporal and seasonal patterns in sunrise and sunset times. The SPL at both sites peaked approximately 45 m before sunrise and post-dawn levels remained higher than pre-dawn levels. Sound pressure levels remained constant during daylight hours.

In terms of spectral composition, both recording sites were again the most consistent/stable among seasons (Figure 3; panels 5 & 6). Both sites had similar overall shapes/frequency contributions, with common biotic signals such as snapping shrimp and multi-species fish vocalizations, the low frequency abiotic signals of wind and waves at the surface, and low to medium frequency signals of small vessels (anthropogenic). The acoustic signals of snapping shrimp produced a relatively broadband rise in the spectra between ~2.5 – 15 kHz, which was consistent through all recording seasons. As the two sites within FKNMS were shallow (~ 15 & 13 m), there was also low frequency signals (10 – 500 Hz) associated with the wind and waves acting on the water surface.

Additional to the ubiquitous peaks at dawn and dusk due to the patterns in snapping shrimp activity there were also additional episodic peaks in FKNMS recordings that did not appear to occur in any defined pattern or time of day. During the Summer recording period at Site 6, octave bands centered on 125 and 251 Hz exhibited a diel trend during the first quarter moon phase in which SPL would rise (5 – 8 dB re 1 µPa) around midnight till around dusk whereby it would drop to daytime levels (Appendix S1: Fig. S2d; panel b). Octave bands centered on 501 & 1000 Hz would also peak on or after dusk (depending on moon phase) before dropping to almost daylight levels after midnight (Appendix S1: Fig. S2d; panel b, c, d). This pattern was not observed at Site 5, except during the first and third quarter moon phases, and the increase in SPL in the dark hours were less pronounced (~3 dB) (Appendix S1: Fig. S2e; panel b & d). Nonetheless, the dusk peaks were still present in select octave bands and would increase by as much as 15 dB around the full moon. This pattern of increase in the octave bands at dusk also continued during the Fall, Winter and Spring recording periods at Site 6. Frequent episodic spikes in SPLs caused by vessel traffic were common in all season but most pronounced around noon in the Fall and Winter periods (Appendix S1: Fig. S2d).

There were no strong linear relationships (*r* > -0.5 or 0.5) between broadband SPL and wind speed (m/s) at sites within FKNMS. Site 6 had weak correlations in the Fall, Winter and Spring recording periods (*r* = 0.13, 0.27, 0.01 respectively). The Fall and Winter recording periods had the strongest (weak to moderate) of relationships between octave bands centered on 251 (*r* = 0.313 & 0.478) and 501 Hz (*r* = 0.331 & 0.422) and wind speed at Site 6.

3.3.2 Vessel presence and contribution to the soundscape

At Site 5 within FKNMS, over the three days per moon phase during the Summer recording period manually examined for vessel presence, there was a low occurrence of vessel presence in the recordings (12.6 % or 36.6 h of 288 h, and a daily average of 3.1 ± 0.37 h of vessel presence per day) (Appendix S1: Fig. S4). Removing times with vessel presence reduced the median SPL in the lower 1/3 octave frequency bands (bands centered on 251.2 Hz and below) by up to 5.3 dB and the 90th percentile by up to 13.24 dB re 1µPa, Figure 7). The 1/3 octave bands centered on 316 Hz and above decreased the 90th percentile by up to 5.9 dB re 1µPa, however, this decrease in SPL dropped to as low as 0.46 dB re 1µPa in the 5012 Hz bands and above (Figure 7).

3.3.3 Detection and classification of biological vocalizers

Snapping shrimp

Sound from the snaps of snapping shrimp were present in all recordings at both sites within FKNMS. During the Summer recording period both sites had very similar average snap rates (361 and 362 snap/60 s) (Table 2, Appendix S1: Fig. S3b). At Site 6, there were significant differences in snap rate among seasons (Kruskal-Wallis; H = 6585, *P* = <0.001). Spring had the highest snap rate (614 snaps/60 s), followed by Summer (362), Fall (296), and then the Winter recording period with the lowest (237).

Over a 24-hour time scale, both sites exhibited a diel pattern in snap rate, with an increase around dawn, dusk time segments compared to noon and midnight (Table 2, Appendix S1: Fig. S3b). There were significant differences in snap rate among time segments (Dawn, Noon, Dusk & Midnight) within both sites (Friedman Test; *P* = <0.001), generally with Dusk and Dawn exhibiting consistently higher snap rates that the other time segments. At both sites during the Summer recording period, Dusk significantly had the highest snap rate, followed by Dawn and Noon, and with Midnight having the lowest. During the Fall and Winter periods both Dusk and Dawn had significantly higher snap rates to Noon and Midnight and the Spring having significantly highest rates at Dusk compared to Dawn Noon and Midnight (Table 2).

Low frequency vocalizing whales

There were no validated detections of vocalizations from any baleen whale species in any seasonal recording periods within FKNMS.

3.4 Flower Garden Banks National Marine Sanctuary

3.4.1 Patterns in broadband sound pressure levels and spectral composition

Broadband (10 – 24,000 Hz) SPL (both median and RMS values) varied by as much as 12 dB among recording sites and seasons within FGBNMS (108.8 – 121.9 dB re 1μPa, Table 1). Site 7 had significantly higher SPL than Site 8 over all season. Season significantly affected broadband SPL at both sites when using 60 sec and 60 min averaging (Kruskal-Wallis; $P = <0.001$) (Table 1 & S3). The Summer and Spring recording periods exhibited the highest broadband median and RMS SPL, followed by Fall and then Winter at both sites.

Diel seasonal averages of broadband SPLs showed similar overall patterns at both sites (Figure 2). Both sites exhibited a consistent peak around dawn and dusk, which followed temporal and seasonal patterns in sunrise and sunset times (length of day), for approximately 1.5 hours, with daytime hours (defined as post-dawn peak to pre-dusk peak) being lower than nighttime hours (defined as post-dusk peak to pre-dawn peak). On average, Site 7 had consistently higher broadband SPLs than Site 8 during all recording periods.

Both sites exhibited a broadband rise in the spectra between ~2 – 15 kHz, and this rise was consistent through all recording periods (Figure 3; panels 7 & 8). Site 7 was dominated by low frequencies (40 – 150 Hz), due to long periods of stationary and slow-moving vessel activity close to the recording location and additional distant human activity sources (e.g., vessels and seismic sources used in oil and gas exploration). This peak was not observed at Site 8, though did exhibit a distinctive peak in the spectra at ~600 – 1500 Hz, only present in the 90th percentile. Extensive low frequency biological signals associated with the vocalizations from fishes were apparent at both sites in FGBNMS, however, due to the high proportion of overlap with the low frequency anthropogenic signals, particularly at Site 7, the presence of any periodicity in these biological signals was not apparent within any of the 50 % spectral level measurements during any of the recording seasons (Figure 3).

Broadband and octave band SPLs at Site 7 were on average 6 – 15 dB re 1μPa higher than at Site 8, depending on the season (Table 1 & Appendix S1: Fig. S2f & g). The influence of the peak of snapping shrimp signal and dawn and dusk maxima were less prominent due to low frequency dominance from other acoustic activities. At Site 7, during all recording periods, there were episodic peaks (≤ 16 dB re 1μPa RMS) in the selected octave bands, although they did not occur in a consistent diel or other pattern that could be determined. During the Fall recording period, over all moon phases, there was a substantial rise in SPLs (16 – 18 dB re 1μPa) in the

501 and 1000 Hz octave bands, beginning around dusk and returning to ambient levels just before or around midnight depending on the moon phase (Appendix S1: Fig. S2f; panels e, f, g, h). Smaller peaks also occurred at Site 8 in the Fall recording period, however, these occurred earlier in the day and in the 251 and 501 Hz octave bands (Appendix S1: Fig. S2g; panels e, f, g, h).

There was no strong linear relationship (*r* > -0.5 or 0.5) between broadband (10 – 24,000 Hz) SPL and wind speed (m/s) at either site within FGBNMS, although, both sites showed a weak correlation in the Fall season (Pearson Test; *r* = 0.182 & 0.207 Sites 7 & 8 respectively). There were strong linear relationships between the octave band levels centered on 63, 125, 251 and 501 Hz and wind speed at Site 8 during the Fall recording season (*r* = 0.650, 0.654, 0.596, and 0.730 respectively). Site 8 also had a weak to moderate relationships between octave bands 251 and 501 Hz (*r* = 0.237 & 0.247 respectively) and wind speed during the Spring recording period.

3.4.2 Vessel presence and contribution to the soundscape

At Site 8 within FGBNMS, over the three days per moon phase during the Summer recording period manually examined for vessel presence, there was a moderate occurrence of vessel presence in the recordings (27.3 % or 78.6 h of 288 h, and a daily average of 7.1 ± 0.99 h of vessel presence per day) (Appendix S1: Table S4). Removing times with vessel presence produced a notable reduction in median SPL in the lower 1/3 octave frequency bands (bands centered on 251.2 Hz and below) reduced by as much as 10.63 dB and the 90th percentile by up to 12.58 dB re 1μPa (Figure 7). Octave bands centered on 316 Hz and above decreased the 90th percentile by up to 5.2 dB re 1μPa, but above 2512 Hz the differences were negligible (< 0.28 dB) (Figure 7).

3.4.3 Detection and classification of biological vocalizers

Snapping shrimp

Sound from the snaps of snapping shrimp were present in all files recorded at both sites within FGBNMS though Site 7 had higher overall snap rates than Site 8 for all seasonal recording periods (Table 2, Appendix S1: Fig. S3c). At Site 7, there were significant differences among seasons in snap rates (Kruskal-Wallis; H = 8861, *P* = < 0.001). Spring had the highest average snap rate (446 snaps/60 s), followed by Summer (377), and Fall and Winter (300 & 294 respectively). This pattern was also consistent at Site 8 (Kruskal-Wallis; H = 6339, *P* = < 0.001) with Spring (335) having the highest, followed by Summer (306) and then Fall (189) with the lowest. Over a 24-hour time scale both sites exhibited highly variable diel patterns in snap rate that varied among seasons. (Table 4, Appendix S1: Fig. S3c). There were significant differences in snap rate among diel time segments (dawn, noon, dusk & midnight) within both sites during all recording periods (Friedman Test; *P* = <0.001), with the exception of the Summer at Site 8. Site 7 was the most variable of all sites in, however, Dusk most often had the highest snap rate.

During the Summer recording period at Site 7, Noon and Dusk had a significantly higher snap rate than Midnight and Dawn, whereas Site 8 had no significant differences. During the Fall periods Site 7 and 8, had differing patterns in snap rate, with Site 7 showing significantly highest rates during the Dusk time segment, followed by Midnight and Dawn, and then Noon. Whereas Site 8 exhibited significantly higher rates at Dusk, Dawn and Midnight segments, compared to Noon segments. During the Winter recording period Site 7 had significantly higher snap rates in the Dawn and Midnight time segments compared to Noon and Dusk. Again, in the Spring period both sites had different patterns in snap rate with Site 7 showing significantly higher rate in the Midnight and Dusk segments than Noon and Dawn. At Site 8, Dusk was significantly higher than Midnight and Dawn, with Noon being the lowest (Table 2).

Low frequency vocalizing whales

There were no validated detections of vocalizations from any baleen whale species in any seasonal recording periods within FGBNMS.

3.5 Inter-Sanctuary Comparisons

3.5.1 Patterns in broadband sound pressure and spectral composition

Among sanctuaries, seasonal frequency power spectra varied in overall appearance, due to differing biotic, abiotic and anthropogenic signals contributions. Sites within GRNMS, FKNMS and FGBNMS exhibited a similar broadband rise in the spectra between ~2 – 15 kHz, and this rise was consistent through all recording seasons. Sites within GRNMS displayed the greatest variability in the mid-range frequencies (100 – 10000) among seasons. Broadband SPLs (both median and RMS values) also varied substantially, ranging from 100.2 – 124 dB re 1μPa (Table 1). GRNMS had the highest broadband RMS SPLs across all seasonal recording periods sampled, with maximum levels recorded in the summer and fall and highest median levels in the summer and spring. The highest broadband RMS levels recorded in the winter were within

FGBNMS which also showed the highest median SPLs in the fall and winter (Table 1). FKNMS showed the highest consistency in broadband (10 – 24,000 Hz) SPL (medians and RMS), PSD and frequency distribution among sites and seasons, and SBNMS exhibited the most variation.

Diel trends in broadband SPL also varied among sanctuaries. Seasonal average diel SPL showed similar temporal patterns among the three reef-based sanctuaries (GRNMS, FKNMS and FGBNMS), with a rise around dawn and dusk, and following temporal and seasonal patterns in sunrise and sunset times (length of day) due to biological signaling (Figure 2).

Wavelet analysis indicated that strength and persistence of periodicity in octave band SPLs also varied among sanctuary, site, season, and octave band. The sites GRNMS and FGBNMS sanctuaries exhibited strong (significant at the 95 % confidence level: wavelet scalogram) once per day periodicity in the SPLs in the octave band centered on 7943 Hz during each seasonal sampling period, almost entirely uninterrupted. Those interruptions largely coincided with a twice per day periodicity (Site 3 Fall). Whereas Sites within FKNMS demonstrated a twice per day periodicity in this band during all seasonal sampling periods (see biological vocalizers section below). Sites within GRNMS, which saw distinctive diel patterns in several octave band SPLs and periods of biological chorusing around certain moon phases (Figure 6 & Appendix S1: Fig. S2c), also showed strong once per day periodicity (wavelet analysis) in SPLs in these bands. For example, Site 4 during the Summer recording period in 63, 125, 251 Hz bands and to a lesser extent 501 Hz band, and at Site 3 and 4 in the Spring recording period all bands, with some short interruptions (1 day) in this periodicity in the 63, 125 and 1000 Hz bands at Site 3. Similarly, sites within FKNMS exhibited a strong once per day periodicity in the 251 Hz band during the entire Summer sampling period, and 63, 125 and 501 Hz bands during the full and third quarter moons. Also, in the 251 Hz band for the entirety of the Spring sampling period.

SBNMS showed a dissimilar pattern in average diel SPLs from the other sanctuaries, which varied among seasons, notably with SPLs peaking at approximately midday in the Summer recording period (Figure 2). Site 1 exhibited strong once per day periodicity in the 125, 251 and 501 Hz octave band levels across the entire Summer recording period, however, nothing significant during all other sampling periods. Site 2 showed no strong periodicity.

3.5.2 Relationship between sound levels and wind and wave data

Among all sanctuaries, there were no strong linear relationships (r > -0.5 or 0.5) between broadband (10 – 24,000 Hz) SPL and wind speed or wave height at any site, during any recording period. Of all the sanctuaries, both sites within GRNMS had the strongest linear relationship between wind speed and wave height and the octave bands centered on 125 (> r = 0.56), 251 Hz (> r = 0.68) and 501 Hz (r = 0.62) during the Fall recording period. Also, during the fall period, Site 8 within FGBNMS had a strong linear relationship between wind speed and 63, 125, 251, 501 Hz octave band levels (r = 0.65, 0.65, 0.6 and 0.73). See individual Sanctuary sections for further detail.

3.5.3 Vessel presence and contribution to the soundscape

In the three days per moon phase manually examined for vessel presence in each sanctuary, SBNMS had the highest occurrence of vessel presence in recordings (261 of 288 h) and an average of 21.75 hours of vessel presence per day. The lowest vessel presence was in GRNMS (18.9 of 288 h), with vessel presence in FKNMS and FGBNMS sanctuaries more moderate (36.6 h of 288 and 36.6 h of 288 h respectively). Overall, vessel presence contributed the largest amount of energy to low frequency 1/3 octave bands between 31.6 and 398.1 Hz, with 63 to 125 Hz bands being the most influenced at all sites. Only GR, FK and FGBNMS had enough variance in vessel presence to support comparison of levels between periods without vs. with vessels. Of these sanctuaries, FGBNMS had the greatest increase in median SPL (10.63 dB re 1μPa in band centered on 251.2 Hz) and GRNMS has the smallest increased in median SPL (4 dB re 1μPa) due to the contribution of vessels when times with vessels versus no vessels were compared.

3.5.4 Detection and classification of biological vocalizers

Due to the geographically disparate locations of the sanctuaries, most vocalizing species were sanctuary specific and their presence could not be compared among sites. However, the snaps from snapping shrimp were detected at sites within GRNMS, FKNMS and FGBNMS. At a 24-hour time scale all three sanctuaries exhibited strong diel patterns in snap rate, with an increase around dawn and dusk, however, rates during the daytime and nighttime periods differed among sanctuary. Both sites within GRNMS and FGBNMS generally exhibited higher snap rates during the Midnight time segments than Noon segments (Table 2). This was not the case at sites within FKNMS, with Midnight segments being more similar to Noon time segments, and hence seeing twice per day periodicity in SPLs in the 7943 Hz octave band.

Sound pressure levels in the 2000 – 20,000 Hz analysis band was a significant predictor of snap rate at several sites during several seasons. At both sites within GRNMS $SPL_{(snap\ band)}$ was a significant predictor of snap rate during all seasons with the exception of Spring at Site 3. This model was stronger at Site 4 than Site 3.

At sites within FKNMS, SPL did not show this same predictor strength, with both sites having a weak to no predictor value of SPL (2000 – 20,000 Hz) to snap rate during all seasons ($R^2 \leq 0.27$). FGBNMS was more similar to FKNMS than GRNMS with both sites also having a weak to no predictor value of SPL to snap rate during all seasons ($R^2 \leq 0.28$), with the exception of Site 8 in the Fall ($R^2 \geq 0.62$).

4. Discussion

This study provided baseline acoustic characterization information, exploring the daily drivers, seasonal patterns, and identified the abiotic complexities and compared these attributes across geographically distributed underwater soundscapes within four ecologically varying U.S. National Marine Sanctuaries. Studies investigating marine soundscapes have largely focused on temporal trends or variations within a single habitat (Curtis et al. 1999, Radford et al. 2008, Staaterman et al. 2014). Such studies can be used to design and target continued monitoring of a site or habitat to better understand changes in biological contributors, anthropogenic activities, and/or some degree of habitat 'health' or regime shifts (Rossi et al. 2017). However, increasingly studies are exploring spatial variation within and among geographically distributed underwater habitats (McWilliam and Hawkins 2013, Putland et al. 2017a, Haver et al. 2018).

When undertaking acoustic monitoring efforts in geographically separated and biologically and physically dissimilar systems, a standardized approach towards both data collection and analyses is necessary for comparisons. The standardized equipment, field design and analyses in this study assisted in identifying measurements that most effectively summarized soundscape attributes at sites both within and among sanctuaries. Some factors remain difficult to standardize when recording among different systems but are important for data interpretation. Due to the distinct environmental features of individual sites (e.g., differences in depth, substrate type, temperature, complexity) over wide ranging monitoring projects, direct quantitative comparisons among sites should note the possible influence in varying acoustic propagation characteristics. In this study, the most prominent example of this is the moderately deeper (50-68 meter) locations of the recording sites in SBNMS, relative to the more similar depth conditions of the remaining recorders (~20 meters). Depth can play a major role in how signals propagate from the source to the recorder, as the cutoff frequency increases at decreasing depths (according to normal-mode theory). Modes near the cutoff frequency are strongly attenuated and therefore the shallower the site the greater the low frequencies may be affected (Tindle et al. 1978, Tindle 1982). Due to more efficient propagation of low frequencies in deeper waters, sound levels over a larger area in the vicinity of SBNMS recording sites may have contributed to levels at these sites, more than what was possible at the other recording locations. Therefore, care needs to be taken when considering SPLs among sites, especially at low frequencies. Despite this, differences in propagation characteristics cannot account for many sources of variation in soundscape parameters studied here.

Spectral composition and identification of contributors

All four U.S. National Marine Sanctuaries were found to have differences in broadband sound pressure level (10 – 24,000), one third octave band levels and distinct spectral compositions, each with unique characteristics due to differences in biology, human use patterns, propagation properties, and climate. Unsurprisingly, there was less variation in the measured soundscape parameters within a sanctuary, compared to among sanctuaries. In three out of the four sanctuaries monitored, variation in sound levels over the course of the project among sampled locations in the same sanctuary was relatively low. However, variance among sampled locations in Flower Garden Bank National Marine Sanctuary (FGBNMS) was relatively high.

The difference underscores the role that 'baseline' or pilot projects can play in determining sampling needs for longer-duration efforts, as well as highlighting that even small, protected areas can still demand higher sampling levels. Small changes in physical habitat, biological and oceanographic processes and/or human use can lead to very distinct changes in the soundscape even within a relatively short distance (Radford et al. 2010, Radford et al. 2014).

In general, SBNMS soundscapes were most dissimilar to the sites within GRNMS, FKNMS and FGBNMS, with the polarizing feature being the frequency of the dominant signals within the soundscape. The frequency composition of the two sites within SBNMS were largely dominated by low frequency signals (10 – 100 Hz) with a median PSD found to be between approximately 58 – 101 dB re 1μPa^2 Hz^{-1}. This was largely due to the near constant presence of signal from large vessels travelling to and from Boston Harbor (Hatch et al. 2008). The more trafficked site in FGBNMS showed the most similarity to this pattern among the other sanctuaries. There was also a substantial peak in SBNMS recordings (up to 22 dB re 1μPa^2 Hz^{-1}) in the spectra at approximately 15 – 25 Hz during all seasonal recording periods, except for the Spring, due to the presence of the fin whale (*Balaenoptera* physalus) pulse vocalizations, which was also consistent with detection output from the Low Frequency Detection and Classification and System (LFDCS) (Baumgartner and Mussoline 2011). In the western North Atlantic, fin whales regularly occur within Massachusetts Bay and SBNMS (Hain et al. 1992) and have been reported to sing from approximately September through June (Clark and Gagnon 2002). In a study by Moreno *et al*, (2012) they reported fin whales vocalizations received at an acoustic listening station, very close to one of the SBNMS sites in the current study, in 814 of 817 days analyzed from October 2007 to March 2010. This differs to some extent to the results seen here at the comparable site in 2016/17, where the 20 Hz vocalizations were present in everyday sampled within the Summer, Fall and Winter, however, absent in the Spring Sampling Period. Fin whale vocalizations, and subsequently this ~20 Hz peak in the spectra, were not observed in any of the other sanctuaries.

Sound levels in higher frequencies, 2 – 24 kHz, were much lower at the sites within SBNMS compared to the other sites, likely due to the absence of reef dwelling snapping shrimp. SBNMS is thought to be beyond their northern distribution (McClure 1995). However, during all the seasonal recording periods there were narrowband impulsive signals present centered around 10 kHz (9 – 12 kHz) due to the presence of signals from acoustic deterrent devices. These devices are attached to pelagic or bottom gillnets in attempt to reduce cetacean and pinniped bycatch (Coram et al. 2014).

At the reef sites within GRNMS, FKNMS and Site 8 within FGBNMS, signals at low frequencies (< 50 Hz) were largely due to abiotic factors such and wind and waves acting at the water surface (Knudsen et al. 1948) and sporadic vessel activity. Site 7 within FGBNMS was the exception to this, as it was dominated by the lower frequency bands (40 – 150 Hz) with a peak centered around 70 Hz during all seasons with a median and 90th percentile PSD between approximately 72 – 85 dB and 87 – 91 dB re 1μPa^2 Hz^{-1} respectively. This low frequency contribution was identified to be in part due to near continuous heavy commercial shipping and to a lesser extent, distant seismic exploration (NOAA & ONMS, 2012, BOEM & NOAA, 2018).

The northwest Gulf of Mexico is one of the most active areas of oil and gas exploration and development in the world, with approximately 150 oil and gas platforms located within 40 km of the boundaries of FGBNM (NOAA & ONMS, 2012). These anthropogenic activities have also been documented in other areas of the Gulf of Mexico, with seismic survey sources dominating (Estabrook et al. 2016, Wiggins et al. 2016). Site 8 within FGBNMS had a similar spectral shape to Site 7 from 10 – 30 and 300 – 24,000 Hz, however it lacked this low frequency peak centered on 70 Hz. These differences observed between Site 7 and Site 8 are likely due to differences in anthropogenic activity and the distance between the two sites being outside of the propagation limits of these signals to be present in both soundscapes. Sites within FGBNMS were the most geographically separated of all sites occurring within the same sanctuary, with Site 7 located on the mid-shelf and Site 8 located near the outer edge of the continental shelf, separated by approximately 74 kilometers, which is over double the distance of any of the other sanctuaries. Site 7 also had a heavily used shipping fareway within 10 km from the site, where as Site 8 and had less used shipping fareway at a greater distance during the recording periods (Bureau of Ocean Energy Management & National Oceanic and Atmospheric Administration 2018).

Where the low frequencies dominated in SBNMS and FGBNMS (Site 7), the shallower sites within GRNMS, FKNMS and FGBNMS (Site 8), were largely dominated by the mid- to high-frequencies (200 – 20,000 Hz). This was consistent during all seasonal recording periods, and by large, all driven by a common signal in the 2000 – 20,000 Hz frequency range and produced by various species of snapping shrimp (member of the *Alpheus* and *Synalpheus* genera) (Au and Banks 1997, Versluis et al. 2000). These sites exhibited the highest median and percentile values of PSD in this 'snap band' frequency, with a median at the peak of the band found to be between 67 – 78 dB re 1μPa^2 Hz^{-1} during the Summer and Spring recording periods. All three sanctuaries that contained snapping shrimp exhibited clear spatial differences in snap rate and generally exhibited strong seasonal and diel patterns, increasing around dawn and/or dusk, a pattern which has been previously observed in many different locations and habitats around the world (Radford et al. 2010, Ricci et al. 2016, Lillis and Mooney 2018). However, in support of the observed trend by Lillis & Mooney, 2018, not all sites showed the typically reported increased rate during dark periods compared with light periods. For example, sites within the FKNMS showed a peak in snaps at dusk and exhibited higher snap rates during the day compared to night (light and dark periods respectively). Understanding of these spatial variations in snap rate and pattern is not well understood and could be at times be due to small bathymetric and depth differences in the sound propagation and reflections. However, these inter-sanctuary variations could also be indicative of ecological differences such as species composition and the diversity of hosts (Lillis and Mooney 2018).

There were also various distinct spectral peaks in the mid-frequencies (101 – 1000 Hz) depending on the season and site. At times, these peaks were due to the vocalizations of a large number of various fish species. Most perceptible was the pulse repetition rate or fundamental frequency and 1st harmonic (peak 231 & 462 Hz respectively) of the boat-whistle calls produced by the toadfish, thought to be *Opsanus tau* (Fine 1978), seen within GRNMS during the Spring. As water temperatures rise in the spring sexually mature males of the species establish nests and produce advertisement signals or boat-whistles for the females (Maruska and Mensinger 2009, Van Wert and Mensinger 2019). These signals also presented a peak in the spectra during the Summer recording period, however to a much lesser degree due to diminishing mating season, and the fundamental frequency and 1st harmonic were higher in frequency (270 & 540 Hz respectively) due to the increase in water temperature (Fine 1978). During certain seasons, fish vocalizations would constitute a traditionally defined chorus, whereby the sound from many individuals is continuously above ambient background levels for an extended period using an averaging time of 1 sec., and several distinct types of choruses were present together. However, during this time they largely held their own aural or temporal niche within the soundscape. For example, during the spring at Sites 3 & 4 within GRNMS, there were up to four distinctive fish choruses occupying the same time but residing in different frequency bands (See Figure 4b). These choruses would often peak together around dusk with two choruses subsequently dropping to just above ambient levels, one staying elevated during the night and dropping sharply after dawn, and one chorus exhibiting a peak around dusk and again a smaller peak approximately 2 hours later before dropping again (See Figure 6). Interestingly, these choruses during the dark hours were most often frequency partitioned (peak frequency), although they also exhibited some temporal partitioning in the peak of the energy. In contrast, the vocalizations occurring during light hours were often overlapping and would not usually constitute a ‘chorus’ by the traditional definition. This observation gives evidence for environmental constraints (dark vs. light) and the use of different acoustic strategies to avoid masking or misinterpretation by the targeted receiver during these time periods, supporting the acoustic niche hypothesis (Krause 1993). Partitioning of the acoustic environment with temporal or frequency separation has been demonstrated in a wide variety of animal groups, including insects, birds and mammals (Wilkins et al. 2013), however, partitioning of the acoustic space in the marine environment, and especially in fishes, is not well documented (Ruppe et al. 2015, Desiderà et al. 2019).

In this study, broadband SPLs, the diel plots, and wavelet analyses were used to illustrate the diel patterns and differences among sanctuaries and seasons. The use of broadband sound pressure levels illustrates the ability of certain identifiable signals to raise ambient background levels irrespective of their frequency. Various other unidentified fish, invertebrate, and marine mammal species were also regularly contributing to the monitored soundscapes, however, their acoustic intensity was either not high enough or they were not calling in significant numbers to raise the ambient background levels for detection when examining the PSD (seasonal) or averaged SPLs (60 s). For example, Atlantic cod and haddock are present and producing low frequency spawning vocalizations (40 – 400 Hz peak in energy) within SBNMS during the spring and winter seasons. However, these signals are not raising the ambient background levels over any extended duration as they are completely dominated by the higher amplitude signals of large vessels. This overlap could also be resulting in periods of acoustic masking and a reduction in the communication spaces of these animals during critical life history periods (Putland et al. 2017b, Stanley et al. 2017).

Anthropogenic contributions

In the last decade it has become apparent that the signals produced by large vessels are increasing rapidly in many ocean regions (Hildebrand 2009). Scientists and policy makers are viewing it as a major concern as it has many implications for the populations of acoustic signalers, from behavioral changes to reduction in communication spaces during critical biological periods (Erbe 2002, Halliday et al. 2017, Putland et al. 2017b). In the current study, the signals from various vessel types raised the ambient sound level by up to 13.2 dB in the 251.2 Hz 1/3 octave band and below when comparing times with and without vessels (subsampled in the summer, one site per sanctuary, three days surrounding each lunar phase).

However, at Site 1 within SBNMS where analyses were unable to be run due to the lack of time samples where the ambient soundscape did not include vessel signal, it was noted that an individual vessel transit past the hydrophone could raise ambient sound pressure levels by as much as 60 dB re 1 μPa between 50–2500 Hz. This frequency bandwidth overlaps with a large majority of biological sources in these sanctuaries' soundscapes, potentially causing energetic masking in species who use acoustic communication during vital life history events e.g., Atlantic cod and haddock (Clark et al. 2009, Putland et al. 2017b, Stanley et al. 2017). Site 1 within SBNMS had the highest amount of vessel presence in the recordings analyzed (90.6 % of h per day), corresponding to close proximity to the Boston Traffic Separation Scheme which is utilized by large oceangoing cargo ships, tankers and cruise ships (Hatch et al. 2008). Despite this, sites within SBNMS did not exhibit the greatest median broadband sound pressure levels during any seasonal recording period and was found to be between 10.3 – 18.7 dB re 1µPa lower than the greatest site. This is likely due to the relative absence of biological contributions in the higher frequency range (> 1000 Hz), especially seasons relevant to onshore fishes spawning cycles and snapping shrimp peaks. Care must be taken when using and reporting broadband SPL metrics, as it does not reflect the frequency contributions that make up the level and is not necessarily an appropriate metric when referring to comparable levels encountered by biological receivers at different locations.

Within the shallower sanctuaries, occurrence of vessels in the recordings was much reduced (< 7.09 h/day average) and was composed of smaller vessel types. Despite this, during the times when vessels were present, they could significantly raise the SPL within the 50 – 10,000 Hz frequency band. When comparing periods of time with and without vessels, and its modification of the frequency spectra, care needs to be taken especially when removing times with vessels present. For example, this study highlighted that often high energy biological contributions can be greatly time dependent, therefore if the duration of a vessel presence spans a long enough time window, particularly at a biologically significant time of day, removing it could be also be removing time that is greatly influenced by peaks biological activity.

Teasing apart the contribution of human activities vs. abiotic sources (e.g., wind & waves) to the ambient soundscape can also be difficult, especially if there is no reliable wind speed or wave height data available in close proximity to the recording site. The current study found Site 8 (FGBNMS) exhibited strong linear relationships between wind speed and low frequency octave bands during seasons of high wind. However, at the other site within the sanctuary, where there were higher occurrences and levels of low frequency anthropogenic sound, these relationships were not present. Site 2 (SBNMS) had the highest broadband SPLs of any site during the Winter recording period, it also had significantly higher winds speeds during this time when compared to the other seasonal recording periods. However, there was only a moderate association between factors, again another site with significant vessel activity and consequently low frequency ambient sound.

Future directions

As passive acoustic monitoring capacity has increased, a variety of challenges arise from these progressively longer-term and larger-scale programs. They are producing terabytes of data over multiple years and consequently demanding storage and analysis methods that can efficiently ingest high volumes of data, identify signals of interest and effectively summarize attributes of descriptive value. Techniques such as signal recognition software or computer learning techniques and automated and semi-automated acoustic detectors seek to enable the eventual unsupervised detection, and in some cases, classification of vessels, impulsive signals, baleen whale, fishes, and invertebrates (Baumgartner and Mussoline 2011, Bohnenstiehl et al. 2016, Urazghildiiev and Van Parijs 2016, Ranjard et al. 2017, Ricci et al. 2017, Lin et al. 2018). While output from detectors designed to identify specific sounds of interest remain important, peak performance is often constrained to a relatively small number of target sounds (biological and anthropogenic) and specific contexts or geographic regions. Methods that necessitate significant human oversight are less feasible to apply to such large and wide-ranging datasets, and transitions to more automation often require significant training and ground-truthing with additional information sources. For example, the current study utilized a time intensive method of vessel identification by hand browsing subsampled data. While this method was accurate and sufficient for the current use, it is not sustainable for application to the entire data set. This confirmed data set, however, is useful for ground-truthing more automated approaches.

There has been significant interest by both scientists and managers in metrics that can summarize the full range of acoustical energy a soundscape of interest and extract information on the local habitats biodiversity, state and/or health (Sueur et al. 2014). However, several marine based studies and research working groups have identified the challenges and complexities in applying terrestrially derived metrics (e.g., Acoustic Richness, Acoustic Entropy Index, Acoustic Complexity Index, Acoustic Diversity Index) to marine acoustic environments. For example, a few loud or omnipresent but varying sound sources (e.g., snapping shrimp, seismic air guns, large vessels) can strongly modulate these metrics, masking other biologically important characteristics. Unlike terrestrial environments in which species are often partitioned in acoustic space, marine species tend to overlap in both frequency and temporal space (Parks et al. 2014, Bohnenstiehl et al. 2018). However, it's also important to note that the characteristics of biological signals and the health/biodiversity of a habitat may not always be directly related, therefore, applying a single metric or method is not going to necessarily represent the multitude of factors that determine this (Mooney et al. 2020). It is important that we understand these dynamic and address the biases and limitations they can potentially produce when conducting soundscape measurements.

Answering questions of management interest often requires the ability to compare both contemporary and time-series soundscape measurements among wide-ranging (regional, international) projects. Such comparisons must be able to account for or at least acknowledge the variation introduced by differences in recording location and habitat, recording hardware and/or analytics and a standardized approach towards both data collection and analysis is necessary for valuable results (Erbe et al. 2016). Increased standardization both within and among projects is therefore a subject of keen interest within the soundscape monitoring community (see International Quiet Ocean Experiment – Standardization and Marine Bioacoustical Standardization, ISO-terminology, Consortium for Ocean Leadership report— https://adeon.unh.edu/standards, https://www.iso.org/standard/62406.html, http://oceanleadership.org/understanding/u-s-quiet-ocean-project/). Within U.S. National Marine Sanctuaries, levels of anthropogenic input of sound are not directly managed, but instead are the subject of interagency dialog and recommendations as part of NOAA's mandate to reduce or eliminate likely injury to resources within these sites (Hatch and Fristrup 2009). Understanding the relative contributions of noise from proposed new activities in relation to previous baseline conditions can be essential to site assessments of potential impacts, as well as supporting the design of mitigating recommendations. A standardized system-wide passive acoustic monitoring network, allows for the extraction of several measures of condition "state", both contemporarily and showing trends over time, including the presence of sound producing marine wildlife, the presence of human activities, and, as developed, metrics that correspond with biological diversity (e.g., Freeman and Freeman 2016). In addition, metrics can be further developed to address reported conditions on "pressure" to the "states", including impacts associated with levels of noise produced by human activities, further defined within sanctuaries to frequencies, time periods and areas within particular biological importance. This study indicated a need for more continuous sampling early in site evaluations to quantify base sampling needs required to capture indicators of interest.

Ongoing work is also focusing on integration of acoustic measures used together with complimentary data types and sources (e.g., environmental information, Automatic Identification System (AIS) vessel tracking, acoustic telemetry, and underwater visual surveying, as well as additional development of automated techniques) can provide more complete measures and wider understanding of ecosystem health and species interactions and potential impacts of specific sound-producing human activities (Kaplan et al. 2015, Putland et al. 2017c, Staaterman et al. 2017, Solsona Berga 2018, Zemeckis et al. 2019). With this data integration and ground-truthing, such metrics have been used to rapidly assess large areas of coral reef habitat and assist in detection and characterization of ecological changes (Freeman and Freeman 2016). Further identification of vocalizing and chorusing species will also continue to inform studies of biological acoustic partitioning and aid in long-term monitoring of visitation patterns and acoustic ecology within these protected areas (Erbe et al. 2015).

Conclusions

Each sanctuary revealed a complex soundscape that was composed of some relatively rare events, such as seasonal fish chorusing or thunderstorms, and relatively common events, such as large vessel transits and shimming shrimp snaps. The variability in geographic location, physical habitat and biological inhabitants found among sanctuaries led to distinct sound signatures that varied in time, e.g., day, moon phase and season. It was found that there were different acoustic dominants among the sanctuaries, ranging from a more anthropogenically driven SBNMS to more biologically driven GRNMS and FKNMS, and with FGBNMS including a combination of both more anthropogenically and more biologically driven locations. These dominant drivers were the foremost cause of the observed seasonal fluctuations in the acoustic measurements recorded, except for strong weather events in some sanctuaries during some seasons. Among all the acoustic signals occurring, the signals from both small and large vessels stood out as the most ubiquitous and chronic soundscape influencers. The collected data begins to report on conditions in ambient sound levels and associated drivers at each sanctuary and support the generation of capacity in sanctuaries for longer-term temporal comparisons to better understand and monitor changes across the systems. The current study identified challenges to monitoring and comparing acoustic conditions in geographically and biologically dissimilar systems. It is hoped that identifying a common framework in terms of field design, equipment, and simple acoustic measurements, will encourage further compatibility and comparisons among future monitoring and management effort.

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Supporting Information

Additional supporting information may be found online at: [link to be added in production]

Open Research

All acoustic data collected for this study is permanently stored at National Oceanic and Atmospheric Administration National Centers for Environmental Information Archive. This can be viewed and requested via the Passive Acoustic Data Map Viewer https://maps.ngdc.noaa.gov/viewers/passive_acoustic/

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6. Tables

Table 1. Broadband (BB) sound pressure level (dB re 1 μPa) statistics, using 60 s bins, for each recording site during each recording season. Stellwagen Bank National Marine Sanctuary (SBNMS), Gray's Reef National Marine Sanctuary (GRNMS), Florida Keys National Marine Sanctuary (FKNMS), Flower Garden Banks National Marine Sanctuary (FGBNMS). NB. Bolded numbers signify the highest median and italicized numbers signify highest Root Mean Squared (RMS) broadband SPL (per site) per sampling season.

Sanctuary	SBNMS		GRNMS		FKNMS		FGBNMS	
Site ID	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Summer: June – September								
BB Median	100.5	100.2	**117.0**	**119.8**	**109.4**	109.5	**118.9**	110.5
10th percentile	93.6	94.8	114.0	117.9	108.3	108.3	116.6	108.8
90th percentile	108.0	107.6	119.6	121.9	111.1	111.0	121.9	113.7
BB RMS	107.8	*114.3*	*123.9*	*121.5*	*112.0*	109.5	*120.3*	*118.0*
Fall: October – December								
BB Median	104.5	106.3	113.3	116.4		108.9	116.8	110.4
10th percentile	98.8	100.9	110.6	114.5		107.7	114.4	110.4
90th percentile	110.4	112.3	115.2	118.1		110.4	119.4	112.1
BB RMS	*109.4*	111.5	117.8	117.5		*113.4*	117.5	111.5
Winter: February – April								
BB Median	**105.2**	**110**				107.8	116.5	
10th percentile	100.35	103.6				106.6	114.3	
90th percentile	110.3	113.9				109.5	118.8	
BB RMS	108.6	111.6				111	117.2	
Spring: April – July								
BB Median	100.9	101.4	115.6	118.6		**109.6**	117.3	**111.2**

10th percentile	94.6	96.4	113.0	116.9		108.4	115.6	109.7
90th percentile	108.1	96.4	118.5	120.3		111.0	119.2	113.7
BB RMS	107.8	106.8	118.2	121.1		111.6	117.9	113.9

Table 2. Median snap rate per season and within Dawn, Noon, Dusk and Midnight time segments in the seasonal recording periods. * indicate significant difference detected among snap rates for the different time segments within a site and season, and lower-case letters indicate differences among seasons or time periods within a site (Friedman Test & Tukey Test). Gray's Reef National Marine Sanctuary (GRNMS), Florida Keys National Marine Sanctuary (FKNMS), Flower Garden Banks National Marine Sanctuary (FGBNMS). NB. Bolded numbers signify sampling season and italicized numbers signify time segment with statically highest snap rate per site.

Sanctuary	**GRNMS**		**FKNMS**		**FGBNMS**	
Site	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8
Summer	675 b	**864 a**	361	362 b	377 b	306 b
Dawn	*904 a*	*1006 a*	340 b	341 b	318 b	253
Noon	461 c	665 c	335 b	340 b	*384 a*	284
Dusk	670 b	838 b	*378 a*	*356 a*	381 a	*307*
Midnight	855 a	997 a	297 c	292 c	355 b	296
Sig	*	*	*	*	*	
χ^2	68	68	61	58	22	5
P	<0.001	<0.001	<0.001	<0.001	<0.001	0.2
Fall	452 c	639 b		296 c	300 c	189 c
Dawn	457 a	672 b		285 a	274 b	205 a
Noon	231 b	398 c		275 b	244 c	139 b
Dusk	*495 a*	*725 a*		*311 a*	*317 a*	*228 a*
Midnight	479 a	703 a		252 b	280 b	196 a
Sig	*	*		*	*	*
χ^2	78	62		66	50	76
P	<0.001	<0.001		<0.001	<0.001	<0.001
Winter				237 d	294 c	
Dawn				258 a	286 a	
Noon				201 b	232 b	
Dusk				*263 a*	226 b	
Midnight				208 b	*291 a*	
Sig				*	*	

χ^2				22	45	
P				<0.001	<0.001	
Spring	**685 a**	**869 a**		**614 a**	**446 a**	**335 a**
Dawn	*783 a*	*970 a*		555 b	373 b	308 b
Noon	491 b	622 c		546 b	384 b	291 c
Dusk	722 a	885 b		*638 a*	410 a	*327 a*
Midnight	726 a	916 a		533 b	*423 a*	314 b
Sig	*	*		*	*	*
χ^2	72	64		53	37	51
P	<0.001	<0.001		<0.001	<0.001	<0.001

7. Figure Legends

Figure 1. Map showing recording sites within each sampled National Marine Sanctuary. Stellwagen Bank National Marine Sanctuary (SBNMS); Site 27 – Site 1, Site 33 – Site 2, Gray's Reef National Marine Sanctuary (GRNMS); FS15 – Site 3, Station 20 – Site 4, Florida Keys National Marine Sanctuary (FKNMS); Western Dry Rocks – Site 5, Eastern Sambo –Site 6, Flower Garden Banks National Marine Sanctuary (FGBNMS); Stetson Bank – Site 7, East Flower Garden Bank – Site 8.

Figure 2. Diel time series plots showing seasonal averages of broadband sound pressure level at each site. Shaded grey bars indicate seasonal range of sunrise and sunset times (in local standard time). Stellwagen Bank National Marine Sanctuary (SBNMS), Gray's Reef National Marine Sanctuary (GRNMS), Florida Keys National Marine Sanctuary (FKNMS), Flower Garden Banks National Marine Sanctuary (FGBNMS). Seasons: Summer (June - Sept), Fall (Oct – Dec), Winter (Feb – April), Spring (May – July). NB. Varying x-axis used to better illustrate fluctuations and all times of day are standardized for local standard time at each site.

Figure 3. Seasonal power spectral density levels for each recording site, including median, 10th and 90th percentiles. Solid line represents seasonal average and dotted line represents percentiles (DFT length = 48000, Hanning window, and 50% overlap). Stellwagen Bank National Marine Sanctuary (Sites 1 & 2), Gray's Reef National Marine Sanctuary (Sites 3 & 4), Florida Keys National Marine Sanctuary (Sites 5 & 6), Flower Garden Banks National Marine Sanctuary (Sites 7 & 8). Seasons: Summer (June - Sept), Fall (Oct – Dec), Winter (Feb – April),

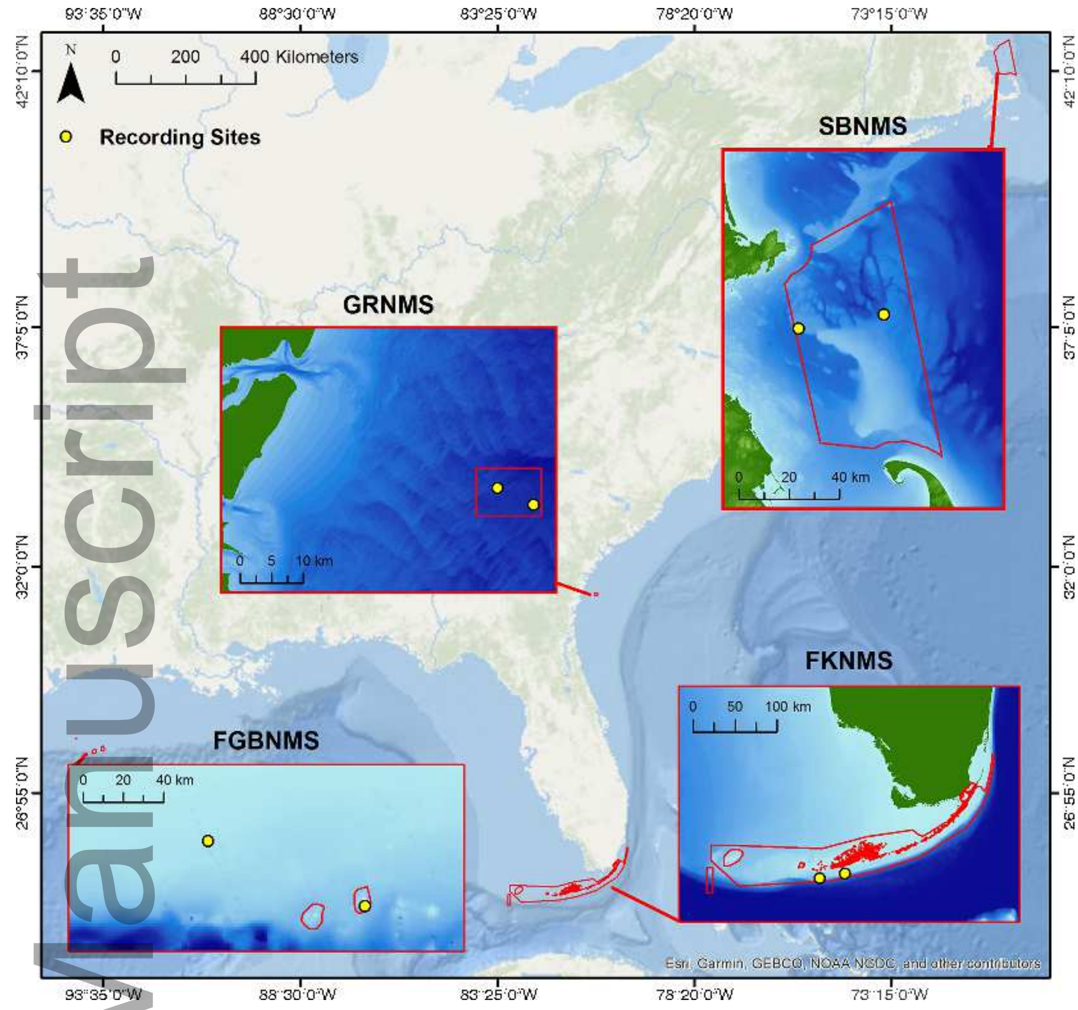
Spring (May – July). NB. data for Fall, Winter and Spring was excluded from Site 5 due to damage to the hydrophone element.

Figure 4. Spectrogram showing 24 h sample and labels indicating signal origin. a) Site 2 in SBNMS (Fall, full moon), b) Site 4 GRNMS (Spring, full moon), c) Site 6 in FKNMS (Spring, Full Moon), & d) Site 7 in FGBNMS (Fall, Full Moon). DFT length = 48000, Hanning window, and 50% overlap and color scale identical in each spectrogram.

Figure 5. Daily number of true cod grunts detected during the seasonal recording periods at Site 1 & 2 in Stellwagen Bank National Marine Sanctuary (SBNMS). Open, right half open, closed, and left half open circles denote new, first quarter, full and third quarter moons respectively. Seasons: Summer (June 26 – Aug 3), Fall (Oct 17 – Dec 7), Winter (Feb 20 – April 13), Spring (May 6 – June 10). NB. Asterisk indicates number of grunts detected on November 23 which exceeded axis scale.

Figure 6. Sound pressure levels in octave bands centered on 63, 125, 251, 501, 1000, and 7943 Hz during three days over all moon phases during the Summer, Fall and Spring recording periods at Site 4 in Gray's Reef National Marine Sanctuary. Open, right half open, closed, and left half open circles indicate new, first quarter, full and third quarter moons respectively.

Figure 7. Median and 90th percentile in 1/3 octave sound pressure levels for periods of time with (red) and without (blue) vessels present during the sub-sampled Summer recording period (June – September) (left panels) and median and 90th percentile change in 1/3 octave band sound pressure levels between all time and time without vessels present (dB re 1µPa) (right panels). Gray's Reef National Marine Sanctuary (GRNMS), Florida Keys National Marine Sanctuary (FKNMS), Flower Garden Banks National Marine Sanctuary (FGBNMS). NB. SBNMS site not included in graphical representation due to the lack of hours without vessel presence for comparison.



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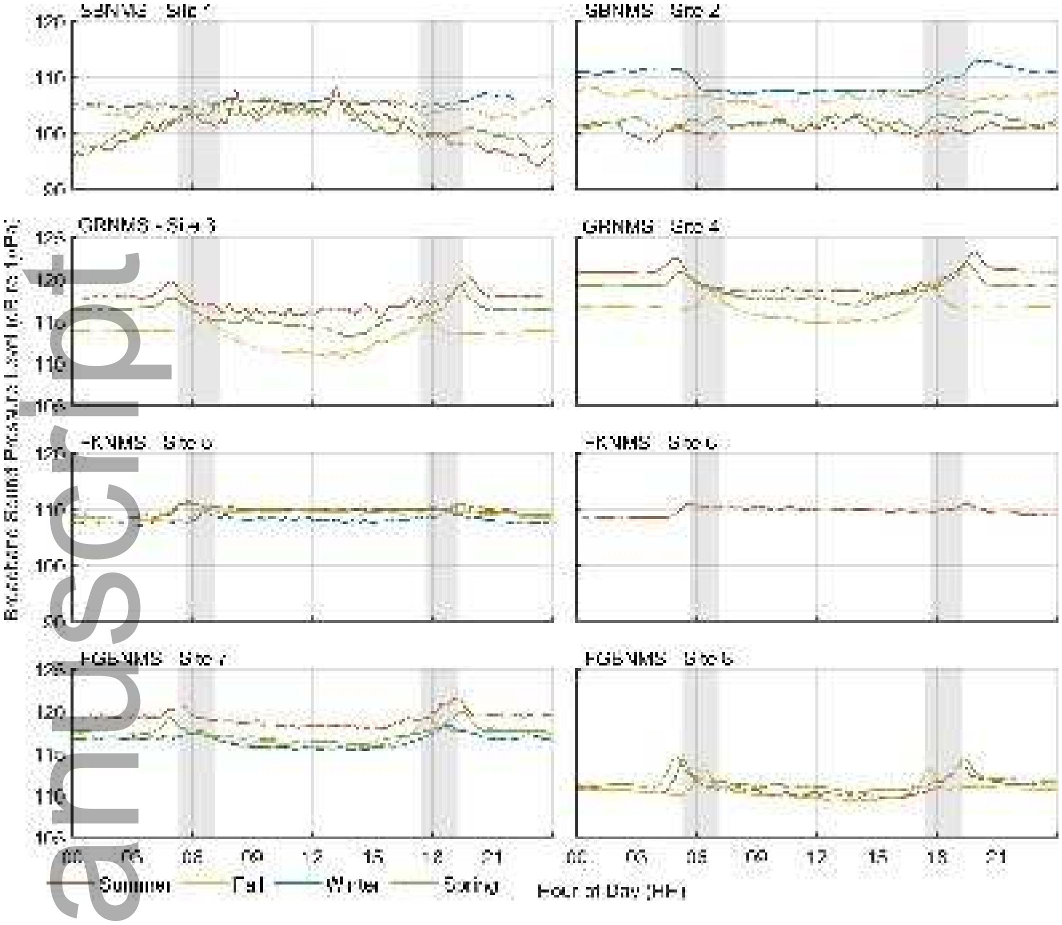

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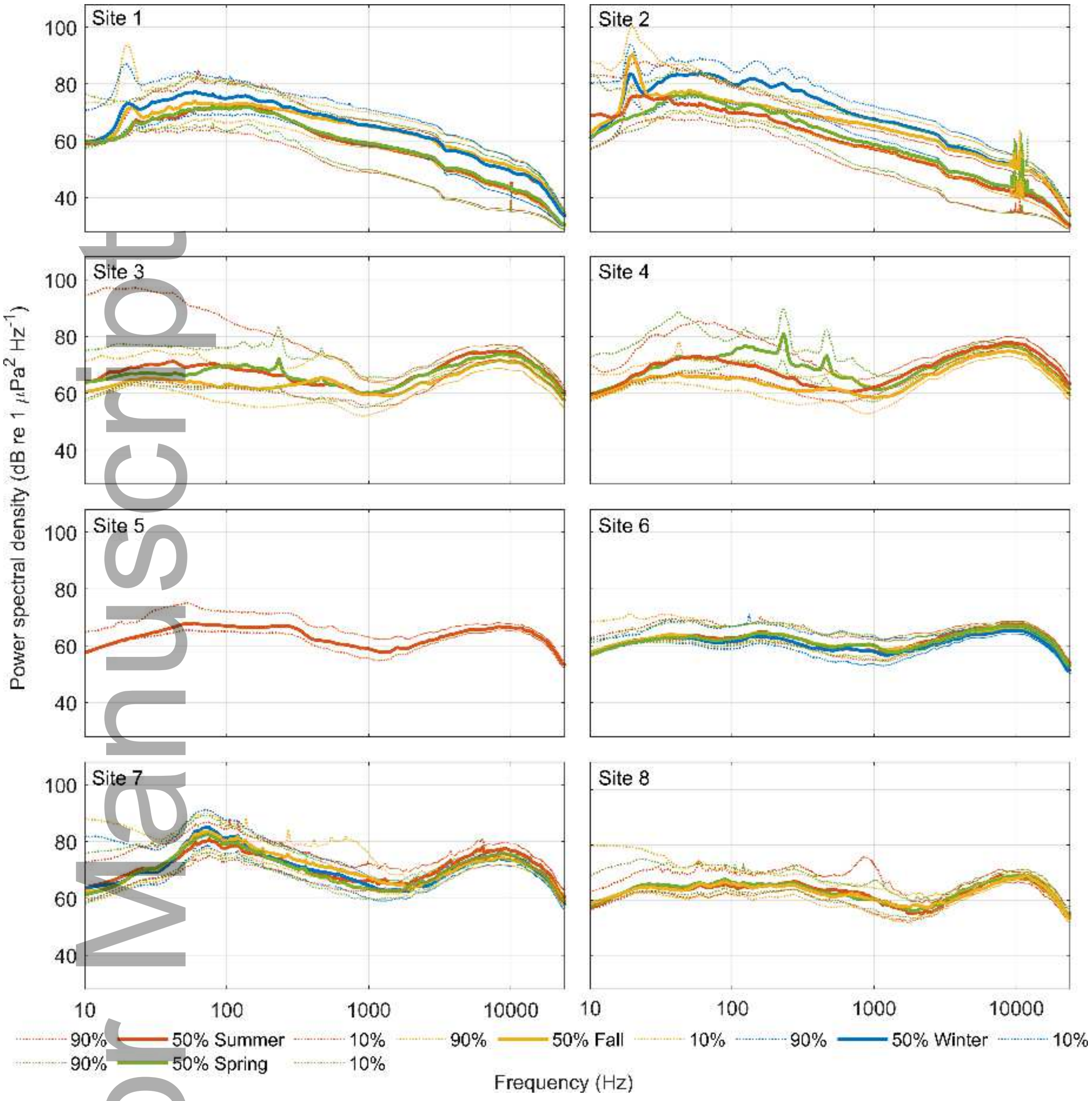

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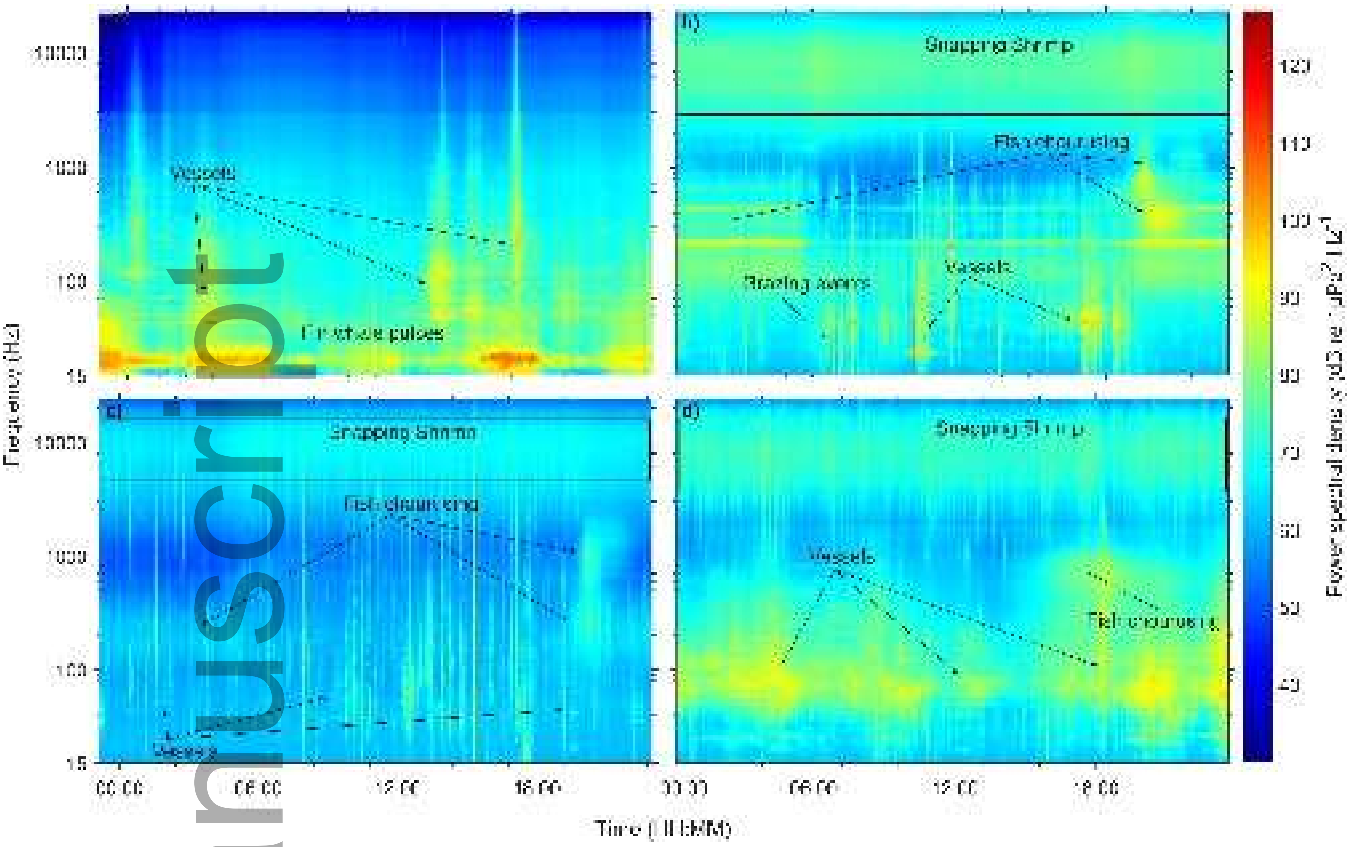

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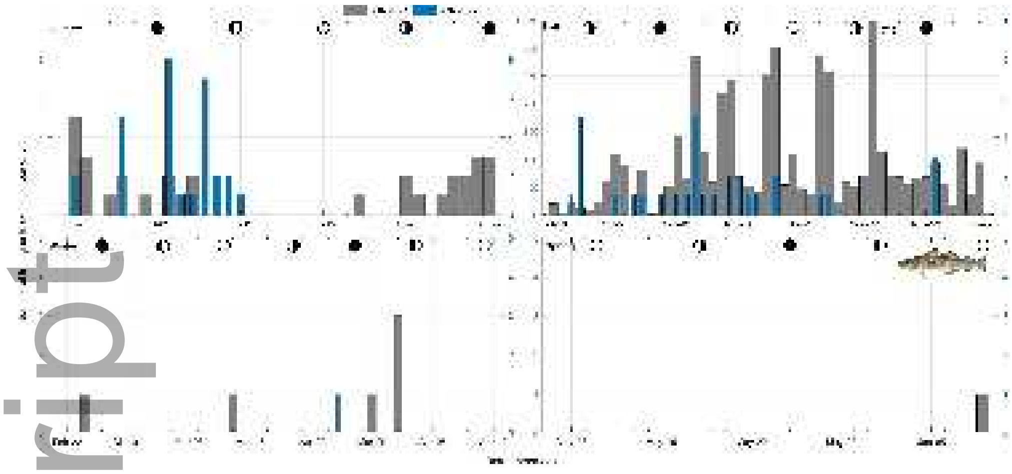

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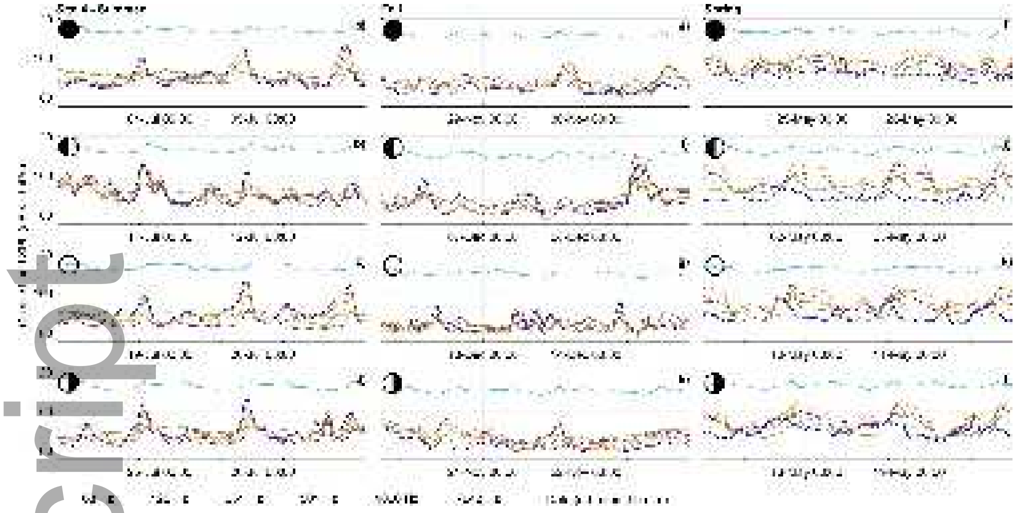

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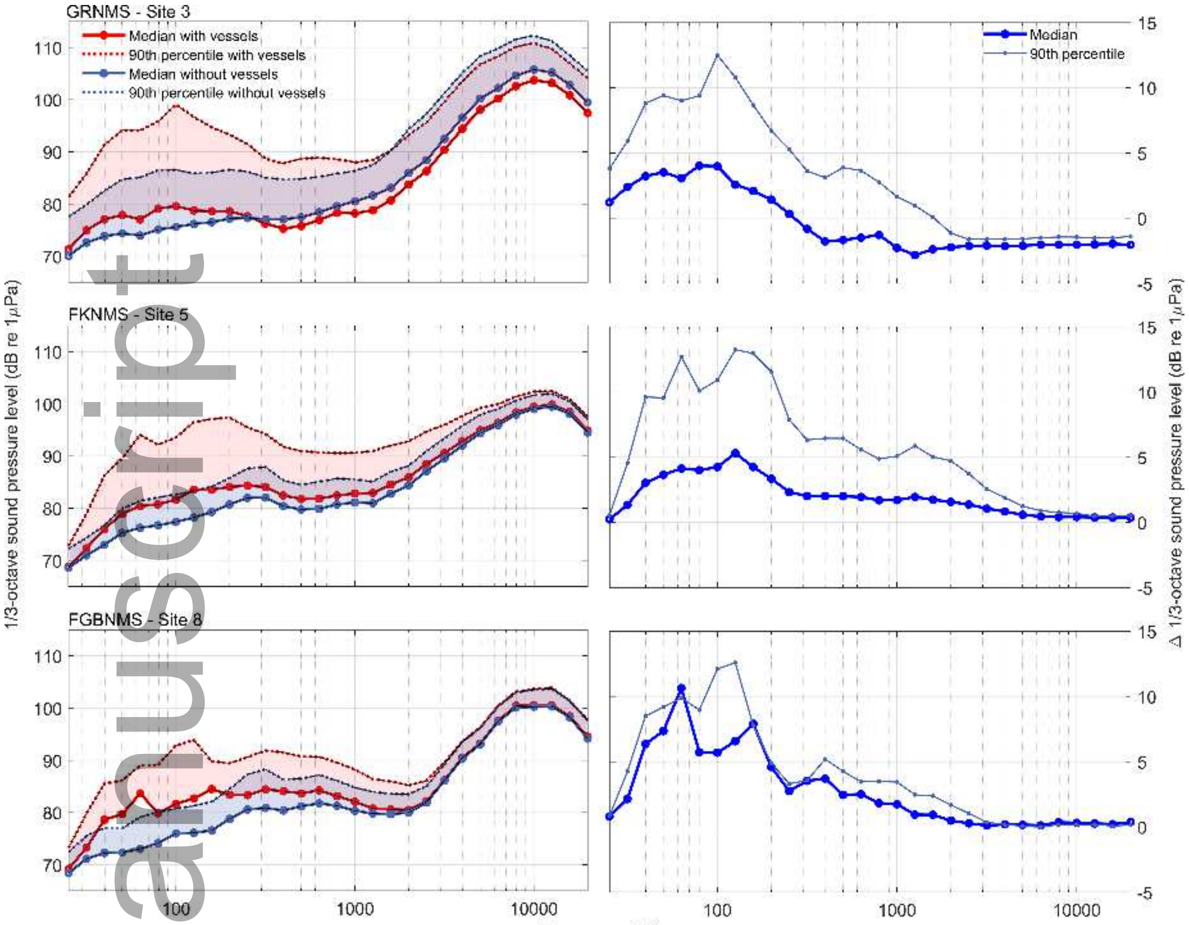

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