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Underwater soundscapes within critical habitats of the endangered Hawaiian monk seal: implications for conservation

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ABSTRACT: Studying underwater soundscapes of critical habitats of marine mammals can provide valuable information on the acoustic environment utilized by sound-reliant animals. For the endangered Hawaiian monk seal *Neomonachus schauinslandi* (HMS), the acoustic scene of their aquatic habitats is poorly understood. We measured ambient noise levels and characterized sound sources at 4 shallow critical habitats of the HMS. Broadband levels ranged from 107.8–123.4 dB re 1 µPa. Octave band levels showed diel patterns associated with biological and anthropogenic sources that mask HMS vocalizations. Biological sources dominated the soundscape at all sites. We opportunistically recorded 2 large-scale geophonic events: Hurricane Douglas (Category 4) and a 6.2 magnitude earthquake. This study provides the first description of underwater soundscapes at critical habitats of the HMS across its expansive range. These measurements serve as a baseline for future studies to understand the impacts of human activities on underwater soundscapes.

KEY WORDS: Acoustics · Vocalizations · Marine mammals · Geophony · Anthropogenic noise · Hawaiian monk seal

1. INTRODUCTION

Low-frequency underwater ambient sound levels have gradually increased globally since the 1950s due largely to anthropogenic sources such as commercial and recreational vessels, sonar systems, and seismic surveys (Wenz 1969, McDonald et al. 2006, Ainslie 2011, Chapman & Price 2011, Frisk 2012, Hermannsen et al. 2019). This increase in noise has altered underwater soundscapes, which are comprised of geophony (sounds of physical events such as wind, rain, earthquakes, and breaking waves), biophony (sounds from biota), and anthrophony (human-made sounds) (Krause 2008). As human activities continue to alter the underwater sonic environment, quantifying soundscapes of ecologically significant environments is a priority for conservation efforts (Au et al. 2012, Kaplan & Mooney 2015). In particular, insights into the soundscapes of underwater critical habitats of marine mammals are important considering that acoustic signaling is used for vital biological functions including foraging, communication, navigation, and orientation (Richardson et al. 1995). Characterizing soundscapes as well as the spatial and temporal over-

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lap of anthropogenic noise with acoustic signals produced by marine mammals can provide critical information to aid in protecting key habitats and limiting the effects of anthropogenic acoustic disturbance.

Despite sound being used as a primary means of communication underwater for most marine mammals (National Research Council 2003), relatively little is known about the acoustic biology of the endangered Hawaiian monk seal *Neomonachus schauinslandi* (HMS) with an estimated population size of 1600 individuals (NOAA Fisheries 2023). While some of the major anthropogenic threats to this endemic species are clearly identified (e.g. introduced disease, trauma, fisheries interactions) (NOAA Fisheries 2021), the impact of underwater noise on HMS behavior, communication, and hearing is poorly understood. Current knowledge of HMS underwater hearing is limited to audiograms performed on 2 seals (Thomas et al. 1990, Sills et al. 2021). Sills et al. (2021) reported that the range of best hearing of an adult male HMS was between 0.2 and 33 kHz, with a lower high-frequency roll-off (33 kHz) compared to other phocid species. This work demonstrated that HMS hear over a wider frequency range than previously understood, which might make HMS more susceptible to low-frequency anthropogenic noise disturbance. The same study revealed that a wild-born monk seal in human care produced 6 different low-frequency call types underwater year-round (Parnell 2018, Sills et al. 2021). This seal's vocal behavior (i.e. number of calls) and testosterone peaked simultaneously prior to the annual molt, suggesting that vocalizations are related to reproduction. These captive studies highlighted the significance of underwater sound production and reception for the HMS. Furthermore, ongoing research on the vocal behavior of free-ranging HMS suggests that acoustic communication plays an important role, but the biological function of the different underwater vocalizations is still unknown. Continued investigations on the vocal behavior of free-ranging HMS and the soundscapes of their critical habitats are needed to achieve a comprehensive understanding of HMS acoustic communication and the potential spatial and temporal overlap with anthropogenic noise.

The expansive range of the HMS, stretching over 2500 km from the Island of Hawaiʻi in the southeast to Kure Atoll (Hōlanikū) in the northwest (Carretta et al. 2023), offers a unique opportunity to compare soundscapes in the presence and absence of anthropogenic activity. A growing population of approximately 400 seals inhabit the main Hawaiian Islands (MHI), where at-sea human activities are common (NOAA Fisheries 2023). These human activities include traffic in frequently used shipping lanes, recreational areas commonly used by visitors and residents in Hawaiʻi, as well as military exercises (e.g. Rim of the Pacific exercise [RIMPAC], the world's largest military exercise). The Northwestern Hawaiian Islands (NWHI), which lie within the Papahānaumokuākea Marine National Monument (PMNM), are home to approximately 1200 seals (NOAA Fisheries 2023). This population is rarely exposed to direct human activity due to restricted access to the PMNM except for regulated research and cultural activities (i.e. commercial and personal vessels are excluded here). Thus, these 2 contrasting locations provide an opportunity for baseline soundscape measurements and comparisons of HMS critical habitats.

Passive acoustic monitoring (PAM) is widely used to study marine mammal occurrence, distribution, behavior, population structure, abundance, and ecology (Mellinger et al. 2007, Van Parijs et al. 2009). PAM efforts in Hawaiian waters have been ongoing since the 1970s for cetacean research including humpback whales *Megaptera novaeangliae* (Payne & McVay 1971, Darling 1983, Tyack 1983, Au et al. 2000) and spinner dolphins *Stenella longirostris* (Heenehan et al. 2016, 2017a,b, Tyne et al. 2018, McElligott & Lammers 2021) and other resident odontocete species (Oleson 2021). Several PAM studies have characterized the soundscapes of Hawaiian nearshore coral reef environments—some of which are underwater critical habitats of the HMS. These studies report that snapping shrimp (Family Alpheidae) dominate and shape the soundscape along with other commonly recorded biological sources which contribute to diel and seasonal patterns (e.g. soniferous reef fish, humpback whales) (Lammers et al. 2008, Au et al. 2012, Lammers & Munger 2016, Kaplan et al. 2018). In contrast, anthropogenic sources shape the soundscape at spinner dolphin resting bays (Heenehan et al. 2017c) and in offshore, deep-water environments off Hawaiʻi Island (Merkens et al. 2021). Although these PAM studies provide foundational knowledge of various underwater soundscapes throughout the Hawaiian archipelago, there is currently no standardized measurement of baseline ambient sound levels within HMS critical habitats, and no studies have considered how HMS vocalizations contribute to the soundscape.

This study aims to describe the spatial, temporal, and frequency characteristics of underwater soundscapes and assess the contributing natural and anthropogenic sources of noise at 4 critical habitats of the HMS. Using continuous passive acoustic recordings from 179 d, we calculated baseline measurements of sound pressure levels (dB re 1 µPa; 'level' will be used throughout) from 20–24 000 Hz and characterized spatial and temporal patterns of geophysical, biological, and anthropogenic sources. This study expands upon our knowledge of underwater soundscapes at critical habitats of the HMS across its expansive range and can serve as a baseline for future studies to assess the impact of human activity on underwater soundscapes in Hawaiian waters.

2. MATERIALS AND METHODS

2.1. Study sites and habitat type

Acoustic recorders were deployed at 4 sites in 2020 and 2021: Rabbit Island (also known as Mānana Island) and Lehua Rock in the MHI, and French Frigate Shoals (also known as Lalo) and Pearl and Hermes Reef (also known as Manawai) in the NWHI (Fig. 1, Table 1). The NWHI sites were chosen based on the accessibility of a small research vessel for equipment deployment. The MHI sites were chosen based on high HMS sighting frequencies. All sites are designated critical terrestrial and aquatic habitats of the HMS (NOAA Fisheries 2015), and landing on these islands is prohibited except for research and cultural activities with appropriate permits. All islands in the Hawaiian Archipelago host marine critical habitat for HMS, which is defined as 'the seafloor, all subsurface waters, and marine habitat within 10 m of the seafloor from the 200-m depth contour line to the water's edge 5 m into the terrestrial environment from the shoreline' (NOAA Fisheries 2015).

Habitat types for Rabbit Island and Lehua Rock were categorized by viewing high-resolution GoPro videos of the deployment locations and comparing with descriptions from Winston et al. (2019). GoPro videos were taken directly after deployment of the recording equipment by snorkelers. Visibility at these sites was >10 m on deployment day and therefore video footage was sufficient to categorize habitat types. Habitat-type classifications for French Frigate Shoals and Pearl and Hermes Reef were determined using maps depicting benthic habitats from high-resolution IKONOS satellite imagery (National Centers for Coastal Ocean Science 2022a,b).

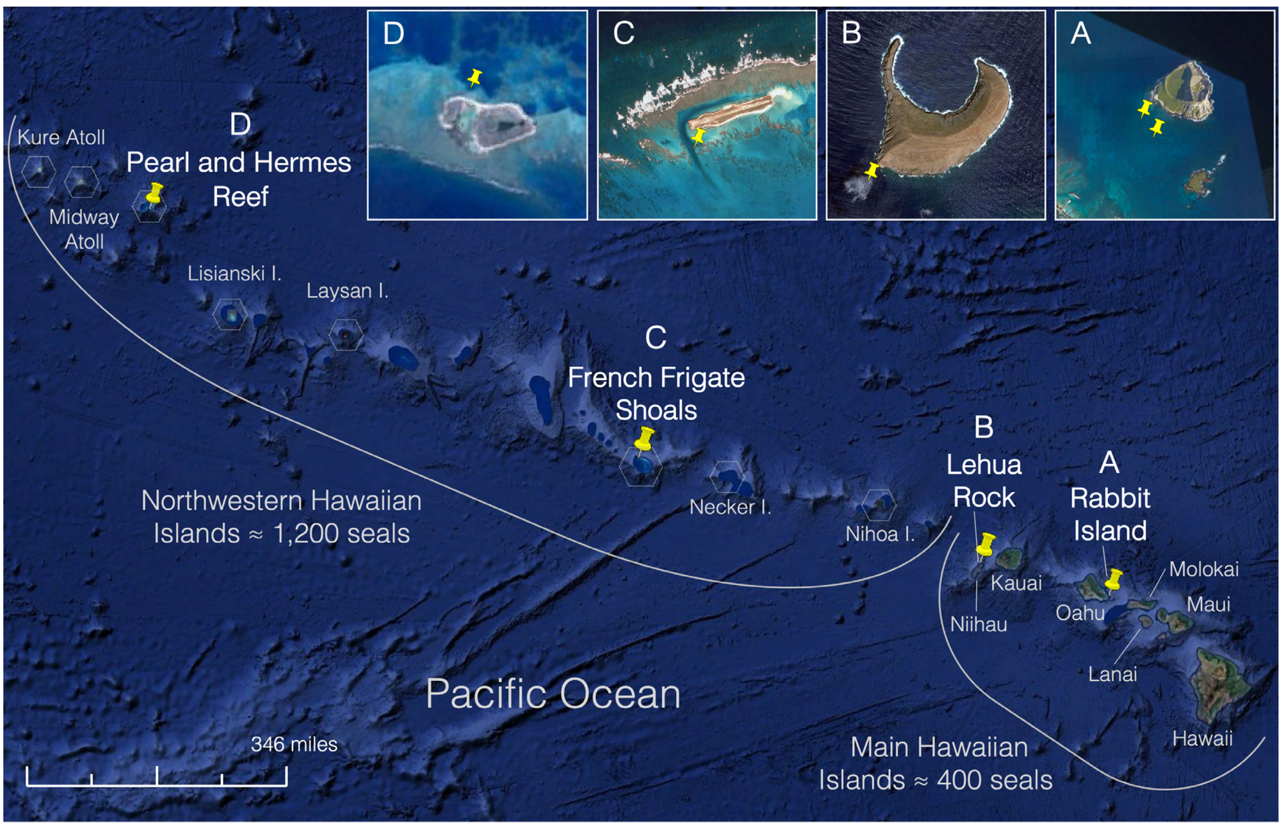

Fig. 1. Hawaiian Archipelago; yellow pins indicate the 4 underwater acoustic monitoring locations at Hawaiian monk seal critical habitats: (A) Rabbit Island, O'ahu; (B) Lehua Rock; (C) Tern Island, French Frigate Shoals; (D) Southeast Island, Pearl and Hermes Reef. Satellite images obtained from Google Earth Pro

Table 1. Acoustic monitoring efforts using a SoundTrap 500HF at 4 underwater critical habitats of the Hawaiian monk seal over 2 field seasons (2020 and 2021). The SoundTrap at Lehua Rock was deployed deeper than the other recorders due to the bathymetry of the site. This recorder was damaged after 6 d of deployment

Site	GPS	Depth (m)	Deployment dates	No. of days recorded
Rabbit Island (**Rabbit1**)	21° 19.503′ N, 157° 39.624′ W	7.9	22 July 2020–18 Aug 2020	27
Rabbit Island (**Rabbit2**)	21° 19.611′ N, 157° 39.689′ W	6.7	22 July 2020–18 Aug 2020	27
Rabbit Island (**Rabbit3**)	21° 19.612′ N, 157° 39.688′ W	6.7	31 Aug 2021–20 Oct 2021	50
Lehua Rock	22° 00.881′ N, 160° 06.194′ W	19.8	10 May 2021–28 May 2021	6
French Frigate Shoals	23° 51.984′ N, 166° 17.321′ W	7.9	23 July 2021–5 Sept 2021	45
Pearl and Hermes Reef	27° 47.523′ N, 175° 49.153′ W	8.2	8 Aug 2021–18 Sep 2021	24

Rabbit Island is an uninhabited islet located 1.5 km off the east coast (windward side) of Oʻahu within the MHI. This site has limited vessel activity compared to the leeward side of Oʻahu. Vessel traffic at Rabbit Island is mostly composed of small boats used for recreational fishing and human-powered devices such as kayaks and surfboards. Anthropogenic noise was documented throughout the entire 27 d recording period at this site in 2020 and vessel noise was only detected on 6 d. Rabbit Island has one of the highest HMS sighting frequencies of Oʻahu beaches (Pacific Islands Fisheries Science Center 2023). In 2020, 2 acoustic recorders were deployed 270 and 226 m offshore of Rabbit Island on the protected landward (southwest) side at sites Rabbit1 and Rabbit2, respectively. These recorders were parallel to the shoreline and separated by 227 m. One recorder was redeployed in 2021 at site Rabbit2 and is referred to as Rabbit3. Site Rabbit1 is an aggregate patch reef habitat (Fig. 2A), and sites Rabbit2 (Fig. 2B) and Rabbit3 (Fig. 2C) are reef rubble habitats.

Lehua Rock is an uninhabited island 1.1 km north of Niʻihau and 31 km west of Kauaʻi. The HMS population estimate for Niʻihau and Lehua was 154 in 2020 (Carretta et al. 2023). One recorder was deployed at a well-known SCUBA diving site approximately 50 m from the mooring at the edge of a shelf break that drops to 200 m depth. This dive site is anecdotally known for the opportunity to observe HMS vocalizing and exhibiting potentially territorial behavior. The recorder at Lehua Rock was placed on pavement habitat (flat, low-relief, solid rock) with minimal and sporadic coral cover (Fig. 2D).

French Frigate Shoals is in the NWHI within the PMNM. It is a crescent-shaped atoll approximately 900 km northwest of Honolulu and is one of 6 field stations of the Hawaiian Monk Seal Research Program (HMSRP). The HMS population estimate at French Frigate Shoals was 221 individuals in 2019 (Carretta et al. 2023). One recorder was deployed 155 m south of Tern Island in the northwest corner of the atoll. The recorder was placed at the base of an uncolonized patch reef.

Pearl and Hermes Reef is in the NWHI within the PMNM. It is 2090 km northwest of Honolulu and is one of 6 field stations of the HMSRP. The HMS population estimate at Pearl and Hermes Reef was 141 individuals in 2019 (Carretta et al. 2023). One recorder was deployed 110 m north of Southeast Island, the largest island within the atoll. The recorder was deployed in an unconsolidated sediment habitat (Fig. 2E).

2.2. Audio recording

Underwater acoustic recordings were obtained using 3 separate SoundTrap 500HF recorders (0.02–150 kHz, ±3 dB; Ocean Instruments). Each SoundTrap and its corresponding hydrophone had a unique flat frequency sensitivity which was accounted for in the analysis process. The SoundTraps were programmed to record continuously at a sampling rate of 96 kHz. The SoundTraps were secured horizontally to concrete blocks and placed on the seafloor where the hydrophone was approximately 0.15 m from the substrate (Fig. 2D). At French Frigate Shoals and Pearl and Hermes Reef, a line with a buoy was connected to the concrete block (Fig. 2E). All SoundTraps were deployed at depths between 6.7 and 19.8 m (Table 1), within the typical diving range of HMS (<50 m; Robinson et al. 2022). The SoundTraps were not deployed simultaneously due to logistical constraints. Lehua Rock is only accessible during the summer months, when weather conditions are favorable. The NWHI recorders were deployed in the summer when the HMSRP field camps were stationed.

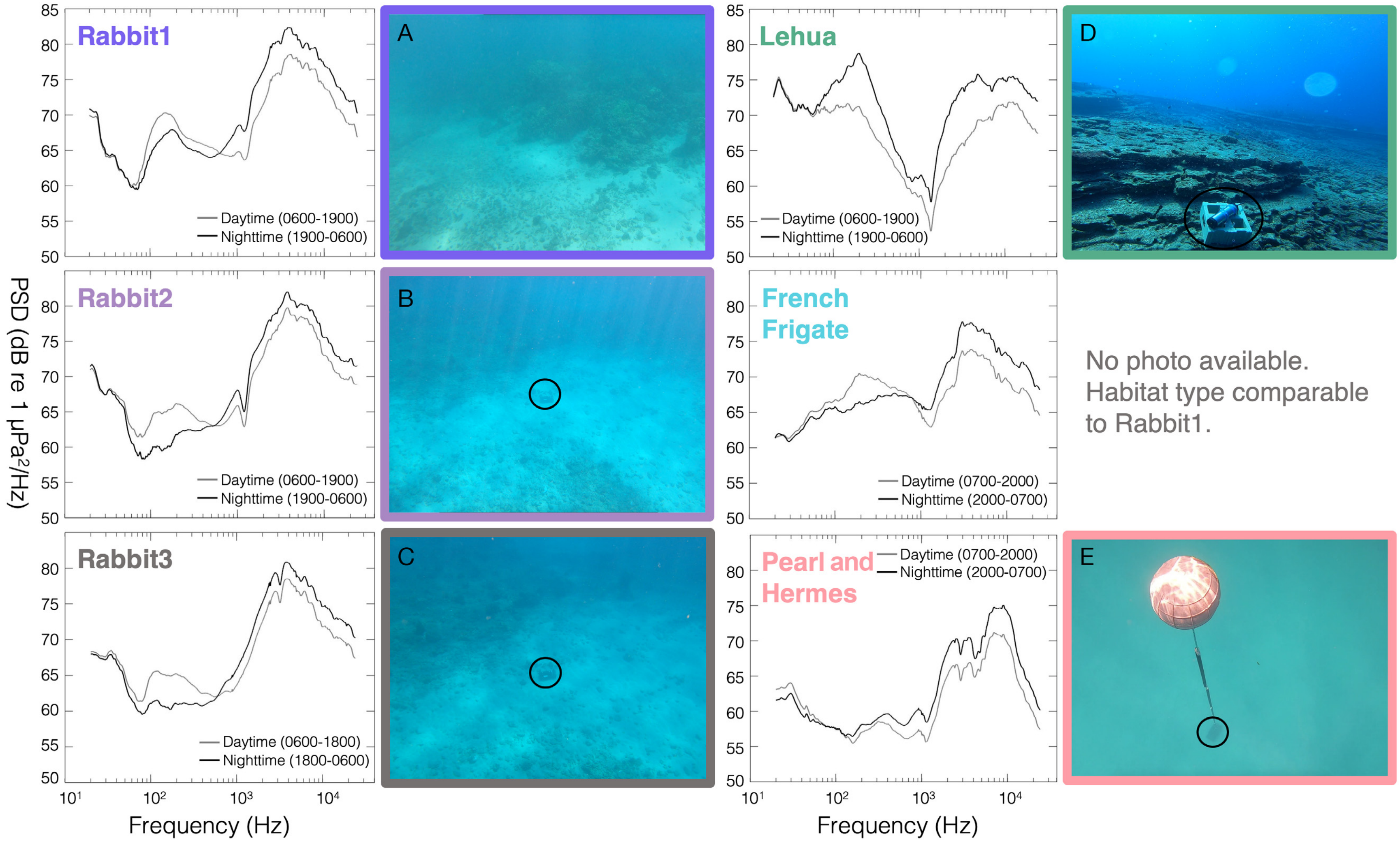

Fig. 2. Daytime and nighttime median power spectral density (PSD) levels from 20–24000 Hz at Rabbit Island (Rabbit1, Rabbit2, Rabbit3), Lehua Rock, French Frigate Shoals, and Pearl and Hermes Reef. Rabbit2 and Rabbit3 are the same sites, but recordings occurred in 2020 and 2021, respectively. (A–E) Photos of the habitat type with the outline color representing the deployment location; black circles indicate the SoundTraps. (A) Site Rabbit1 was aggregate patch reef habitat (SoundTrap not pictured here); (B) Rabbit2 was reef rubble habitat; (C) Rabbit3 was reef rubble habitat; (D) Lehua was pavement with minimal and sporadic coral cover; and (E) Pearl and Hermes was unconsolidated sediment habitat. Photographs of the habitat type were not taken at site French Frigate, which was uncolonized patch reef

2.3. Acoustic analyses

Passive acoustic data were analyzed in the Soundscape Metrics remora in Triton (version 1.93.20160524; Scripps Whale Acoustics Lab) using MATLAB R2021b to create long-term spectral averages (LTSAs; Wiggins & Hildebrand 2007) and R2018b to compute soundscape metrics. The methods described below are used by the National Oceanic and Atmospheric Administration (NOAA) Sanctuary Soundscape Monitoring Project, SanctSound (McKenna et al. 2021). LTSAs were computed in 1 s Hz^{-1} frequency bins for the duration of each deployment excluding 2 h after deployment and 2 h before retrieval to avoid including our boat noise. Using these LTSAs, broadband and octave band levels, and power spectral density (PSD) were computed using the Soundscape Metrics remora. To obtain a baseline measurement of ambient sound levels, we computed hourly median broadband levels over the frequency band of 20–24 000 Hz and averaged over the duration of deployment at each site. Hourly median octave band levels were computed for each of 10 octave bands (International Organization for Standardization 2017), with center frequencies ranging from 31.5–16 000 Hz. We reported sound levels from 5 octave bands: 31.5, 250, 500, 1000, and 16 000 Hz, which represent the main frequencies produced by different sound sources that are likely to be present at these sites. For example, the 1000 and 16 000 Hz octave bands represent the frequencies produced by snapping shrimp, whereas the 250 and 500 Hz octave bands represent anthropogenic and other biological sounds. Hourly PSDs were computed for every 1 Hz band from 20–24 000 Hz. Sunrise and sunset times were determined for each site and the deployment period using data from the United States Naval Observatory and the National Aeronautics and Space Administration via www.timeanddate.com and rounding up or down to the nearest hour.

Finally, we audio-visually inspected LTSAs and spectrograms to confirm sound sources. Signals were examined by trained analysts (K. Parnell, K. Merkens) and classified into sound-source groups and species or species groups when possible. Detected signals were compared to published data on the acoustics of snapping shrimp (Au & Banks 1998), Hawaiian monk seal vocalizations (Sills et al. 2021), Hawaiian coral reef fish (Tricas & Boyle 2014), humpback whales (Au et al. 2000), and the mesopelagic boundary community (MBC; Lammers et al. 2011).

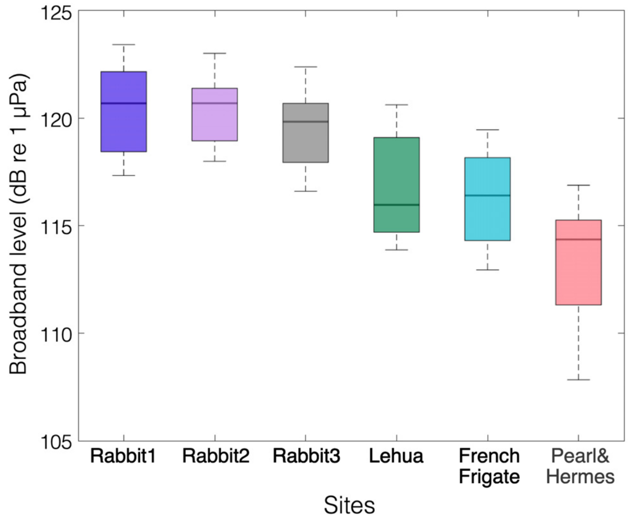

Fig. 3. Hourly median broadband levels averaged across the deployment duration at 4 critical habitats of the Hawaiian monk seal. Lines within the boxes: median; bottom and top of each box: 25th and 75th percentiles; whiskers: minimum and maximum values

3. RESULTS

To describe the underwater soundscape of HMS critical habitats, we collected 179 d (4296 h) of acoustic recordings from shallow-water environments (Table 1).

3.1. Acoustic analyses

3.1.1. Broadband levels

Broadband median levels measured at our 4 study sites ranged from 107.8–123.4 dB re 1 μPa (Fig. 3). Rabbit Island exhibited the highest levels compared to all other sites. These levels may reflect differences in habitat type: Rabbit Island, which is an aggregate patch reef and reef rubble habitat, showed higher levels than pavement, uncolonized patch reef, and unconsolidated sediment habitats at Lehua Rock, French Frigate Shoals, and Pearl and Hermes Reef, respectively.

3.1.2. Octave band levels

Octave band levels increased with increasing frequency (Table 2). The 31.5 Hz octave band had the lowest levels at all sites, whereas the 16 000 Hz octave band showed the highest levels at all sites. Octave band levels exhibited strong diel patterns, except for the 31.5 Hz band. In the low-frequency octave bands of 31.5 Hz (except at Rabbit1) and 250 Hz (except at Lehua and Pearl and Hermes), levels were higher dur-

Table 2. Average daytime and nighttime octave band levels (dB re 1 µPa) and differences at 4 critical habitats of the Hawaiian monk seal. Gray cells indicate that nighttime levels were higher than daytime levels. Daytime values are averaged from all hours between sunrise and sunset. Nighttime values are averaged from all hours between sunset and sunrise

Octave	Rabbit1			Rabbit2			Rabbit3			Lehua			French Frigate			Pearl & Hermes		
band (Hz)	Day	Night	ΔdB	Day	Night	ΔdB	Day	Night	ΔdB	Day	Night	ΔdB	Day	Night	ΔdB	Day	Night	ΔdB
31.5	81.0	81.2	0.2	83.3	83.1	0.2	82.4	81.9	0.5	87.8	87.4	0.4	76.9	76.6	0.3	77.5	76.1	1.4
250	91.5	90.0	1.5	89.2	86.3	2.9	88.2	85.1	3.1	93.3	99.9	6.6	94.1	90.0	4.1	82.0	82.7	0.7
500	92.3	91.4	0.9	90.3	90.2	0.1	89.3	88.9	0.4	90.6	93.7	3.1	95.6	94.7	0.9	84.3	85.8	1.5
1000	94.7	97.9	3.2	95.2	97.3	2.1	94.6	96.8	2.2	88.1	90.6	2.5	95.0	96.1	1.1	87.0	89.9	2.9
16000	112.5	115.4	2.9	112.3	114.6	2.3	112.0	114.8	2.8	111.7	115.6	3.9	109.2	112.6	3.4	104.8	108.3	3.5

ing the day than at night. In the high-frequency octave bands (1000 and 16 000 Hz), nighttime levels displayed an opposite trend and were greater than daytime levels.

3.1.3. Spectral analysis

PSD analysis revealed temporal and habitat type differences. At all sites, acoustic energy between 1500 and 24 000 Hz was higher at night and peaked between 3000 and 9000 Hz (Fig. 2). Acoustic energy between 50 and 600 Hz was higher during the day at all Rabbit Island sites and at French Frigate Shoals, which are all reef habitats. Lehua Rock, a pavement habitat, was the only site where low-frequency energy was higher at night. The noticeable dip in acoustic energy near 1100 Hz at Lehua Rock was due to fewer sounds produced at that frequency. Pearl and Hermes Reef, an unconsolidated sediment habitat, showed the lowest acoustic energy at all frequencies.

3.2. Identification of sound sources and their influence on the soundscape

3.2.1. Biological sources

Biological sources dominated the soundscape at all sites. Elevated levels in the 16 000 Hz octave band at all sites and in the 1000 Hz octave band at Rabbit Island were attributed to snapping shrimp that produced a visible diel pattern that peaked at night (Fig. 4A,C, see Fig. 6A). At Rabbit Island (Fig. 4A,C) and French Frigate Shoals, the 250 Hz octave band levels peaked in the daytime and were likely attributed to sounds produced by unidentified fish species (Fig. 5). At Lehua Rock, the 250 and 500 Hz octave bands showed similar diurnal patterns in levels (Fig. 6). Energy at these frequencies peaked from 10:00−11:00 h, 20:00−21:00 h, and to a lesser extent from 03:00−05:00 h (all local time). The peaks from 10:00−11:00 h can be attributed to a combination of anthropogenic sources and HMS vocalizations (Fig. 6A,B). The peaks from 03:00−05:00 h and from 20:00−21:00 h are potentially an acoustic byproduct of the vertical migration of the MBC. From 22:00−03:00 h, the elevated levels in the 250 Hz octave band are attributed to high-amplitude HMS vocalizations (Fig. 6C). Additional peaks in the 500 Hz octave band throughout the night are representative of broadband knocking sounds from unidentified fish. On 11 May, a second daytime peak is visible in the 250 and 500 Hz octave bands and was a result of overlapping humpback whale song and HMS vocalizations (Fig. 6C).

3.2.2. Geophysical sources

Two large-scale geophysical events were recorded acoustically at Rabbit Island. On 10 October 2021, a 6.2 magnitude earthquake struck off Hawaiʻi Island (https://earthquake.usgs.gov/earthquakes/eventpage/hv72748782/executive). The increase in power in the 31.5 Hz octave band (Fig. 4A) around this event may be associated with nearby seismic activity from 8−17 October 2021 ('View Nearby Seismicity' on the USGS page via the above URL). The emitted seismo-acoustic wave energy would peak at infrasonic frequencies but could be detected in the 31.5 Hz octave band. On 26 July 2020, we recorded a 26 dB increase in the 31.5 Hz octave band as hurricane Douglas passed 48 km north of Oʻahu, with a peak sound pressure level of 106.2 dB (Fig. 4C). The increase in low-frequency power with severe weather is expected and well documented (e.g. Urick 1983).

3.2.3. Anthropogenic sources

Anthropogenic noise sources detected in this study include ecotourism (vessels and SCUBA divers), re-

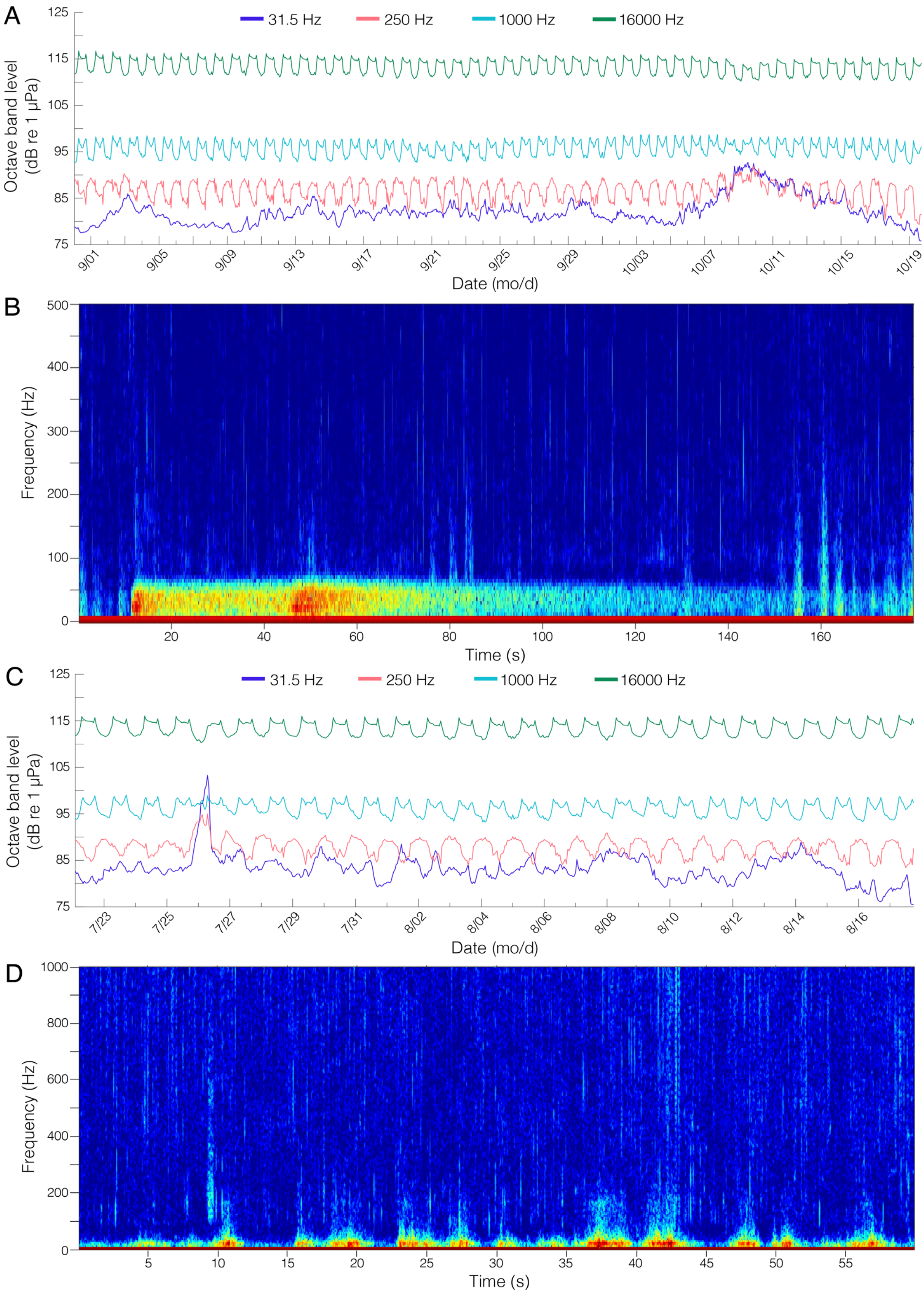

Fig. 4. (A) Average median octave band levels at Rabbit Island, Oʻahu, from 31 August–20 October 2021. The date labels on the *x*-axis mark 12:00 h (noon, local time). The SoundTrap 500HF was deployed on a sand patch in a reef rubble habitat. An increase in low-frequency sound represented by the 31.5 Hz octave band is visible days before, during, and after a 6.2 magnitude earthquake occurred 23 miles (37 km) southeast of Hawaiʻi Island on 10 October 2021. (B) Spectrogram of the low-frequency seismo-acoustic arrivals induced by the earthquake (red and orange pulses between 10 and 80 s). The 3 pulses near 160 s are large ocean waves incident on Rabbit Island; such sounds are common geophonics at this location. (C) Average median octave band levels at Rabbit Island from 22 July–18 August 2020. The peak in the 31.5 Hz octave band on 26 July occurred as Hurricane Douglas passed 48 km north of Oʻahu. (D) Spectrogram of the low-frequency sound produced by waves colliding with Rabbit Island as the hurricane passed. Spectrogram settings for windows (B) and (D): Hanning window, NFFT size 16384, 90% overlap

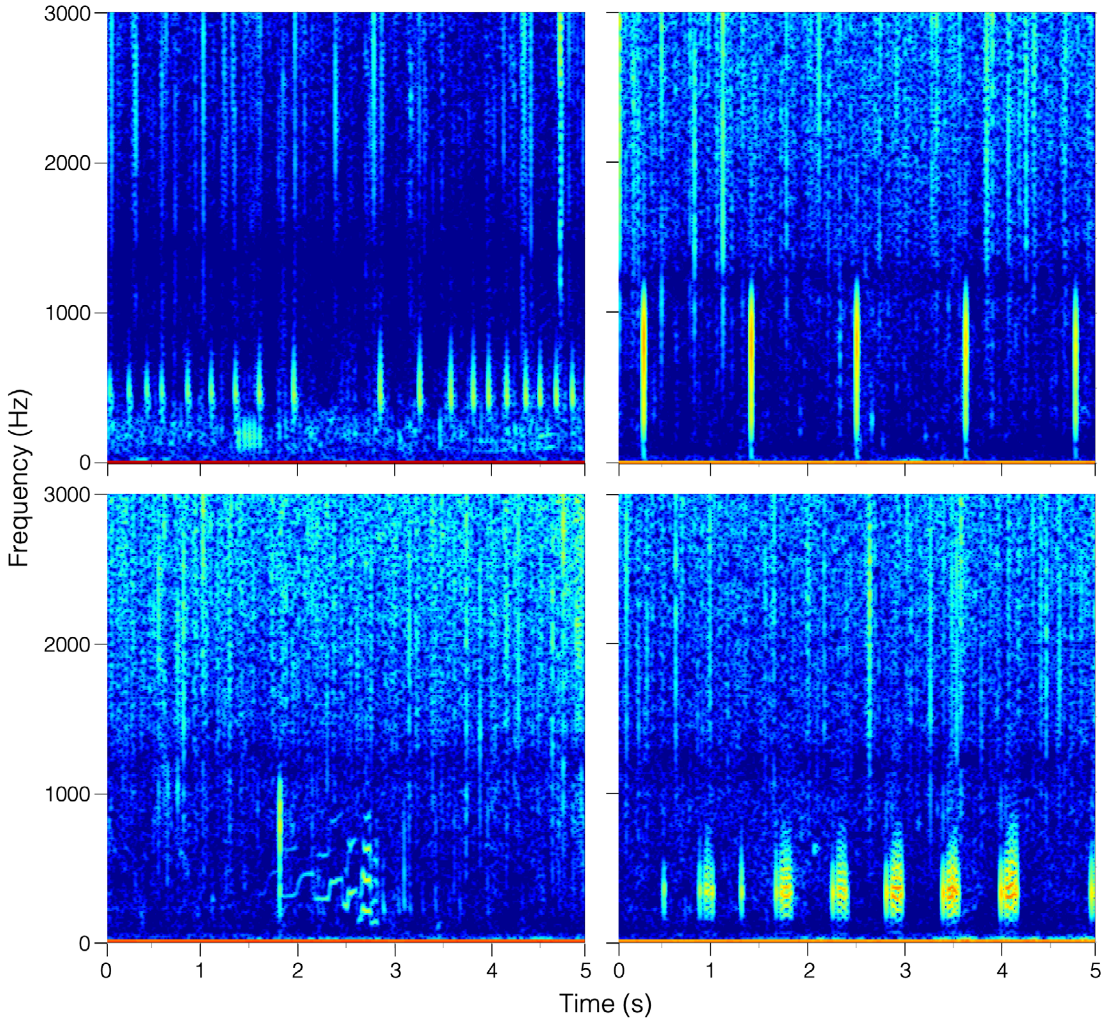

Fig. 5. Spectrograms showing 4 commonly observed fish sounds (below 1100 Hz) recorded at Rabbit Island and Lehua Rock. Snapping shrimp sounds are visible from ~1200 Hz and above. Spectrogram settings for all windows: Hanning window, NFFT size 8192, 90% overlap

search and private boats, and aircraft. At Rabbit Island, vessel noise and unidentified aircraft were infrequently detected. The daytime soundscape of Lehua Rock was heavily influenced by anthropogenic sources. On 5 of 6 days, the 250 and 500 Hz octave bands peaked from 10:00–11:00 h due to a combination of SCUBA divers, boat(s), and HMS underwater vocalizations (Fig. 6). The major source of the peak in the 250 Hz octave band at 10:00 h was attributed to bubbles produced by SCUBA divers during exhalations (Fig. 7). Boat noise, identified through visual inspection of spectrograms, was present during these times on most days, but it was short-lived and sporadic. On 13 May, there were no boats detected and therefore no daytime peak in the 250 and 500 Hz octave bands. The difference in levels in the 250 Hz octave band at 10:00 h between days with boats present (n = 5) and the single day without boats was 7.1 dB. At French Frigate Shoals and Pearl and Hermes Reef, engine noise produced by small research vessels was detected periodically (approximately twice per day). Boat noise and bubbles produced by SCUBA divers acoustically masked the underwater vocalizations of HMS (Fig. 7). Acoustic masking occurs when noise impedes one's ability to understand, recognize, or detect signals of interest, and is considered a threat to marine mammals (Clark et al. 2009).

4. DISCUSSION

Considering the lack of information on HMS acoustic behavior and their endangered status, we aimed to describe the underwater soundscapes at 4 critical habitats in 2 areas with notably different amounts of human activity: the MHI (~1.4 million inhabitants)

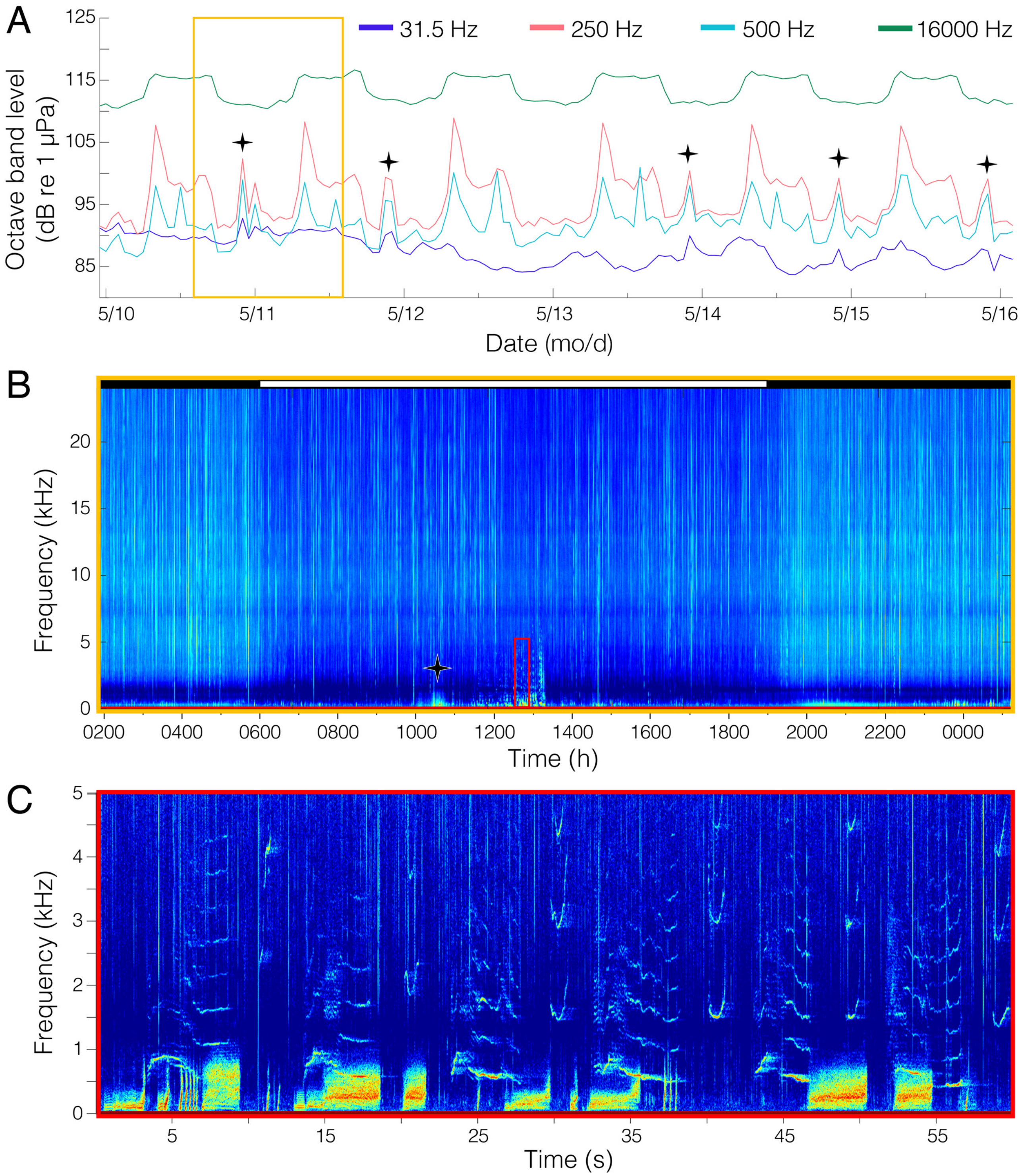

Fig. 6. (A) Average median octave band levels at Lehua Rock from 10–16 May 2021. The date labels on the *x*-axis mark 12:00 h (noon, local time). Sunrise was at 06:00 h and sunset was at 19:00 h. Black stars indicate the presence of boats and SCUBA divers. The yellow box outlines the 24 h period shown in the long-term spectral average (LTSA) in (B). (B) LTSA of a 24 h period on 11 May 2021. The black star at 10:30 h indicates boats and SCUBA divers. Black bars at the top indicate nighttime; white bar indicates daylight. Humpback whale song is present from 11:45–13:15 h. The low-frequency noise from 20:00–22:00 h corresponds with the daily spike in the 250 Hz octave band. The red box at 12:45 h outlines the approximate location of the 60 s window shown in (C). (C) Spectrogram showing overlapping humpback whale song from 500–5000 Hz and Hawaiian monk seal vocalizations from 20–1000 Hz. Spectrogram settings: Hanning window, NFFT size 8192, 90% overlap

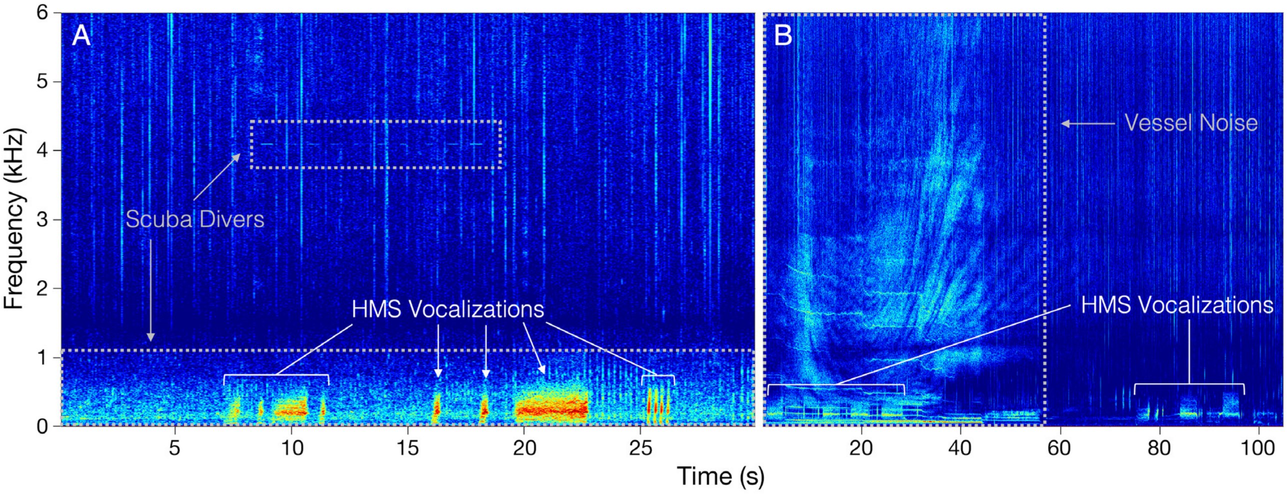

Fig. 7. (A) Spectrogram of Hawaiian monk seal (HMS) underwater vocalizations (7–12 s and 16–27 s, <500 Hz) overlapping with low-frequency bubble noise produced during SCUBA diver exhalation at Lehua Rock. The 4 kHz tone resembles beeping from an underwater camera. (B) Spectrogram showing engine noise from a small research boat (0–55 s, 0–6 kHz) partially masking the underwater vocalizations of HMS (0–30 s, <500 Hz) at Pearl and Hermes Reef. Note that no acoustic masking occurred after 60 s where HMS vocalizations were easily detectable within the ambient sound. Spectrogram settings: Hanning window, NFFT size 16384, 90% overlap

and the NWHI within the PMNM (limited, seasonal inhabitants for scientific and cultural purposes). We measured broadband ambient sound levels, described temporal patterns in various frequency bands, and characterized sonic sources that shape and/or contribute to the soundscapes.

4.1. Biological sources dominated the soundscape at all sites

Broadband levels were generally high in these nearshore reef environments, and they varied slightly with habitat type. Broadband levels were the highest in coral reef environments and lower in pavement and sand habitats (Fig. 3). The elevated levels within coral reef environments (Rabbit1, Rabbit2, Rabbit3) are attributed to biological sources including snapping shrimp (Family Alpheidae) that produce loud, impulsive, broadband clicks (~2 to >200 kHz) (Au & Banks 1998), and soniferous fish species (250 and 500 Hz octave bands) living within the reefs. Broadband levels at these coral reef sites are comparable to broadband levels measured at Gray's Reef on the US Atlantic Coast (McKenna et al. 2021, Stanley et al. 2021). Although the levels reported here are relatively high in comparison to other underwater environments (see McKenna et al. 2021 for broadband levels within US National Marine Sanctuaries), this may be indicative of healthy reef habitat in Hawai'i, as biological sources dominated these soundscapes.

4.1.1. Snapping shrimp

Strong diel patterns were observed at all sites throughout the deployment periods in all octave bands except 31.5 Hz. Nighttime levels in the 1000 and 16 000 Hz octave bands were greater than daytime levels at all sites (Table 2), primarily due to snapping shrimp activity (Fig. 6B). Snapping shrimp produce the most ubiquitous sounds found on tropical and subtropical reefs during feeding and territorial defense behaviors (Au et al. 2012, Lammers & Munger 2016). This loud, impulsive, broadband sound increased ambient sound levels by 3.1 dB on average at night across all sites, a pattern consistent with studies from other shallow-water reefs (Albers 1965, Staaterman et al. 2013, Nedelec et al. 2015, Lammers & Munger 2016). Underwater soundscapes provide vital communication signals and important cues on habitat quality (McKenna et al. 2021). Reef sounds — including snapping shrimp sounds — are used by larval reef fish and invertebrates to orient towards settlement areas (Tolimieri et al. 2000, Jeffs et al. 2003, Radford et al. 2007), and juvenile reef fish use acoustic orientation to distinguish between various reef habitats (Radford et al. 2011). Moreover, Gordon et al. (2019) demonstrated that the playback of healthy reef sounds at degraded reef sites increased fish settlement and retention, leading to enhanced fish community development, which might aid in ecosystem recovery (Gordon et al. 2019).

4.1.2. Fish

Strong diurnal patterns in the 250 Hz octave band were found within coral reef environments at Rabbit Island and French Frigate Shoals, where fish sounds dominated the daytime soundscape. Similarly, McKenna et al. (2021) observed diurnal patterns in the 500 Hz octave band in the Florida Keys National Marine Sanctuary and in the 125 Hz octave band in the Channel Islands National Marine Sanctuary. These patterns were attributed to chorusing plainfin midshipman *Porichthys notatus* (McKenna et al. 2021). At Lehua Rock, high-amplitude broadband pulses produced by fish shaped the 500 Hz octave band at night. Tricas & Boyle (2014) found that 45 species of Hawaiian coral reef fish produce underwater sounds associated with agonistic interactions and resource defense, reproduction, nest defense, feeding, and vigilance behaviors (Tricas & Boyle 2014). Although the fish sounds recorded in this study were not identified to species level, they are clearly an important part of Hawaiian coral reef soundscapes. Healthy reefs boast a wide variety of soniferous fishes and invertebrates (Lamont et al. 2022), both of which are common prey of the Hawaiian monk seal (Cahoon 2011). With the development of soundscape metrics (e.g. acoustic complexity indices and sound pressure level) as indicators of coral reef ecosystem health (Lamont et al. 2022), one could potentially analyze these recordings to identify healthy foraging habitat for Hawaiian monk seals.

4.1.3. Mesopelagic boundary community

At Lehua Rock, the 250 Hz octave band displayed an interesting pattern at night that was not observed at other study sites. Sound levels in this band peaked from 20:00–21:00 h at 108.1 dB, and again from 03:00–05:00 h at 99.6 dB. The source of this high-amplitude, continuous sound was difficult to identify but may be produced by the vertical migration of the MBC (Lammers et al. 2011). Benoit-Bird et al. (2001) showed that the MBC relative abundance and density off Oʻahu and Hawaiʻi peaked around 21:00 and 03:00 h (Benoit-Bird et al. 2001), which coincides with the timing in peak levels documented in our study. This sound was not observed at other study sites, most likely due to the placement of the recorders in shallow-water environments (<10 m). The recorder at Lehua Rock was placed at 20 m depth near a shelf break that drops to 200 m. The origin of this source is still ambiguous, and more research needs to be completed to determine the exact source of this sound. This finding highlights the importance of recorder placement within an environment.

4.1.4. Hawaiian monk seal vocalizations

Underwater vocalizations produced by HMS were detected at all sites. These vocal signals were low frequency (<1 kHz for high-amplitude calls) and short duration (<5 s), with similar frequency and temporal structure as underwater calls produced by 2 adult male HMS under human care (Parnell 2018, Sills et al. 2021). These calls contributed to elevated levels in the 250 Hz octave band, yet they did not shape the soundscape like snapping shrimp (continuous) and fish sounds because of their periodic detection rates (i.e. HMS vocalizations did not result in a diel soundscape pattern). The exception to this finding was at Lehua Rock, where high-amplitude vocalizations were observed consistently from 22:00–03:00 h, with a peak in vocal activity around midnight. The average sound level was 98.5 dB in the 250 Hz octave band during these hours. This intense vocal display at night suggests that Lehua Rock is an important habitat for HMS acoustic communication — likely for breeding purposes, although the exact biological function of vocalizations has not yet been determined. In general, sound levels (e.g. broadband and octave band) cannot be used to detect HMS presence or abundance but may be used to identify transient periods of intense HMS vocal activity. This study has shown that PAM is an effective tool for detecting the acoustic communication of an endangered marine mammal.

4.2. Geophysical sources were prevalent at Rabbit Island

Two geophysical events were acoustically recorded at Rabbit Island. On 26 July 2020, Hurricane Douglas (Category 4) passed 48 km north of Oʻahu and increased the 31.5 Hz octave band by 26 dB. Tripathy (2022) found that hurricanes in the US Mid- and South Atlantic Outer Continental Shelf (at depths >200 m) increased low-frequency ambient sound levels by 25 dB. Increases in ambient sound levels due to hurricanes are commonly attributed to wind–wave interactions (Wilson & Makris 2006, 2008, Zhao et al. 2014, Tripathy 2022). However, in our case, periodic wave sets striking the makai (sea) side of Rabbit Island resulted in this increase in low-frequency noise (Fig. 4C,D) (Garcés et al. 2006). Increased ambient sound levels due to hurricanes may mask the acoustic signals produced by marine mammals and have been shown to decrease the detection probability of their calls, which ultimately impacts population density estimates from passive acoustic recordings (Merkens et al. 2021, Tripathy 2022). However, the rarity of hurricanes in the Hawaiian Islands likely does not present a significant source of masking to the acoustic communication of HMS.

The second geophysical event recorded at Rabbit Island was a 6.2 magnitude earthquake centered off Hawaiʻi Island. The recorder at Rabbit Island was 350 km away from the epicenter of this earthquake. Earthquake sounds have been recorded up to 1000 km away from the epicenter (Heenehan et al. 2019). This earthquake happened 11 d after the volcanic eruption of Kīlauea, starting on 29 September 2021. During this geophysical event, low-frequency sounds (<50 Hz) were elevated days before, during, and after the 6.2 magnitude earthquake occurred (likely due to the occurrence of smaller earthquakes). Throughout the 50 d continuous recording at Rabbit Island, we manually confirmed the acoustic presence of 62 out of 136 earthquakes between 2.5 and 6.5 magnitude reported by the USGS (https://earthquake.usgs.gov/earthquakes/eventpage/hv72748782/executive). Our results suggest that geophysical activity, particularly earthquakes occurring during the ongoing eruption of Kīlauea, significantly increases low-frequency ambient sound for hundreds of kilometers from the epicenter. Considering that HMS settled in the Hawaiian Islands between 3.5 and 11.6 million years ago (Scheel et al. 2014), coincident with the geological formation of the MHI (i.e. periods of high tectonic activity), seals may have always been exposed to this natural and variable increase in low-frequency sound.

It is important to note that the recorders at Rabbit Island were deployed at a depth of less than 8 m, and the recorders were attached to a concrete block that rested on the seafloor. Therefore, the interface between the seafloor and the recorder likely played a role in the seismo-acoustic detection of low-frequency sounds, particularly in the 31.5 Hz octave band, including the 2 geophysical events discussed above.

4.3. Anthropogenic sources influenced the soundscape of Lehua Rock

Lehua Rock was the only site where anthropogenic noise significantly influenced the soundscape. Boat noise and SCUBA divers elevated levels in the 250 and 500 Hz octave bands by 7.1 and 7.3 dB, respectively. These elevated levels occurred between 10:00 and 11:00 h on 5 of the 6 d of recording. Lehua Rock is a popular SCUBA diving and snorkeling destination in the summer months, with at least 5 ecotourism companies based on Kauaʻi offering tours to this remote site. Although vessel noise was present and contributed to this increase in low-frequency noise, the major source of noise in the 250 Hz octave band was attributed to bubbles produced by SCUBA divers during exhalation. Erbe et al. (2016a) showed that bubbles produced as a by-product of SCUBA diving show regions of high power below 3 kHz. Although this is a localized sound source, it is chronic during summer months and its frequencies overlap with HMS vocalizations.

Considering the finding that Lehua Rock is an area with high levels of vocal activity, and thus likely an important habitat for breeding activities, the frequent occurrence of anthropogenic noise at this site may negatively impact seals via acoustic masking and/or alteration of vocal communication (Erbe 2012). Based on anecdotal evidence from ecotourism companies, seals are consistently present at this dive site where the recorder was deployed approximately 50 m from the mooring (i.e. there is physical overlap between seals and vessels suggesting that masking is occurring). Acoustic masking at Lehua Rock could impact HMS breeding behavior and thus reproductive success. Indeed, the increase in low-frequency noise at Lehua Rock masked HMS vocalizations (Fig. 7). Previous studies showed that noise from passenger ships reduced the detection distance of grey seal *Halichoerus grypus* underwater calls in the Baltic Sea (Bagočius 2014). Terhune et al. (1979) found a decrease in harp seal *Pagophilus groenlandicus* vocalizations coincident with vessel noise near whelping sites in the Gulf of St. Lawrence, which may have resulted from a change in seal vocalizations, acoustic masking, or the movement of seals away from the noisy area (Terhune et al. 1979). The biological functions of HMS vocalizations are still undetermined, but calls are thought to be related to reproduction because of their seasonality and timing in relation to the annual molt (Sills et al. 2021), which occurs after the breeding season for many phocid species (Würsig et al. 2018). As HMS breeding season peaks during the spring and summer months (Johnson & Johnson 1984, Johanos et al. 1994), concurrent with high levels of ecotourism at Lehua Rock, anthropogenic noise may present a barrier for successful vocal communication and reproductive behaviors among seals. Future PAM studies should aim to characterize the temporal overlap between anthropogenic noise and

HMS acoustic communication at Lehua Rock throughout the summer months to enable a detailed analysis of potential masking and behavioral impacts on seals.

4.4. Implications for HMS conservation

Despite numerous descriptions of Hawaiʻi's underwater soundscapes, this is the first report of free-ranging HMS vocalizations within these soundscapes. The absence of vocalizations from previous soundscape studies can potentially be explained by (1) the location of the recorders, deployed in deep waters where seals may not vocalize, (2) in locations where seal abundance is low, or (3) recording periods when seal vocal activity is low and/or masked by humpback whale calls.

Adult and large sub-adult male HMS are frequently observed 'patrolling' or 'cruising' beaches (i.e. swimming along the shoreline, presumably looking for females) while emitting in-air vocalizations (Miller & Job 1992, Robinson et al. 2022). These observations suggest that HMS are utilizing shallow-water habitats for acoustic communication and may not produce calls in deeper water (>50 m) where recorders from previous PAM studies have been deployed (McKenna et al. 2021, Merkens et al. 2021). Additionally, PAM studies completed in shallow-water reef habitats in the MHI — some within critical habitats of HMS — may lack seal vocalizations due to the low abundance of HMS on those islands at the time of data collection. The population of seals in the MHI (excluding Lehu and Niʻihau) was estimated to be between 77 and 179 from 2005–2016 (Pacific Islands Fisheries Science Center 2007, 2015, 2018), while PAM studies on Hawaiʻi Island, Maui, and Oʻahu were conducted (Lammers et al. 2008, Heenehan et al. 2017c, Kaplan et al. 2018). Now that the MHI population (including Lehua and Niʻihau) is estimated at 381 seals with a growing population (Pacific Islands Fisheries Science Center 2023), ongoing and future PAM studies in critical habitats may record seal vocalizations more frequently. Lastly, HMS vocalizations may have been recorded but undetected due to acoustic masking by humpback whale songs whose frequencies overlap with HMS vocalizations (Lammers & Munger 2016).

The current study showed that HMS vocalizations are a common sound source found within shallow-water soundscapes throughout the Hawaiian Archipelago and the species should be further investigated to better understand their vocal behavior. This PAM dataset is currently being analyzed to determine the call repertoire and temporal or seasonal patterns in sound production for free-ranging HMS. Thus far, we have detected over 20 000 vocalizations and documented calls throughout the day at 3 sites (authors' unpubl. data), which suggests that acoustic communication is important for HMS.

Filling the knowledge gap regarding the underwater sonic environment of an endangered species is important because marine mammals use hearing as their primary sensory modality, and certain anthropogenic noise can negatively impact their behavior, communication, and physiology (Richardson et al. 1995, Nowacek et al. 2007, Erbe et al. 2018). For pinnipeds, underwater anthropogenic noise can cause permanent or temporary shifts in hearing (Kastak et al. 1999, 2005, Hastie et al. 2015, Reichmuth et al. 2019), mask vocalizations (Erbe et al. 2016b, Sills & Reichmuth 2016), decrease communication space (Bagočius 2014, Casey et al. 2016), and induce behavioral responses including changes to vocalizations (Terhune et al. 1979, Costa et al. 2003, Götz & Janik 2011, 2016, Anderwald et al. 2013, Hastie et al. 2014, Russell et al. 2016, Mikkelsen et al. 2019). Only one of 4 critical habitats examined here was determined to host elevated levels of anthropogenic activity (Lehua Rock). However, the recording periods were not temporally aligned across sites, relatively short in duration, and overlapped with the COVID-19 pandemic so it is possible that other sites may also be impacted by anthropogenic activities. Nevertheless, with a growing HMS population in the MHI (NOAA Fisheries 2023) and a general increase in human activities, more seals will be exposed to anthropogenic noise and its potential deleterious effects in the future.

This study highlights the effectiveness of marine protected areas — specifically the PMNM — for aiding in the conservation of an endangered species and its critical habitats. Given that the PMNM has restricted access except for specific purposes (e.g. research, cultural practices, habitat restoration), anthropogenic noise is not likely to present a threat to seals in these remote critical habitats where the population is generally stable. Results from this study showed that while vessel noise was infrequently present at 2 sites within the PMNM, this was a byproduct of small research boats that were used for HMS research and survival-enhancing interventions during NOAA's HMSRP field season (e.g. translocations, disentanglement, and dehooking; Harting et al. 2014). This sound source did not influence the soundscape at either study site. Conversely, within the MHI where the HMS population is increasing, we found that anthropogenic sources from recreational vessels influenced the soundscape at Lehua Rock and were commonly recorded at Rabbit Island. In comparable shallow coastal waters of Denmark, recreational vessels dominated the soundscape, leading to a 47–51 dB increase in third-octave band noise centered at 0.125, 2, and 16 kHz (Hermannsen et al. 2019). Our results showed that vessel noise acoustically masks HMS vocalizations at Lehua Rock and is likely occurring elsewhere within the MHI where vessel traffic is high. Therefore, management measures to mitigate noise impacts may need to be considered.

4.5. Study limitations and future directions

Acoustic recordings obtained during this study were continuous, relatively short-term (between 6 and 50 d), and not simultaneous. Therefore, seasonality cannot be excluded from the observed differences in broadband levels shown here. However, we expect limited seasonal differences based on the tropical climate with stable environmental conditions year-round and sampling during 2 sequential seasons (spring and summer) (see Fig. 3 in Merkens et al. 2021). We also expect limited differences in HMS vocalizations between spring and summer as this timing correlates with peak breeding season and therefore increased calling behavior. Nonetheless, it would be advantageous to record for longer durations and simultaneously to assess seasonal patterns within the soundscape, including temporal patterns in HMS vocalizations, and to perform long-term monitoring of important reef habitats throughout Hawaiʻi.

With the development of automated call detectors for marine mammal sounds (Allen et al. 2021, Miller et al. 2021, White et al. 2022), long-term PAM data sets could be 'quickly' analyzed (at least in a reasonable time scale) to detect HMS calls and to verify that vocalizations were absent in past soundscape studies. Additionally, metrics such as ecoacoustic indices could be used to further investigate these soundscapes (Minello et al. 2021). This is important, considering that climate change and increasing ocean temperatures may cause ecosystem changes in these sensitive reef environments (Hoegh-Guldberg et al. 2017).

To gain a better understanding of the anthropogenic influence on underwater soundscapes, more recordings should be obtained in the MHI where HMS and human presence overlap. For example, additional recorders should be placed along the south and west shores of Oʻahu where commercial and recreational vessel traffic is high, as well as areas where HMS habitat overlaps with military activities (e.g. Pacific Missile Range Facility off Kauaʻi). Recorders deployed in areas of elevated human activity would also enable investigations of the effects of anthropogenic noise on HMS vocal behavior including quantification of the loss of communication space (Jensen et al. 2009, Williams et al. 2014).

Biologging instruments with hydrophones could be deployed on seals to document behavioral responses to anthropogenic noise (Johnson & Tyack 2003, Nowacek et al. 2004, Johnson et al. 2009, Curé et al. 2016, Miller et al. 2022). For example, Mikkelsen et al. (2019) successfully instrumented gray and harbor seals with acoustic recording tags for up to 21 d of continuous recording to quantify the soundscape of their aquatic habitat, to document time budgets, and to assess their noise-induced behavioral responses (Mikkelsen et al. 2019). Future studies should aim to instrument HMS with multi-sensor acoustic tags to systematically evaluate their underwater vocal behavior and sonic environment and to assess their behavioral responses to anthropogenic sounds.

Lastly, future studies should aim to characterize the in-air soundscape of seal haul-out locations in both the MHI and NWHI. Seals spend about one-third of their time on land for parturition, nursing, molting, and resting (Cahoon 2011, Harting et al. 2017, Wilson et al. 2017), and the soundscapes of those terrestrial locations remain uncharacterized.

5. CONCLUSIONS

Overall, this study has shown that PAM is an effective tool for characterizing soundscapes of HMS underwater critical habitats. Using PAM methods, we measured ambient sound levels, described temporal patterns on short timescales, characterized various geophysical, biological, and anthropogenic sound sources, and detected and briefly described HMS vocalizations in the wild for the first time. Three of the 4 critical habitats examined here were dominated by biological sources — only Lehua Rock had a significant input from anthropogenic activity. These findings suggest that the acoustic environment of HMS underwater critical habitats remains relatively pristine at specific times of the year and under specific restrictions on anthropogenic activities. This is a promising result considering that the endangered HMS is facing numerous anthropogenic threats throughout its expansive range, even within the highly protected PMNM. Additionally, because there was limited human activity at these recording locations, the ambient sound measurements can be considered baseline values which can serve as a comparison for future studies that utilize long-term PAM to assess the impact of human activity on underwater soundscapes at these locations.

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