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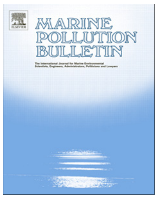

Ambient noise and temporal patterns of boat activity in the US Virgin Islands National Park

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ABSTRACT

Human activity is contributing increasing noise to marine ecosystems. Recent studies have examined the effects of boat noise on marine fishes, but there is limited understanding of the prevalence of this type of sound source. This investigation tracks vessel noise on three reefs in the US Virgin Islands National Park over four months in 2013. Ambient noise levels ranged from 106 to 129 $\mathrm{dB_{rms}}$ re 1 μPa (100 Hz–20 kHz). Boat noise occurred in 6–12% of samples. In the presence of boat noise, ambient noise in a low-frequency band (100–1000 Hz) increased by >7 dB above baseline levels and sound levels were significantly higher. The frequency with the most acoustic energy shifted to a significantly lower frequency when boat noise was present during the day. These results indicate the abundance of boat noise and its overlap with reef organism sound production, raising concern for the communication abilities of these animals.

1. Introduction

Anthropogenic noise is increasingly prevalent in the global ocean (reviewed in Hildebrand, 2009). Human activities such as shipping, pile driving, geophysical exploration, and sonar all introduce noise into the marine environment and this noise can propagate over a range of spatial scales (Urick, 1984). Anthropogenic noise may affect the behavior and physiology of marine organisms from invertebrates (Beets and Friedlander, 1998; Pine et al., 2012) to fishes (Popper and Hastings, 2009) and marine mammals (Di Iorio and Clark, 2010). However, noise levels and their effects are largely unknown (Slabbekoorn et al., 2010).

Much of the documented increase in ocean noise levels has been attributed to commercial shipping activities (Andrew et al., 2002; Chapman and Price, 2011; McDonald et al., 2006) and has primarily been quantified for open-ocean environments. However, small boats can act as transient, high-amplitude noise sources (e.g. Erbe, 2002). These vessels are often operated in near-shore, coastal waters within a range of ecosystems (e.g. Codarin et al., 2009). At present, the extent to and timescales over which small vessel traffic increases ambient noise levels are unknown for most habitats.

As ocean noise increases, so does concern for its impacts on the behavior and physiology of marine animals. Effects have been documented from both transient and continuous anthropogenic noise, with research largely focusing on high-amplitude sources such as air guns (e.g. Fewtrell and McCauley, 2012; McCauley et al., 2003; Popper et al., 2005). However, there is growing evidence that small boat noise can impact fishes. Exposure to boat noise from a range of vessels disrupted schooling behavior in captive bluefin tuna, which the authors argued could affect feeding if a similar response occurred in wild tuna (Sara et al., 2007). Playbacks of vessel noise in the lab raised hearing thresholds for three species of Mediterranean fish, particularly in the frequency range where acoustic communication takes place (Codarin et al., 2009). There is some evidence that boat noise may disrupt orientation behavior in captive larval fish (Holles et al., 2013); however, the extent to which this may occur in the wild is unknown.

Vessel sounds may also help quantify how often boats enter areas of interest. While commercial ship activity can be tracked via Automatic Identification System (AIS) software (Hatch et al., 2008), this technology is typically not used aboard smaller boats. However, small boat presence can be tracked through vessel engine noise (Lammers et al., 2008). Listening for this noise may offer resource managers a way to track the occurrence of at least some boats. Such a tool may be particularly valuable in marine protected areas or locations that are not easily accessed or monitored visually.

In light of these data limitations on small boat noise prevalence and characteristics in coastal waters, and the potential utility of boat noise as means of tracking small vessel activity, the purpose

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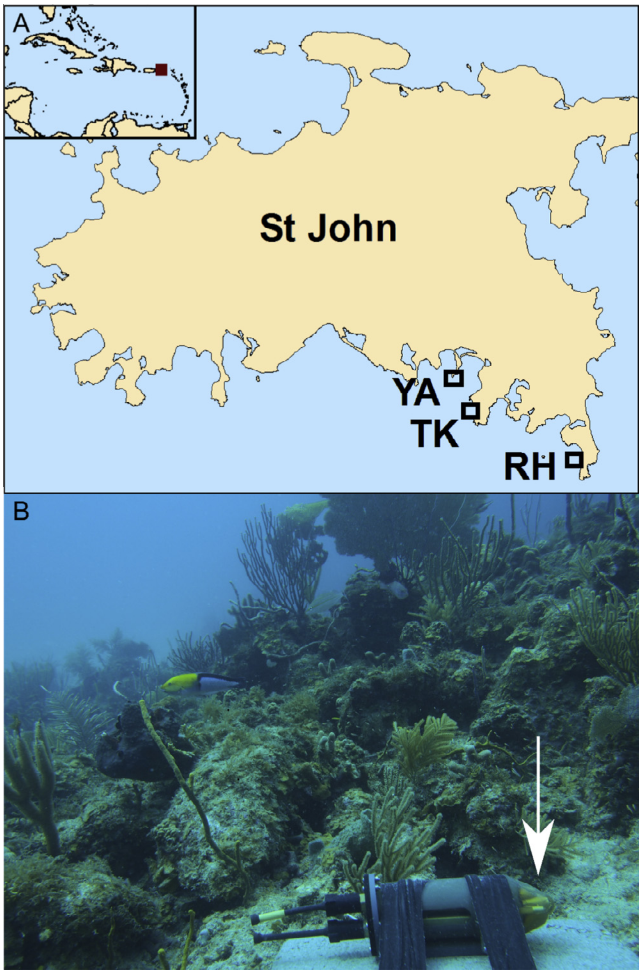

Fig. 1. Deployment map (A) showing locations of three reefs located within the U.S. Virgin Islands National Park on which acoustic recording devices were deployed (TK – Tektite, YA – Yawzi, RH – Ram Head) in 2013. Example of an acoustic recorder mooring (B) showing a DMON (arrow points to hydrophones).

Table 1
Boat noise occurrences and proportion of recording time with boat noise by reef.

Reef	Number of boat noise occurrences	Total minutes recorded	Proportion of minutes with boat noise	Proportion of days free of boat noise
Tektite	115	939	0.12	0.24
Yawzi	72	1267	0.06	0.48
Ram Head	83	1257	0.07	0.50

of this investigation was to characterize the diel, weekly and summer trends in boat noise at three coral reefs located off the island of St. John in the U.S. Virgin Islands National Park. St. John contains a popular marine park, seeing ca. 500,000 visitors per year, many of whom use boats to access local reefs. The island is nearly 60% National Park, with the Park containing ca. 5650 acres of submerged coral reefs, mangrove, and seagrass habitats. It is also a system under stress, seeing declines in coral cover in recent years (Edmunds, 2013). The quantification of potential stressors such as boat noise is needed to gauge the extent of human activity in this ecosystem. The results present a means to potentially track boat occurrence and noise levels in areas of interest.

2. Methods

Three reefs located in the US Virgin Islands National Park were instrumented with acoustic recording devices for ca. four months, starting in April 2013 (Fig. 1). Reefs were chosen based on long-term survey data (Edmunds, 2013) and a rapid, preliminary visual survey of 10 reefs in the area. Two of these – Tektite and Yawzi Point – have been studied for 25 years (see Edmunds, 2013 for review). The third reef – Ram Head – was selected as a comparison site. Mooring balls were located near each of these reefs, some of which were for daytime use only while others could be used for overnight mooring. Tektite ranged from ~9–18 m depth and consisted of a large sloping reef face, Yawzi ranged from ~5–10 m depth and was composed of a large mound that sloped down to sand, and Ram Head ranged from ~8–13 m and was

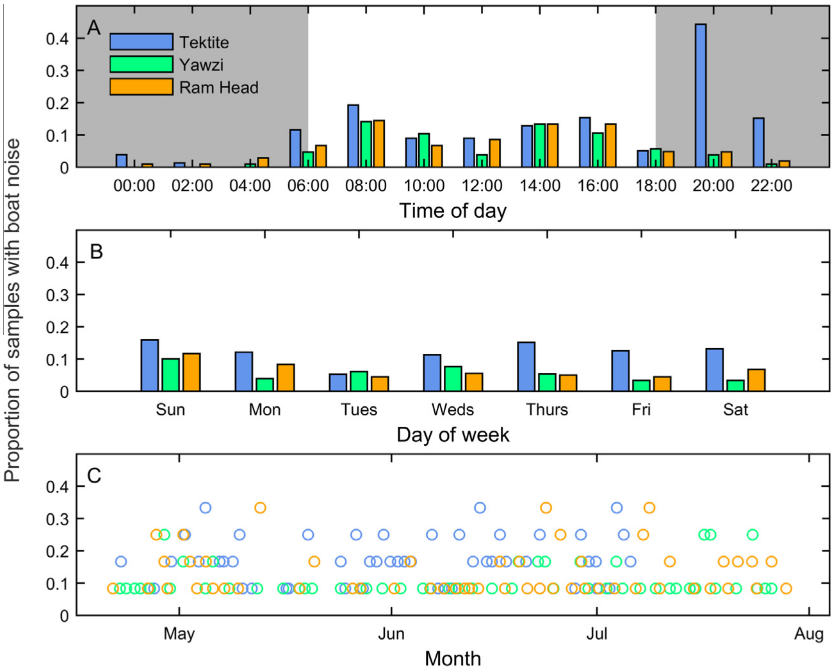

Fig. 2. Summary of the presence of boat noise at three reefs in the US Virgin Islands from April to August 2013 (A) by time of day (gray is 20:00–04:00), (B) by day of week, and (C) summed by day over the entire deployment period.

Table 2
Sound pressure levels in three frequency bands from three reefs.

Reef	SPL$_{rms}$ (dB re 1 μPa)								
	100–1000 Hz			2–20 kHz			100–20000 Hz		
	Min	Median	Max	Min	Median	Max	Min	Median	Max
Tektite	98.1	103.3	130.6	106.5	109.6	121.8	106.6	110.0	126.1
Yawzi	89.8	93.8	125.3	110.2	113.2	126.4	110.3	113.3	129.8
Ram Head	88.4	92.4	124.2	108.6	111.1	124.8	108.8	111.4	128.4

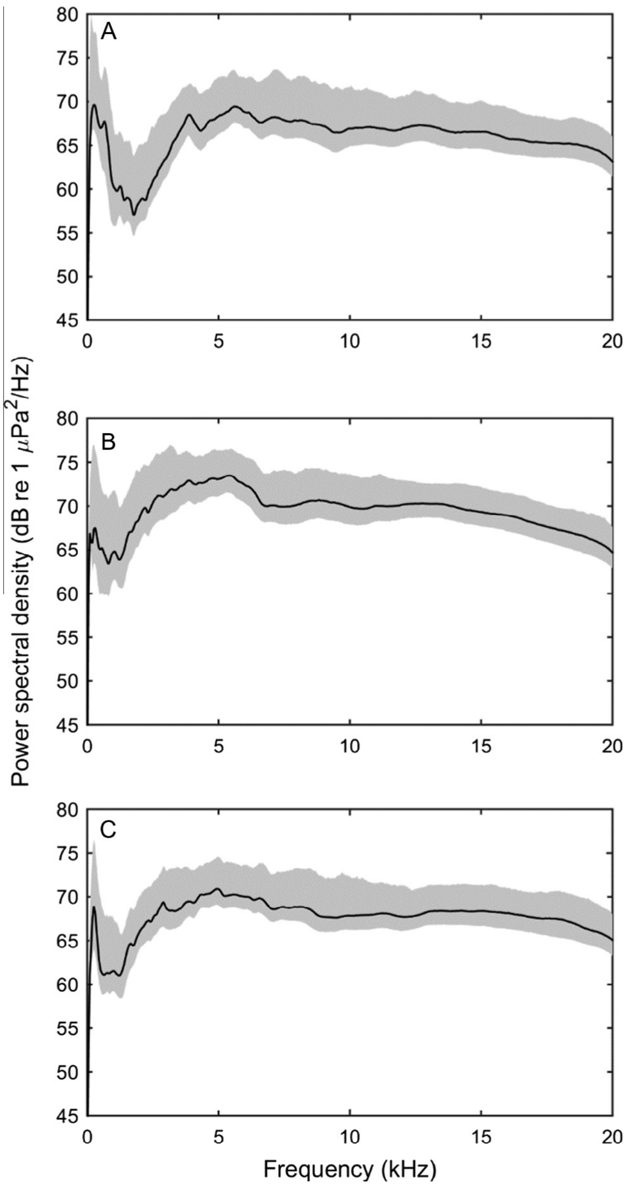

Fig. 3. Background noise measured as full bandwidth (10 Hz–20 kHz) for the full sampled period for (A) Tektite, (B) Yawzi and (C) Ram Head. Line is median with shaded area depicting 5–95 percentiles.

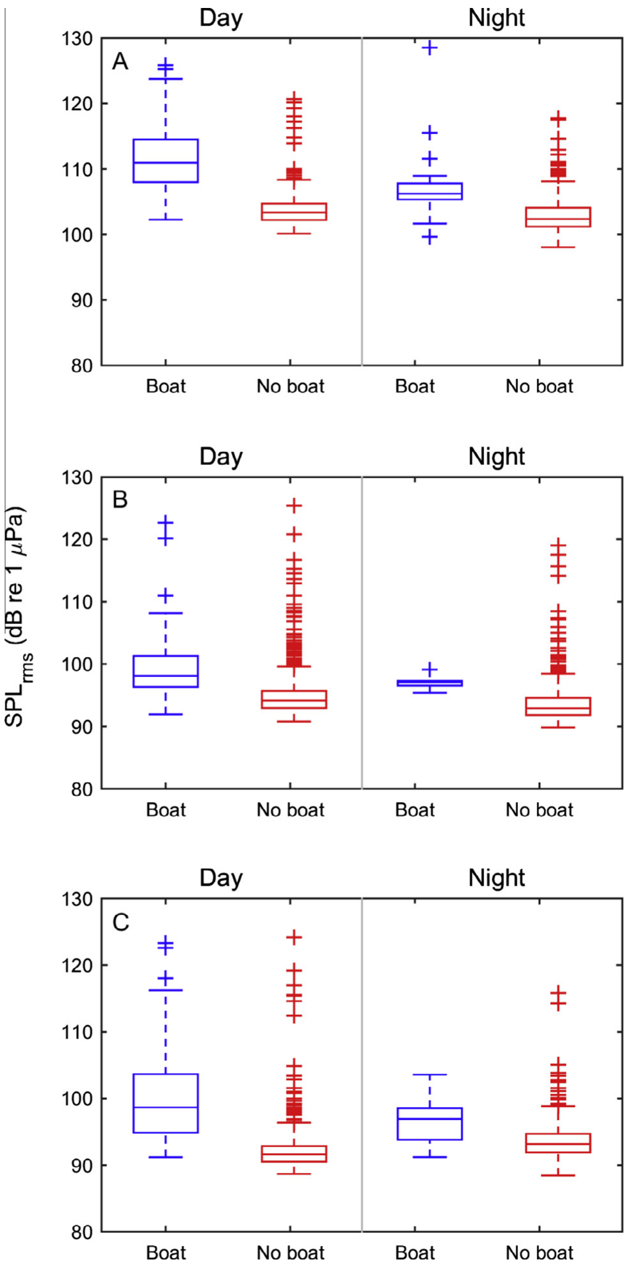

Fig. 4. Low-frequency sound pressure level (100–1000 Hz) during times of day with boat noise present (blue) and otherwise (red) at each of three reefs in the US Virgin Islands (A, Tektite; B, Yawzi; C, Ram Head). SPL was always significantly higher when boat noise was present during both day and night. Central bar – median; box – 25–75 percentiles; whiskers – most extreme data points not considered as outliers; crosses – outliers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

mostly flat, with patch reef sparsely located throughout the site. All three reefs were similar in distance from shore and wave exposure (Fig. 1).

Recordings were collected using two types of autonomous underwater recording devices: the DMON (Woods Hole Oceanographic Institution, Woods Hole, MA) and the DSG (Loggerhead Instruments, Sarasota, FL). The DMONs were configured with a low-noise preamplifier (20 dB gain), 13.2 dB user programmable gain, a 6-pole Sallen-Key anti-alias filter, a 16-bit analog-to-digital converter, and 32 GB of FLASH memory. We

Table 3
Statistical comparison of sound pressure level and peak frequency between day and night and boat presence and absence for each reef. Medians shown with 25–75 percentiles.

Reef	Sound pressure level 100–1000 Hz (dB_{rms} re 1 μPa)					Peak frequency (Hz)				
	Time of day	Boat absent:	Boat present:	X^2	*df*	*p*	Time of day	Boat absent:	Boat present:	X^2	*df*	*p*
Tektite	Day	103.4 (102.2–104.7)	111.0 (108.0–114.5)	132.8028	545	<0.0001	Day	5400 (410–6140)	200 (150–300)	75.7596	545	<0.001
	Night	102.4 (101.2–104.1)	106.3 (105.4–107.8)	62.755	390	<0.0001	Night	350 (300–5550)	350 (350–350)	0.3464	390	>0.05
Yawzi	Day	94.1 (92.9–95.6	98.1 (96.3–101.3)	80.4118	736	<0.0001	Day	5050 (3750–5450)	700 (200–5150)	30.9081	736	<0.0001
	Night	92.9 (91.8–94.6)	97.1 (96.5–97.3)	11.3823	527	<0.001	Night	4900 (3750–5450)	4300 (350–5550)	0.1979	527	>0.05
Ram Head	Day	91.6 (90.5–92.8)	98.7 (94.9–103.7)	137.8874	728	<0.0001	Day	4950 (4320–5050)	400 (200–4500)	71.5301	728	<0.0001
	Night	93.2 (91.9–94.7)	96.9 (93.8–98.5)	11.4715	522	<0.001	Night	4200 (250–5000)	275 (230–350)	5.1606	522	0.023

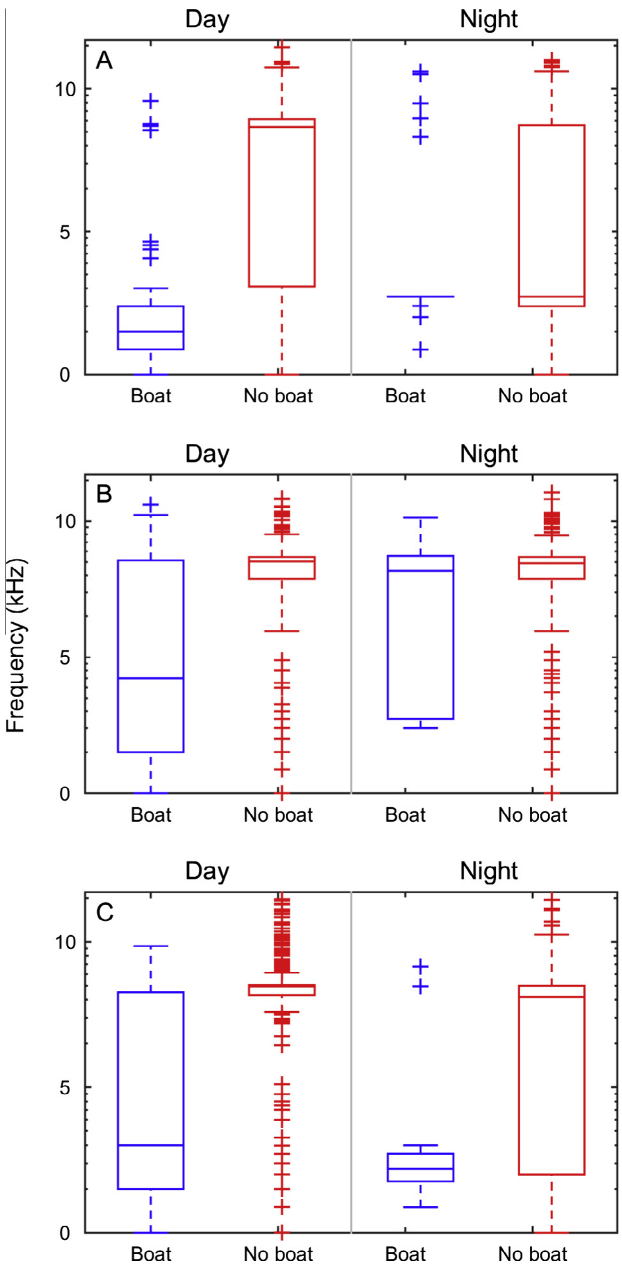

Fig. 5. Peak frequency during times of day with boat noise (blue) and otherwise (red) at each of three reefs in the U.S. Virgin Islands (A, Tektite; B, Yawzi; C, Ram Head). Peak frequency was significantly lower when boat noise was present than otherwise for each reef during the day, but there were no significant differences in peak frequencies at night. Central bar – median; box – 25–75 percentiles; whiskers – most extreme data points not considered as outliers; crosses – outliers. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

programmed the DMON to record on two hydrophone (Navy type II ceramics) channels: LF (16 kHz sample rate with an anti-aliasing filter at 7.5 kHz and high pass filter at 8 Hz) and MF (120 kHz sample rate with an anti-aliasing filter at 50 kHz and high pass filter at 100 Hz). The DSG records on a single-channel at 80 kHz sample rate using a HTI-96 hydrophone (High-Tech Inc., Gulfport, Mississippi) and contains a 16-bit computer board. There is a user-selectable gain setting; for these recordings, 20 dB was used, which results in a high-pass filter being implemented at 80 Hz.

Two concrete moorings (ca. 100 lbs in air) were prepared for each reef. Mooring one consisted of a DMON with customized duty-cycling software (2.5 min/2 h, 2% duty-cycle) and a DSG acoustic recorder (1 min/20 min, 5% duty cycle,). Mooring two consisted of a DMON only. Acoustic recorders were attached to the mooring horizontally using hose clamps and cable ties and hydrophones were ca. 0.3 m off the bottom. Moorings were deployed by SCUBA between 17–19 April 2013 and retrieved between 2–3 August 2013, yielding approximately 103 days of potential data collection per site.

The redundancy of recorders proved essential as the DSGs deployed at Yawzi and Ram Head did not successfully record and the only instrument to properly record at Tektite was the DSG. As a result, acoustic comparisons between sites involved multiple recording devices. Only the first 60 s of the 2.5 min DMON recordings were used, and one minute from every two hours was taken from the DSG recordings such that there was temporal overlap across reefs. The recording durations were as follows: Tektite – 19 April – 6 July 2013; Yawzi: 17 April – 1 August 2013; Ram Head: 19 April – 2 August 2013.

Boat noise and any other sporadic noise was identified visually and confirmed aurally using long-term spectral average (LTSA) plots created in Triton (version 1.90; Scripps Whale Acoustics Lab, San Diego, CA). The LTSAs were computed with 2 s averages and in 200 Hz bins. Boat noise events were summed by hour of day, week and month to describe the temporal distribution across the sampled periods. All acoustic analyses were carried out in Matlab 8.1 (The MathWorks, Inc., Natick, MA) Analyzed files were corrected for calibrated hydrophone sensitivity and resampled to 44 kHz because frequencies higher than 22 kHz were not of interest for this study. Spectral analysis used Fast Fourier Transform (FFT) size of 880 points with a Hamming window and no overlap, which yielded a spectral resolution of 50 Hz and a temporal resolution of 20 ms.

Each 60-s sound file was band pass filtered (100–20,500 Hz) and median peak frequency (the frequency with the highest power) and percentiles were calculated for the day (06:00–18:00) and night (20:00–04:00) periods. The median was used because of the wide range in peak frequencies and the potential for outliers to bias estimates. Median sound pressure level (SPL) and percentiles in root-mean-square (dB_{rms}) were calculated separately for three frequency bands – a low-frequency fish band (100–1000 Hz), a high-frequency snapping shrimp band (2–20 kHz) and the full bandwidth (100–20,000 Hz).

Medians were compared statistically using Kruskal–Wallis tests and the critical *p*-value was corrected for multiple comparisons using the Bonferroni correction.

3. Results

Boats were detected at all three reefs throughout the deployment period (Fig. 2C). Tektite had the highest number of detections, followed by Ram Head and Yawzi (Table 1). Consequently, the Tektite deployment had the highest proportion of recordings that contained boat noise. In addition, approximately one quarter of deployment days were free of vessel noise at Tektite, whereas roughly half of the deployment days were free of vessel noise at Yawzi and Ram Head. Similarly, Tektite was exposed to the highest proportion of boat noise nearly every day of the week (Fig. 2B). There were no significant differences in boat presence by day of week (Tektite: $\chi^2_6 = 0.059, p > 0.05$; Yawzi: $\chi^2_6 = 0.066, p > 0.05$; Ram Head: $\chi^2_6 = 0.063, p > 0.05$; Fig. 2). However, there was a clear diel trend, with significant differences in boat presence by time of day on all reefs (Tektite: $\chi^2_{11} = 98.2, p < 0.0001$; Yawzi: $\chi^2_{11} = 54.3, p < 0.0001$; Ram Head: $\chi^2_{11} = 41.5, p < 0.0001$ Fig. 2A). At Tektite, the hours of 08:00, 20:00 and 22:00 showed the greatest proportions of boat noise. There was a substantial decrease in boat detections in the early morning hours (00:00–04:00) and a brief lull around 10:00–12:00 at all reefs.

Ambient noise levels at the three reefs ranged from 88 to 130 dB in the low-frequency band (100–1000 Hz), 106–126 dB in the high-frequency band (2–20 kHz), and 106–129 dB in the full band (100–20000 Hz; Table 2). Power spectral density followed a roughly similar pattern at all three reefs, with elevated low frequency sound levels, a trough between 2 and 5 kHz and elevated sound levels from 5 to 15 kHz (Fig. 3).

There were notable differences in sound intensity between sound files that contained boat noise and those that did not for a

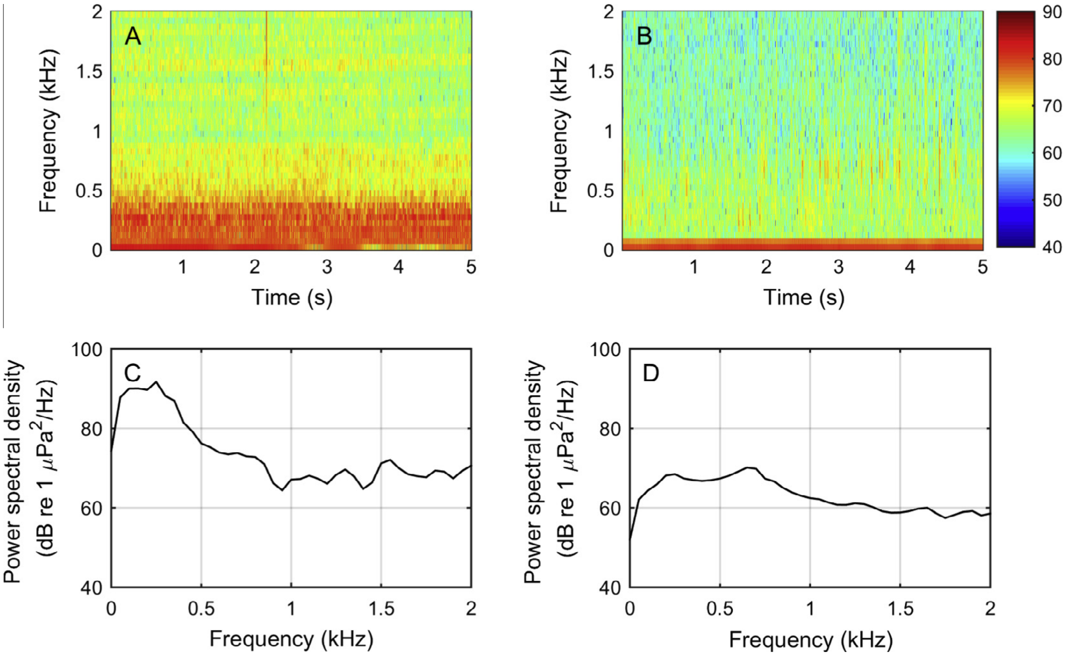

Fig. 6. Spectrograms of the first five seconds of recordings made at 18:00 at Tektite on two consecutive days in June with boat noise present (A) and absent (B) and associated power spectra (C and D). Color bar units are dB re 1 µPa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

given reef and at a given time of day. Median low-frequency SPL was always significantly higher in the presence of boat noise (Fig. 4 and Table 3) and was elevated by up to 10 dB during the day and by up to 7 dB at night compared to sound files without boat noise.

There were also spectral differences among sound files based on the presence of boat noise. Median peak frequency was significantly lower in the presence of boat noise during the day but not at night for all three reefs (Fig. 5 and Table 3).

Sound files with boat noise present had considerably greater low-frequency energy content at frequencies below 1000 Hz, where power spectral density could be 20 dB greater at certain frequencies (Fig. 6). There was some variation among incidences of boat noise but the associated power spectra were broadly similar (Fig. 7). Peak frequencies were typically between 100 and 500 Hz when vessel noise was present.

4. Discussion

Anthropogenic noise is increasing in many parts of the oceans, yet the extent to which various acoustic frequencies and sound levels are changing are often uncertain, particularly in dynamic, coastal ecosystems. Because increased noise may affect the behavior and physiology of various marine organisms, detailed assessments of noise levels are needed for many habitats to better understand the extent to which animals may be exposed to increasing noise. The current effort represents an initial measure of small boat activity at three coral reefs in the U.S. Virgin Islands National Park. There was substantial overlap between vessel noise and the relevant frequency bands for fish communication and hearing. The abundance of boat noise on these reefs reflects the prevalence of this potential stressor. However, boat noise also stands out as an obvious cue to monitor the occurrence of human

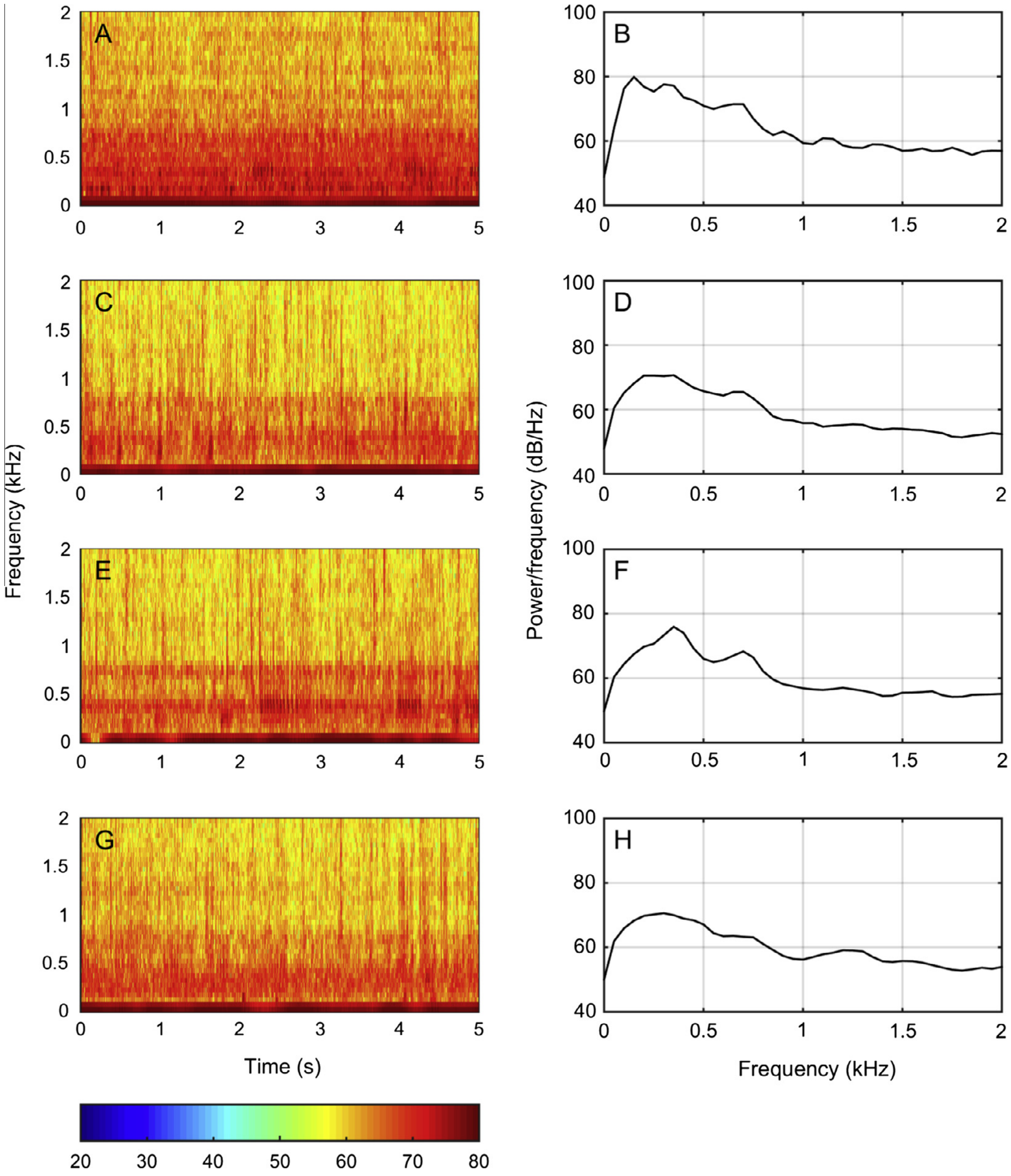

Fig. 7. Four short clips of boat noise from randomly selected recordings from Tektite at 20:00, the time with most boat activity at that site. While there are differences among these recordings, the spectra follow a similar pattern, with elevated energy below 1 kHz. Color bar units are dB re 1 μPa. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

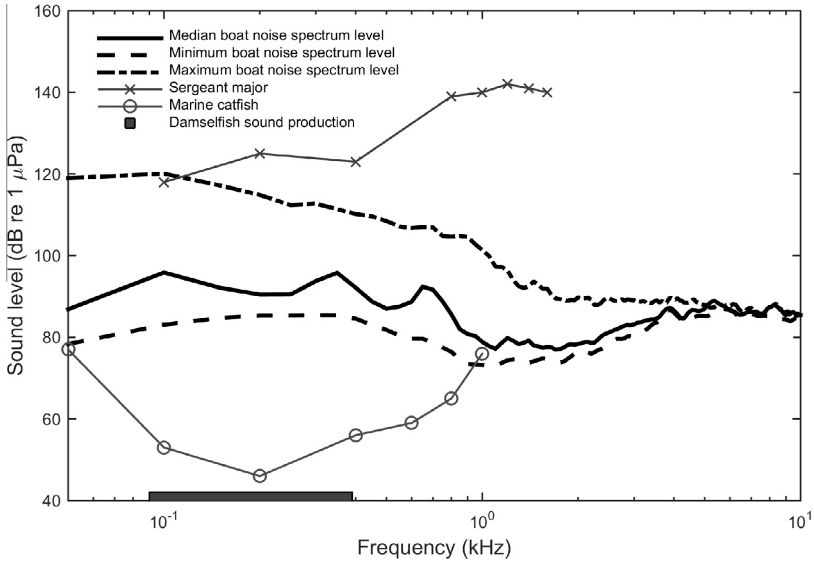

Fig. 8. Power spectra of the minimum, median, and maximum received levels of boat noise (thick lines), the hearing thresholds for a generalist, the sergeant major (Egner and Mann, 2005), a specialist, the marine catfish (Popper and Tavolga, 1981), and the frequency ranges of damselfish sound production (Maruska et al., 2007).

activity on these reefs and other coastal ecosystems, where such data is urgently needed.

In general, the pattern of boat noise observations would seem to reflect human activity, with more noise when people are awake and active (daytime) and little activity in early morning hours. Peaks near 08:00 could reflect transiting to or from mooring balls nearby. There were no differences in boat activity by day of week, which suggests relatively consistent activity irrespective of day. While it is uncertain precisely why Tektite demonstrated a substantial peak at 20:00, it may result from running engines or generators on nearby moorings.

Sound pressure levels pooled across reefs from the entire deployment period varied approximately 40 dB in the low-frequency band whereas levels varied only about 20 dB in the high-frequency band. This is likely a result of the fact that vessel noise is predominately low-frequency and therefore has a disproportionate effect on sound levels and variability below about 5 kHz.

The shapes of power spectra from vessel-free recordings was consistent with coral reef soundscapes in which the dominant sound source is snapping shrimp (Cato and Bell, 1992), thus elevating acoustic energy at higher frequencies compared to open-ocean noise spectra (Hildebrand, 2009). However, differences between the shallow water spectra reported here and open ocean spectra could also result from differences in acoustic propagation.

Acoustic recordings made in the presence of boats had lower peak frequencies and higher sound pressure values. In the absence of boat noise, peak frequency was relatively high (ca. 5 kHz) as a result of snapping shrimp acoustic activity, which is ubiquitous in tropical, coastal habitats (Table 3). Lower peak frequencies at Tektite at night (when boats were detected less) could be a result of elevated fish calling activity at that site (Kaplan et al., 2015). The range of peak frequencies when boats are present could be a result of variability with respect to vessel engine types, speeds, and distances to the hydrophone.

Fish sounds and hearing abilities (for species without auditory specializations) are largely below 1000 Hz (Popper and Fay, 2011; Tricas and Boyle, 2014). The frequency overlap with vessel noise could result in masking of sounds vital to reproduction, feeding and territorial defense (Ladich, 2013), adding another stressor on these already impacted reefs (Fig. 8). While these sound levels were far below those which induce temporary hearing loss (Smith et al., 2004), they occurred frequently, suggesting that the exposure durations and overall energy of introduced noise might be relatively high. It has been suggested that boat noise may impact the behavior of larval fish settling on reefs (e.g. Holles et al., 2013). This might indicate that reefs exposed to boats such as these might see such impacts. This is a particular concern for reefs that are already declining in recruitment, and coral or fish abundance. Understanding the extent and mechanism of these effects is in its infancy and more work is needed to characterize the effects of this masking noise on behavior, recruitment and resiliency of reefs.

The trends shown here suggest that soundscape recordings can be used to track human activity. While relationships between container ship speed and sound level have been identified (McKenna et al., 2013), such data is limited for smaller vessels. Thus, visual observations would help to assign noise signatures to vessel types and relate received levels to vessel speed. These measurements may be particularly valuable in marine protected areas such as this study site or in remote reefs where quantifying fishing or other human activity is needed.

Boat noise can be highly transient, varying in both space and time; accordingly, further investigations should use a duty cycle with higher temporal coverage in order to increase the probability that boats that do pass through a given area are detected. The development of automatic detection algorithms for boat noise have been hindered by the variable nature of this source (e.g. speed, engine size and type, direction of movement); however, using SPL as an aural and visual cue to determine when boat noise may be occurring potentially misses some low-amplitude sources. Thus, the development of a detector based on the distribution of energy across frequencies or on the temporal pattern of boat acoustic energy could increase the variety of sources that can be identified on acoustic recordings.

These are perhaps the first data describing the temporal, spectral, and sound level patterns of small boat noise on coral reefs. The data also provide a novel means of quantifying human usage. While the changes to coral reef soundscapes in the presence of vessel noise may be concerning, boat noise may also be used by managers interested in evaluating patterns of area use. Human activity in the marine environment is often challenging to quantify, and perhaps these passive acoustic measures could aid in evaluating the ecosystem services that these reefs provide.

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References

Andrew, R.K., Howe, B.M., Mercer, J.A., Dzieciuch, M.A., 2002. Ocean ambient sound: comparing the 1960s with the 1990s for a receiver off the California coast. Acoust. Res. Lett. Online 3, 65.

Beets, J., Friedlander, A., 1998. Evaluation of a conservation strategy: a spawning aggreation closure for red hing, *Epinephelus guttatus*, in the U.S. Virgin Islands. Environ. Biol. Fishes 55, 91–98.

Cato, D.H., Bell, M.J., 1992. Ultrasonic Ambient Noise in Australian Shallow Waters at Frequencies up to 200 kHz, MRL Technical Report. Materials Research Laboratory.

Chapman, N.R., Price, A., 2011. Low frequency deep ocean ambient noise trend in the Northeast Pacific Ocean. J. Acoust. Soc. Am. 129, EL161–EL165.

Codarin, A., Wysocki, L.E., Ladich, F., Picciulin, M., 2009. Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). Mar. Pollut. Bull. 58, 1880–1887.

Di Iorio, L., Clark, C.W., 2010. Exposure to seismic survey alters blue whale acoustic communication. Biol. Lett. 6, 51–54.

Edmunds, P.J., 2013. Decadal-scale changes in the community structure of coral reefs of St. John, US Virgin Islands. Mar. Ecol. Prog. Ser. 489, 107–123.

Egner, S.A., Mann, D.A., 2005. Auditory sensitivity of sergeant major damselfish *Abudefduf saxatilis* from post-settlement juvenile to adult. Mar. Ecol. Prog. Ser. 285, 213–222.

Erbe, C., 2002. Underwater noise of whale-watching boats and potential effects on killer whales (*Orcinus orca*), based on an acoustic impact model. Mar. Mamm. Sci. 18, 394–418.

Fewtrell, J.L., McCauley, R.D., 2012. Impact of air gun noise on the behaviour of marine fish and squid. Mar. Pollut. Bull. 64, 984–993.

Hatch, L., Clark, C., Merrick, R., Van Parijs, S., Ponirakis, D., Schwehr, K., Thompson, M., Wiley, D., 2008. Characterizing the relative contributions of large vessels to total ocean noise fields: a case study using the Gerry E. Studds Stellwagen Bank National Marine Sanctuary. Environ. Manage. 42, 735–752.

Hildebrand, J.A., 2009. Anthropogenic and natural sources of ambient noise in the ocean. Mar. Ecol. Prog. Ser. 395, 5–20.

Holles, S., Simpson, S.D., Radford, A.N., Berten, L., Lecchini, D., 2013. Boat noise disrupts orientation behaviour in a coral reef fish. Mar. Ecol. Prog. Ser. 485, 295–300.

Kaplan, M.B., Mooney, T.A., Partan, J., Solow, A.R., 2015. Coral reef species assemblages are associated with ambient soundscapes. http://dx.doi.org/10.3354/meps11382.

Ladich, F., 2013. Effects of noise on sound detection and acoustic communication in fishes. Animal Commun. Noise 2, 65–90.

Lammers, M.O., Brainard, R.E., Au, W.W., Mooney, T.A., Wong, K.B., 2008. An ecological acoustic recorder (EAR) for long-term monitoring of biological and anthropogenic sounds on coral reefs and other marine habitats. J. Acoust. Soc. Am. 123, 1720–1728.

Maruska, K.P., Boyle, K.S., Dewan, L.R., Tricas, T.C., 2007. Sound production and spectral hearing sensitivity in the Hawaiian sergeant damselfish, *Abudefduf abdominalis*. J. Exp. Biol. 210, 3990–4004.

McCauley, R.D., Fewtrell, J., Popper, A.N., 2003. High intensity anthropogenic sound damages fish ears. J. Acoust. Soc. Am. 113, 638.

McDonald, M.A., Hildebrand, J.A., Wiggins, S.M., 2006. Increases in deep ocean ambient noise in the northeast pacific west of San Nicolas Island, California. J. Acoust. Soc. Am. 120, 711–718.

McKenna, M.F., Wiggins, S.M., Hildebrand, J.A., 2013. Relationship between container ship underwater noise levels and ship design, operational and oceanographic conditions. Scientific Reports 3.

Pine, M.K., Jeffs, A.G., Radford, C.A., 2012. Turbine sound may influence the metamorphosis behaviour of estuarine crab megalopae. PLoS ONE 7, e51790.

Popper, A.N., Fay, R.R., 2011. Rethinking sound detection by fishes. Hear. Res. 273, 25–36.

Popper, A.N., Hastings, M.C., 2009. The effects of anthropogenic sources of sound on fishes. J. Fish Biol. 75, 455–489.

Popper, A.N., Smith, M.E., Cott, P.A., Hanna, B.W., MacGillivray, A.O., Austin, M.E., Mann, D.A., 2005. Effects of exposure to seismic airgun use on hearing of three fish species. J. Acoust. Soc. Am. 117, 3958.

Popper, A.N., Tavolga, W.N., 1981. Structure and function of the ear in the marine catfish, *Arius felis*. J. Comp. Physiol. 144, 27–34.

Sara, G., Dean, J.M., D'Amato, D., Buscaino, G., Oliveri, A., Genovese, S., Ferro, S., Buffa, G., Lo Martire, M., Mazzola, S., 2007. Effect of boat noise on the behaviour of bluefin tuna *Thunnus thynnus* in the Mediterranean Sea. Mar. Ecol. Prog. Ser. 331, 243–253.

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., Popper, A.N., 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. Trends Ecol. Evol. 25, 419–427.

Smith, M.E., Kane, A.S., Popper, A.N., 2004. Noise-induced stress response and hearing loss in goldfish. J. Exp. Biol. 207, 427–435.

Tricas, T.C., Boyle, K.S., 2014. Acoustic behaviors in Hawaiian coral reef fish communities. Mar. Ecol. Prog. Ser. 511, 1–16.

Urick, R.J., 1984. Ambient Noise in the Sea. Naval Sea Systems Command, Washington D.C.