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Low-cost action cameras offer potential for widespread acoustic monitoring of marine ecosystems

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Abstract:	Underwater passive acoustic monitoring (PAM) is of growing importance for monitoring the health of aquatic environments. Standard practices use expensive hydrophones to sample soundscapes. They must either be linked to surface recording rigs or use autonomous instrumentation which comes at a premium cost. Although citizen science projects could be of great value to PAM by increasing the number of underwater recordings collected around the world, there is a lack of available low-cost and user-friendly recording hardware. However, consumer-grade action cameras potentially offer an accessible alternative to traditional hydrophones, capable of capturing underwater acoustic recordings. We evaluated the performance of two models of GoPro underwater action cameras deployed as PAM recorders. We tested these cameras against a research-grade hydrophone in a range of shallow tropical sea environments. First, in a sandy area away from reef habitat, we took simultaneous recordings of loudspeaker playbacks of known acoustic signals using all three instruments. We then performed repeated deployments on different coral reef sites in which all three instruments were placed side-by-side to record simultaneously the same natural reef soundscapes. We calculated eight of the most commonly used ecoacoustic indices used in marine soundscape ecology, and assessed the reliability and quantitative accuracy of these compared to the hydrophone. Although not calibrated, GoPros captured recordings from which selected ecoacoustic indices could be calculated reliably, including temporal variability, the acoustic complexity index and acoustic richness. Metrics derived from GoPros can be valuably compared between recordings taken using the same model, but are not directly comparable with hydrophone-derived values. We outline the best settings for collecting soundscape data with GoPros. Underwater action cameras are used frequently by marine scientists, sports enthusiasts and tourists around the world. Their capacity to capture soundscape recordings represents a valuable approach for the global expansion of PAM through citizen science.
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Highlights

- We tested the value of low-cost consumer-grade action cameras (GoPro) to record underwater soundscapes for passive acoustic monitoring
- We show that GoPro recordings, if taken with the right settings, can issue reliable acoustic indices including temporal variability, acoustic complexity and acoustic richness
- Although GoPros are less sensitive than hydrophones, they can still be used as event detectors and for monitoring aquatic animal vocalisations

Low-cost action cameras offer potential for widespread acoustic monitoring of marine ecosystems

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Abstract

Underwater passive acoustic monitoring (PAM) is of growing importance for monitoring the health of aquatic environments. Standard practices use expensive hydrophones to sample soundscapes. They must either be linked to surface recording rigs or use autonomous instrumentation which comes at a premium cost. Although citizen science projects could be of great value to PAM by increasing the number of underwater recordings collected around the world, there is a lack of available low-cost and user-friendly recording hardware. However, consumer-grade action cameras potentially offer an accessible alternative to traditional hydrophones, capable of capturing underwater acoustic recordings.

We evaluated the performance of two models of GoPro underwater action cameras deployed as PAM recorders. We tested these cameras against a research-grade hydrophone in a range of shallow tropical sea environments. First, in a sandy area away from reef habitat, we took simultaneous recordings of loudspeaker playbacks of known acoustic signals using all three instruments. We then performed repeated deployments on different coral reef sites in which all three instruments were placed side-by-side to record simultaneously the same natural reef soundscapes. We calculated eight of the most commonly used ecoacoustic indices used in marine soundscape ecology, and assessed the reliability and quantitative accuracy of these compared to the hydrophone.

Although not calibrated, GoPros captured recordings from which selected ecoacoustic indices could be calculated reliably, including temporal variability, the acoustic complexity index and acoustic richness. Metrics derived from GoPros can be valuably compared between recordings taken using the same model, but are not directly comparable with hydrophone-derived values. We outline the best settings for collecting soundscape data with GoPros.

Underwater action cameras are used frequently by marine scientists, sports enthusiasts and tourists around the world. Their capacity to capture soundscape recordings represents a valuable approach for the global expansion of PAM through citizen science.

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1. Introduction

Aquatic invertebrates, fish and mammals produce a diverse array of sounds during communication and foraging (Tricas & Boyle, 2009; Gedamke & Robinson, 2010; Coquereau et al., 2016). The cumulative presence of this biophony combines with geophonic inputs such as weather and tidal sounds to produce a natural soundscape that contains valuable acoustic information about an ecosystem (Erbe et al., 2015), although in some places the natural soundscape is also becoming increasingly modified by human activities (Duarte et al., 2021). Listening to the soundscape can reveal important information to ecologists about habitat quality and the abundance and diversity of sound-producing organisms (Lindseth & Lobel, 2018; Bradfer-Lawrence et al., 2019). The emerging practice of soundscape ecology uses underwater acoustic recorders for passive acoustic monitoring (PAM) of these habitats (Merchant et al., 2015). This approach provides a low effort, non-invasive complement to remote and in-water visual surveys, that is capable of continuous data collection over previously impossible temporal scales, including at night and in deep and turbid environments.

Recent progress in PAM includes development of acoustic indices that predict for biodiversity and habitat quality (Depraetere et al., 2012; Sueur et al., 2014). Each index produces a single value for a recording that characterises a property of the soundscape, such as its complexity or uniformity (Sueur, 2018). Typically, this is performed on short windows of time and compared across broader temporal or spatial scales to reveal useful trends. The use of acoustic indices to assess ecosystems is well established in terrestrial ecology (Bradfer-Lawrence et al., 2019), but relating acoustic indices with other ecological characteristics in marine environments is less developed (Kennedy et al., 2010; Piercy et al., 2014; Kaplan et al., 2015; Nedelec et al., 2015; Bohnenstiehl et al., 2018; Bradfer-Lawrence et al., 2019). Nevertheless, generalised patterns in marine soundscapes are beginning to emerge and acoustic indices are becoming recognised as useful tools to advance the use of PAM to perform rapid monitoring of marine habitats (Harris et al., 2016; Gordon et al., 2018; Lindseth & Lobel, 2018; Elise et al., 2019).

Acoustic indices are usually calculated from recordings that have been taken using one or more omnidirectional hydrophones linked to an acoustic recorder and a battery (Sousa-Lima et al., 2013; Merchant et al., 2015). These hydrophones contain a piezoelectric transducer which converts sound pressure into an electrical current which is amplified and cabled to a digital recorder on the surface or on land (Lau et al., 2002). Modern autonomous setups include a hydrophone, battery, recorder and memory in a compact, self-contained waterproof system; greatly improving the ease of deployment and widening the scope of investigations compared to traditional cabled systems (Sousa-Lima et al., 2013). Cabled setups cost hundreds to thousands of dollars (USD) and autonomous hydrophones cost several thousand dollars (Sousa-Lima et al., 2013; Merchant et al., 2015). Low-cost alternatives may be possible through self-assembly, but this requires a high level of expertise for assembly and deployment. Underwater acoustic recordings are therefore rarely included in citizen science projects, because the hydrophones required are expensive and not sufficiently user-friendly for citizen scientists.

Consumer-grade action cameras are an accessible, easy to operate and rugged tool which are capable of collecting acoustic recordings underwater. For example, GoPro sport cameras (GoPro™, California, US), primarily designed to collect high-definition videos and images, also record audio underwater using three internal microphones, and have an underwater housing rated to 40 m depth. These devices combine the three audio channels and video into a single MP4 (MPEG-4) file, and all but the earliest versions (HERO3 onwards) offer 'Protune' settings that enable audio to also be captured as a raw wave file (WAV; Waveform Audio File Format) with no automated dynamic gain, compression or other processing. This provides higher quality audio than that embedded in the MP4 video. GoPros are frequently used in marine science as effective low cost video cameras for surveys and behavioural observations (Ford et al., 2018; Villon et al., 2018; Lefcheck et al., 2019). They are self-contained and easily deployed, and popularly used in citizen science projects, for example as an underwater photogrammetry tool (Raoult et al., 2016), or for monitoring artificial reefs (de Virgilio et al., 2020) and seagrass meadows (Florisson et al., 2018). However, the prospect of capitalising on the audio capabilities of consumer-grade devices such as these for soundscape ecology is yet to be explored.

In this study, we assessed the reliability of GoPro cameras as sound recorders, to use in projects where calibrated recordings are not essential. We tested (i) the performance of GoPro sports cameras by recording the playback of known acoustic signals, and (ii) the reliability and quantitative accuracy of acoustic indices calculated from their recordings, by deploying these devices in coral reef habitats known for their rich soundscape (Staaterman et al., 2013; Nedelec et al., 2015). Acoustic metrics from sports cameras were compared with those from simultaneous recordings from a calibrated research-grade hydrophone (SoundTrap 300 STD, Ocean Instruments, Auckland, NZ). We defined reliability as the consistency of results obtained from GoPros, measured by the strength of their correlation with results obtained by the hydrophone. If reliability was satisfactory, we also tested for quantitative accuracy, defined as how closely the metrics deviated from those from the hydrophone recordings.

2. <u>Materials and Methods</u>

2.1 Study site

All recordings were taken in November and December 2019, in shallow-water coral reef habitat south-west of Lizard Island Research Station, Great Barrier Reef, Australia (14°40.8′S, 145°26.4′E; Fig. 1). Lizard Island is a mid-shelf island in the northern Great Barrier Reef, situated 27 km offshore and 17 km from the outer Greater Barrier Reef. A playback experiment was performed on a 4 m deep sandflat site 50 m from the nearest reef (red arrow in Fig. 1C). To sample the reef soundscape, the recording devices were then deployed by snorkelers at 11 randomly selected reef flat sites at depths from 2–8 m (black and white arrows in Fig. 1C).

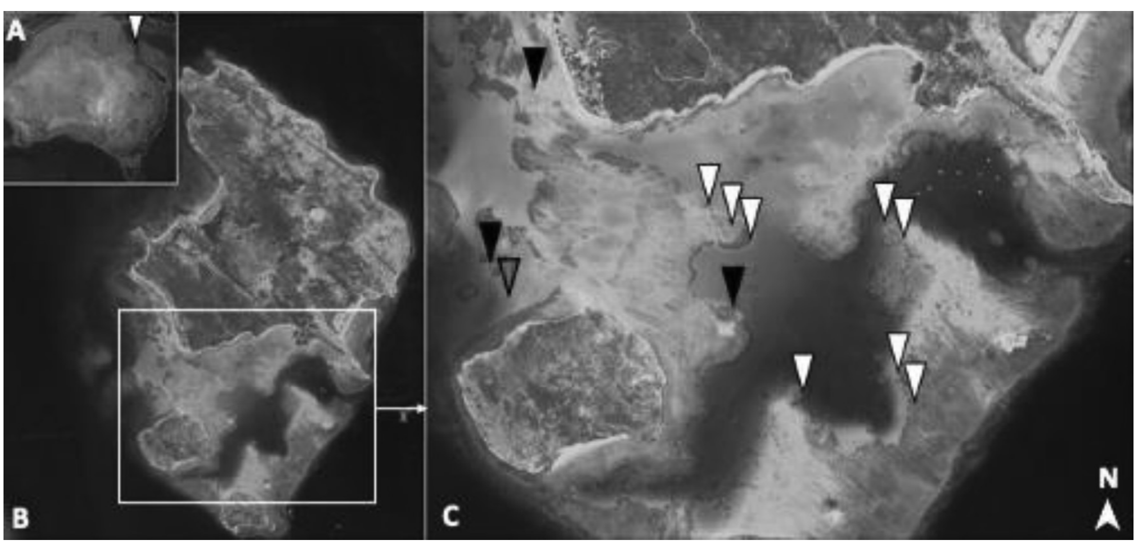


Figure 1. Study sites used for comparing sports camera acoustic recordings with simultaneous recordings from a research-grade hydrophone. (A) Lizard Island (14°40.8'S, 145°26.4'E) relative to mainland Australia. (B) Aerial view of Lizard Island. (C) Locations where GoPros were placed alongside the hydrophone to collect recordings: red arrow indicates location of the playback

experiment, white arrows indicate where both GoPro 5 & 7 recordings were taken, black arrows indicate GoPro 7 recordings only (Maps: Google Earth, Maxar Technologies).

2.2 Equipment

A calibrated SoundTrap (300STD, Oceans Instruments, NZ) was used as the reference standard hydrophone. It is a self-contained device with an omnidirectional receiver and an inbuilt digital recorder (288 kHz maximal sampling rate (48 kHz used in this study), 16-bit resolution, 0.02–60 kHz ± 3dB frequency range, 34 dB re 1 μPa self-noise above 2 kHz, maximum gain before clipping 186 dB re 1 μPa, calibrated by manufacturer).

Three GoPro HERO5 Black and two GoPro HERO7 Black (GoPro™, California, USA) cameras were used, hereafter referred to as GoPro 5 and GoPro 7 respectively. All cameras were enclosed in the manufacturer's 'Super Suit' underwater housing. Each GoPro contains three internal microphones with a sampling rate of 48 kHz. To maximise battery and memory, cameras were set to record videos at the lowest resolution and frames rate per second possible for both cameras (720p, 60fps), and they were also set to record a 'raw' audio file in the WAV format using the 'Protune' settings accessible through the user interface. Detailed set-up guidance is included in Appendix Fig A.1.

2.3 Playback experiment

To investigate differences between GoPro models (5 and 7), between devices of the same model,between GoPros and the SoundTrap, and between the two forms of audio captured by GoPros (raw and within the video), a playback experiment was performed using two artificial acoustic signals generated by an underwater speaker. The acoustic signals were created in Audacity (v2.3.1, The Audacity Team, 2020). The first signal consisted of nine pure tones (1 to 17 kHz in 2 kHz intervals) played simultaneously. The second signal was a sine sweep that increased linearly from 0 to 20 kHz over a 10 second duration. An underwater speaker (University Sound UW-30; max output 156 dB re 1 μPa at 1m, frequency response 0.1–10 kHz; Lubell Labs) powered by an amplifier (M033N, 18 W, frequency response 0.04–20 kHz; Kemo Electronic GmbH), and a battery (12v 12Ah sealed lead acid) was used. Playback sounds were generated by an MP3 player (Clip Jam; San Disk, Milpitas, CA, USA). In turn, each device was placed on a 2 m marker in front of the underwater speaker and left for several cycles of the playback track. Each device was suspended and set to record in the same manner outlined for the reef deployment. To prevent disturbance, recordings were taken whilst the sea-state was calm (Douglas scale), the wind was 0 on the Beaufort scale, there was no rain, and no snorkelers, divers or boats were in the area during each recording.

In addition, we used the same playback setup to investigate the signal-to-noise ratios (SNR) of two SoundTraps and three GoPros (model 5), but deployed them in a tank onshore to benefit from a quieter environment. We used a 1000 L tank, filled with seawater and placed on polyethylene foam to isolate it from vibrations. The devices were placed one by one into a set position and exposed to a playback of white noise and silence played by the speaker. Three sections of 0.5 s of white noise and 0.5 s of silence were recorded to calculate the SNR for each device.

2.4 Acoustic Analysis

To explore similarities and differences between each GoPro recording and the hydrophone recordings from the playback experiment, spectrograms and power spectral density (PSD) plots were generated and SNR calculated using a custom made script in MATLAB (v. 9.8.0, R2020a, The MathWorks Inc. Natticks, MA, USA). These were performed on recordings of playback of the two controlled acoustic signals, and also on 30-second reef soundscape recordings taken simultaneously at 11 different reef sites (see Materials and Methods 2.3). All sounds were first normalised before building spectrograms, for which FFT windows of 128, 256, and 512 samples with a 75% overlap were used for the multi-tone, sweep and reef soundscape recordings respectively. The PSDs were computed using a rectangular window, and the bandwidth containing 99% of the total integrated power of the spectrum was also calculated. The hydrophone was used as the standard reference against which GoPro recordings were compared.

2.5 Recordings of reef soundscapes

Both the hydrophone and GoPros were suspended on vertical ropes at matching heights of 0.5 m above the seabed, less than 0.5 m apart, using small sub-surface buoys, dive weights, rope and cable ties (Fig. 2). The devices were left to record for 120 minutes, which was the limit of the battery life of the GoPros. Recordings with excessive motorboat noise, whereby five 30 s segments could not be extracted without boat disturbance, were discarded. As with the playback experiment, recordings were only taken when the wind was low (0– 2 on the Beaufort scale), the sea state was calm or smooth (on the Douglas scale) and there was no rain.

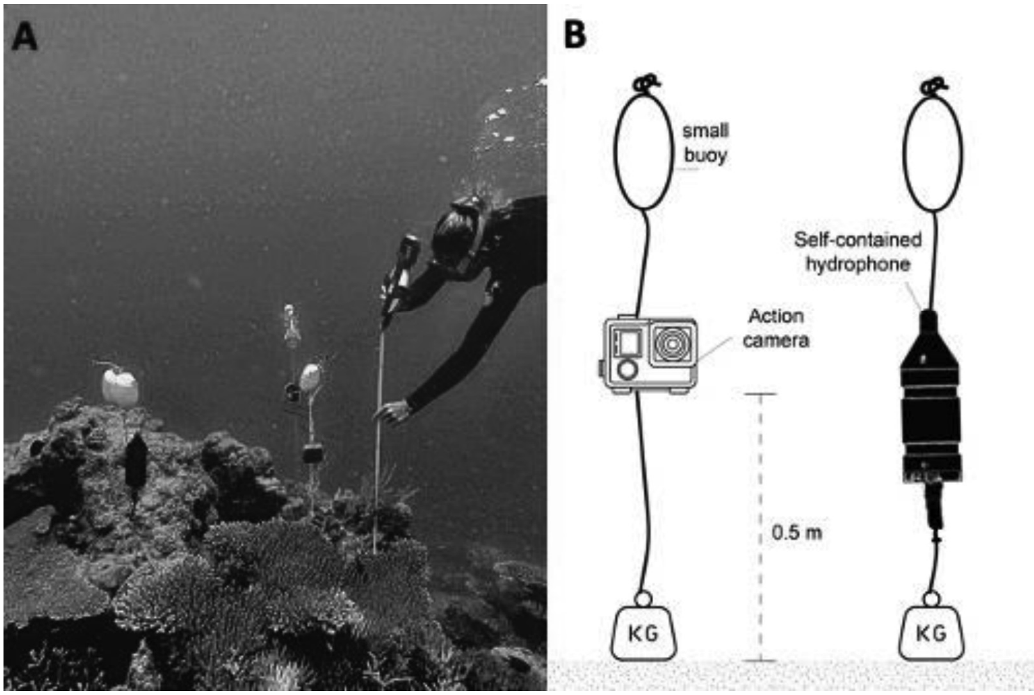


Figure 2. (A) GoPro 5 & 7 being deployed next to the hydrophone which can be seen on the left. (B) Devices were repositioned until all were suspended 0.5 m above the seabed.

Eleven successful recordings were taken with GoPro 7s and eight with GoPro 5s (due to camera/battery failure). Audio tracks were extracted as WAV files from the GoPro MP4 videos (hereafter called Video Audio) using ‘WavePad’ (v.9.6.3, NCH Software, Canberra, Australia). These tracks, alongside WAV files from the hydrophone and Raw Audio GoPro files, were uploaded into MATLAB and temporally aligned to a high precision using the AlignWave function (Chen, 2020). The first fifteen minutes were removed from each track to remove any disturbance created by the snorkelers deploying the recording devices underwater. The following 15 minute period was used in all recordings for further analysis. From this 15 minute window we subsampled five randomly selected non-overlapping 30 second periods from each track, which were temporally matched between GoPros and the hydrophone. These subsamples were screened for boat noise aurally and by inspecting spectrograms; if boat noise was present an alternative 30 second period that did not overlap any of the existing periods was selected randomly. In total, 55 subsamples were collected from the GoPro 7s cameras (55 Raw Audio (WAV), 55 Video Audio (from MP4)), and 40 subsamples from the GoPro 5s

(40 WAV, 40 MP4), which were temporally matched across the eleven and eight successful recording days respectively, all with time-matched hydrophone subsamples.

2.6 Ecoacoustic indices

We identified eight indices (Table A.1) that have been shown in one or more published studies to exhibit a relationship with some aspect of the local community ecology when applied to the marine environment: Acoustic Complexity Index (ACI), Acoustic Diversity Index (ADI), Acoustic Entropy (H), Acoustic Evenness Index (AEI), Acoustic Richness (AR), Bioacoustic Index (BI), Temporal Variability (TV), and Snap Rate. The selected indices were calculated in R (v3.4.2. R Development Core Team, 2020) using the *Seewave* (Jerome Sueur, Aubin, & Simonis, 2008) and *Soundecology* (Villanueva-Rivera, Pijanowski, & Villanueva-Rivera, 2018) packages, except for Snap Rate which was calculated in MATLAB using a custom-made script adapted from Gordon *et al*. (2018). Two frequency bands were considered for every index (low: 0.1**–**1.5 kHz; high: 1.5**–**20 kHz) except for Snap Rate as the low-band alone is typically not considered (Bohnenstiehl et al., 2016), instead the high band alongside the full spectra (0.1**–**20 kHz) were used. These bands were created using inbuilt frequency filters in *Seewave* and *Soundecology* for indices for which this was available. If not, minimum order Butterworth bandpass filters with a 40 dB roll off were implemented in MATLAB to tracks prior to analysis.

2.7 Statistical Analysis

We used a method comparison approach (Magari, 2002; Carstensen, 2011) to assess the reliability and quantitative accuracy of the GoPro recordings against the hydrophone recordings (our reference standard). Individual comparisons between the hydrophone and GoPro recordings were made for each ecoacoustic index using a single paired measure method comparison approach (Abu-Arafeh, Jordan, & Drummond, 2016). Little consistency in the distribution of datasets was observed, therefore, non-parametric statistical tests were selected. All analysis was performed in *R* using the *MethComp v1.30.0* package (Carstensen et al., 2012).

Two complementary tests were selected: (i) a Spearman’s rank-order correlation test was used to quantify the reliability of the GoPros against hydrophones by testing the strength of their linear relationship (Magari, 2002); (ii) a Passing-Bablok regression was used to determine whether the sensitivity of each GoPro-index combination under inspection was numerically equivalent to that of the hydrophone by quantifying the proportional and constant bias (Bilic-Zulle, 2011). In combination, these two tests provide information on the reliability of GoPro recordings for calculating the ecoacoustic indices in question and whether they are equivalent to indices derived from the hydrophones recordings (Magari, 2002). Without the Spearman test, the reliability of GoPro results against the hydrophone cannot be determined, and without the Passing-Bablok test, it is not be possible to determine whether a GoPro-derived index can be used interchangeably with a hydrophone, or whether it may need correcting based on consistent bias.

3. <u>Results</u>

3.1 Playback experiment: spectrograms

Spectrograms obtained from the playback experiment demonstrate success in recording underwater sound with GoPros (Fig. 3). On each plot, the occupied bandwidth shows the frequency band that contains 99% of the power of the signal. Under visual inspection, the main features of the multi-tone and the sine sweep signals are clear in all spectrograms. Differences within the same model (5 or 7) and audio (Raw or Video) options were negligible (Appendix Fig. A.2). However, notable differences between models and audio options were observed. This included a difference in average power due to a different level of automatic gain applied by each device: the gain was highest for the GoPro Video Audio, lowest for the GoPro Raw Audio with the hydrophone gain in the middle. The sensitivity at different frequencies is seen in the sine sweep, where a consistent intensity is observed with the hydrophone, in accordance with its flat response. The distribution of power also appears reasonably consistent on the GoPro 7 Raw Audio spectrogram. However, for audio extracted from videos recorded by both models, lower frequencies exhibit an increased power compared to higher frequencies. This skewed frequency response is also shown in the reef soundscape spectrograms, in which the hydrophone displays consistent broadband noise from a low frequency up to 20 kHz (also see Fig. 4), whereas the Video Audio for both devices shows a greatly reduced intensity at frequencies above 15 kHz. To a lesser degree, the GoPro7 Raw Audio exhibits a slightly reduced intensity for signals above 10 kHz, whilst the GoPro 5 shows more consistency. Additionally, the presence of more discrete discrepancies in the amplitude of some narrower frequency bands are present in all the GoPro recordings whereas the hydrophone appears uniform. The sine sweep also revealed an interesting artefact in the Video Audio files. As the sweep passed through the 8–10 kHz band a second sweep appeared following the opposite gradient. This second sweep begins at approximately 15 kHz until it reaches 11 kHz where it stops.

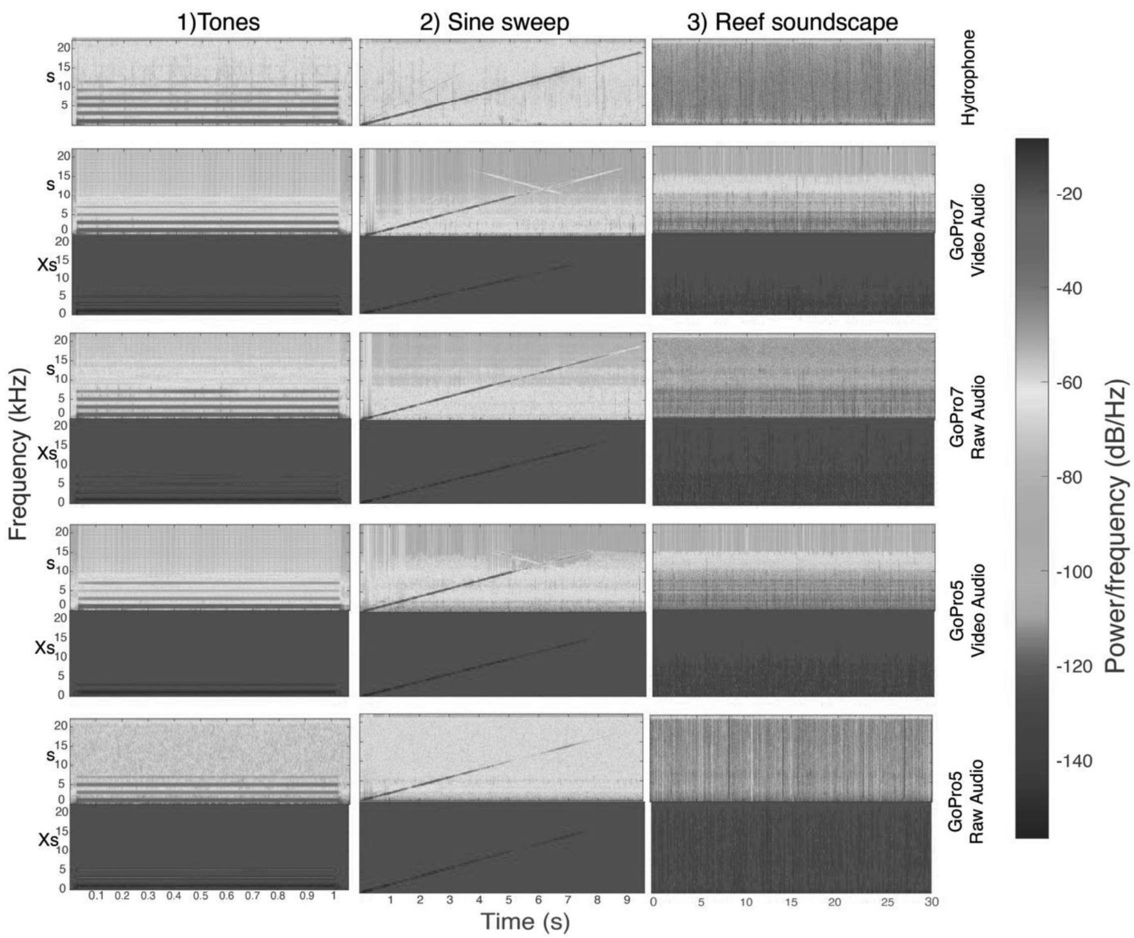


Figure 3. Comparison of recordings from a hydrophone, GoPro7 Video Audio and Raw Audio, and GoPro5 Video Audio and Raw Audio. Spectrograms (s) show (1) simultaneous pure tones, (2) a sine sweep and (3) a coral reef soundscape. A Hamming window was used with 75% overlap, multitone window length = 128, sine sweep window length = 256, reef soundscape window length = 512. Cross-spectrograms (Xs) of each signal recorded by GoPros and the hydrophone (reference): signals were divided into 30 sample segments and each segment was windowed with a Kaiser window. High power values indicate regions of common frequencies.

3.2 Playback experiment: Power spectral densities

Power spectral density (PSD) plots of the multi-tone signal revealed 18 clear peaks for the hydrophone, most likely including the nine pure tones and associated harmonics (Fig. 4). Peaks on the GoPro plots were not as clearly defined, although it was evident that the Raw Audio recording from the GoPro 7 was the closest fit to the hydrophone, with at least 14 peaks (though many at a reduced amplitude), followed by the GoPro 7 Video Audio with 11. The GoPro 5 Raw and Video Audio showed fewer peaks (around seven visible). The occupied bandwidth (containing 99% of the signal) was 8.7 kHz for the hydrophone which was closely matched by the GoPro 7 Raw Audio bandwidth of 6.7 kHz, with both at the lower end of the spectrum, whereas the GoPro 5 Raw Audio was spread over a broader range of frequencies (11.0 kHz). Occupied bandwidths for audio extracted from video for both GoPro models were narrow (2.2 kHz and 2.8 kHz for the GoPro 5 and GoPro 7 respectively) and present at the lower end of the spectrum.

The PSD plots of the sine sweep revealed a drop off in frequencies in the Video Audio above 15 kHz and 16 kHz for the GoPro 5 and GoPro7 respectively and exhibited 99% of their occupied bandwidth across 5.2 kHz to 9.2 kHz. Conversely, the hydrophone showed a consistent intensity across the full spectrum up to 20 kHz, with its power distributed across a broader range (99% of occupied bandwidth was 16.7 kHz).

PSD plots of the reef soundscape recorded by each device also revealed that frequency responses for both GoPro devices were not flat. The Raw Audio recordings taken by both GoPros showed a slightly increased intensity relative to the hydrophone at the lower end of the spectrum (up to 7 kHz), before exhibiting a flatter response from 7–20 kHz. The Video Audio files for both GoPros showed an increased intensity at the lower end of the spectrum relative to the hydrophone which then decreased steadily as frequency increased. The PSD plots also highlight the discrepancy in the 99% occupied bandwidth between the GoPro Video Audio and the hydrophone. The bandwidth of the hydrophone was spread across 20 kHz, whereas this was only 8.8 kHz for the GoPro 5 and 8.8 kHz for the GoPro7. The Raw Audio files had a closer broadband spread to that of the hydrophone (19.6 and 20.7 kHz respectively) than the Video Audio files.

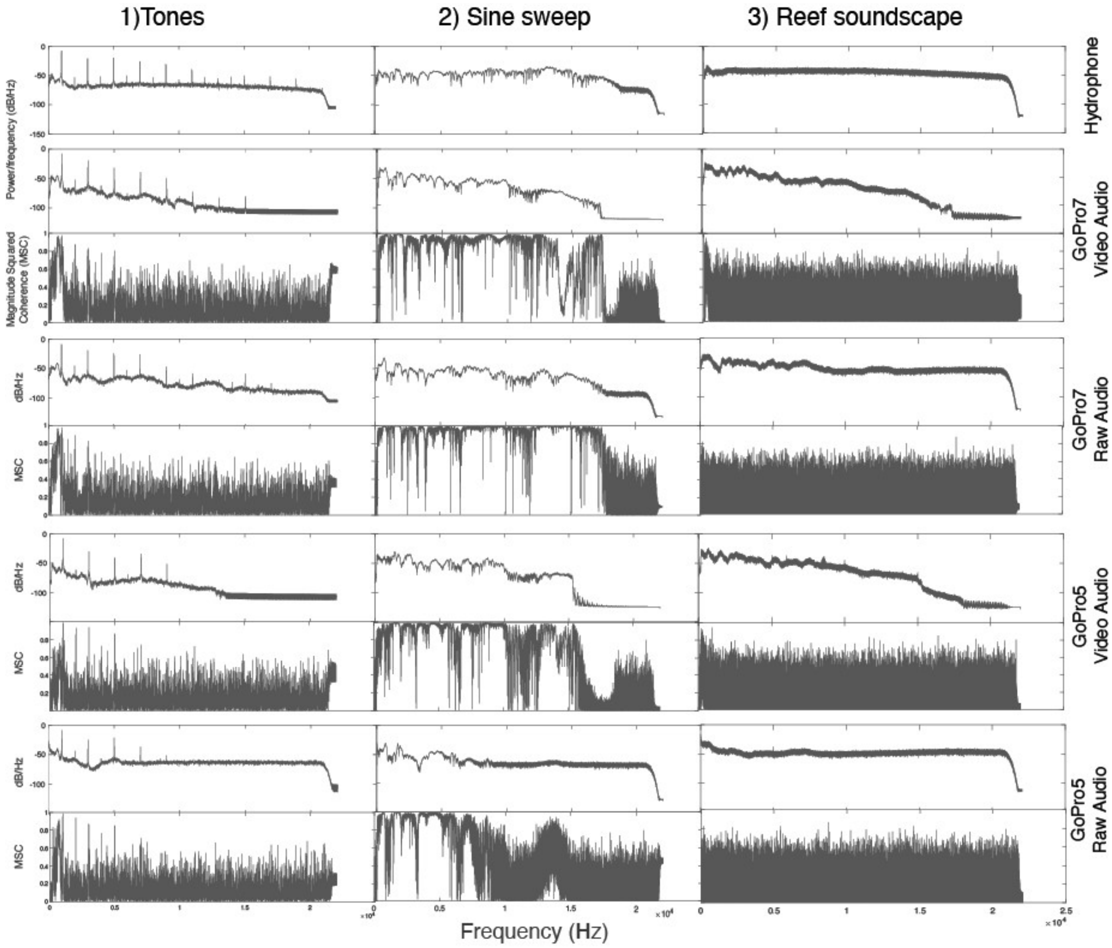


Figure 4. Welch's power spectral density (PSD) plots of a pure tone (left), a sine sweep (middle) and a coral reef soundscape (right) recorded by the hydrophone, GoPro 7 Raw and Video Audio, and, GoPro 5 Raw and Video Audio. The 99% occupied bandwidth is represented by the blue shading with the size of the frequency range included in the bandwidth estimated shown above each plot.

3.3 Playback experiment: signal-to-noise ratio

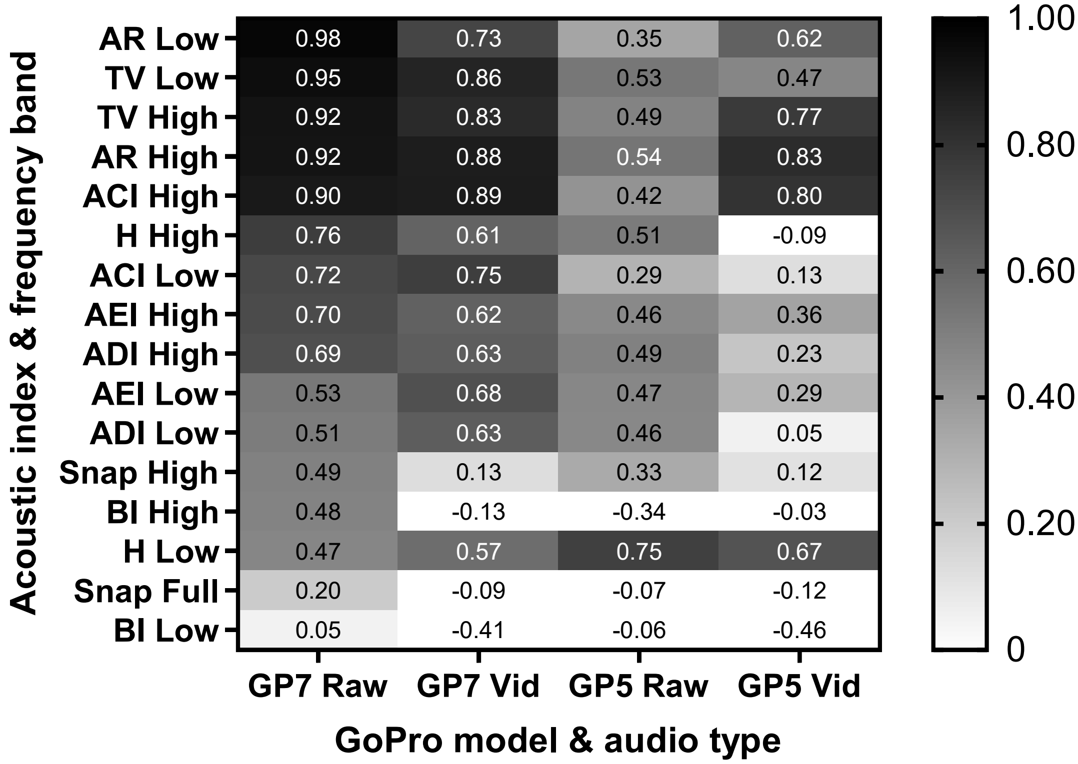
The mean SNR of the white noise was 35.7 dB (± 1.83 SE) for the two Soundtraps and 10.17 dB (± 2.00 SE) for the 3 GoPro 5 (Raw format).

3.4 Reef soundscape: Reliability of GoPro-derived acoustic indices

The correlation between indices from the GoPro and hydrophone recordings was tested to assess the reliability of the indices calculated from GoPro recordings (Fig. 5; all values for each index calculated are presented in Appendix B. Low band acoustic richness (AR) calculated from GoPro 7 Raw Audio recordings had the strongest correlation (rho = 0.98, $p<0.001$) with AR from the hydrophone, with four other indices also exhibiting highly significant correlations (rho>0.9, $p<0.001$). At the lower end, other GoPro-derived indices showed little to no correlation with those derived from hydrophone recordings.

Indices derived from GoPro 7 recordings were consistently more highly correlated with the hydrophone, outperforming the GoPro 5s, with the strongest correlations seen with GoPro 7s for 15 out of the 16 ecoacoustic indices. The exception was low band acoustic entropy (H) calculated from GoPro 5 Raw Audio recordings (rho = 0.75, $p<0.001$). Raw Audio was more strongly correlated with the hydrophone than Video Audio in 12 cases for GoPro 7 and 11 cases for GoPro 5.

Results for any one index were often inconsistent across models and Raw/Video Audio. However, some were generally more strongly correlated. Across both frequency bands, AR, TV, ACI and H reported strong correlations for three out of four model/audio types (rho>0.5, $p<0.001$). At the lower end, BI and Snap Rate showed little correlation in most instances. ADI and AEI exhibited a general reliability (rho = 0.46–0.7, $p<0.001$) except when GoPro 5 Video Audio was used which showed little to no correlation (rho<0.4, $p>0.05$ or above).



Significance: *** denotes p<0.001, ** denotes p<0.01, * denotes p<0.05

Figure 5. Spearman's rank-order correlation test scores between indices calculated from GoPro and Hydrophone recordings. Colour gradient indicates strength of correlation, with no correlation (rho = 0) indicated by white and a perfect correlation (rho = 1 or -1) indicated by black. Rows are presented in ascending rank order of the GoPro 7 Raw Audio results. AR: Acoustic Richness; TV: Temporal Variability; ACI: Acoustic Complexity Index; H: Acoustic Entropy; AEI, Acoustic Eveness Index; ADI: Acoustic Diversity Index; Snap: Snap Rate; BI: Bioacoustic Index. Low: 0.1–1.5 kHz; High: 1.5–20 kHz.

3.5 Reef soundscape: Quantitative accuracy of GoPro-derived acoustic indices

Results with a significant positive correlation were tested for quantitative accuracy using the Passing-Bablok regression analysis. This test reports a slope and intercept used to indicate proportional and constant bias respectively, with upper and lower confidence intervals for each (Appendix D). If these intervals encompass 1 for the slope and 0 for the intercept then the two methods under comparison (GoPro and hydrophone) are said to be in agreement and can be used interchangeably at the level of confidence set.

No GoPro-index combinations satisfied these criteria when confidence was set to 90% and above. When confidence was set to 80% one measure passed the test; low band ACI calculated from GoPro 7 Raw Audio recordings, reporting adequate intervals for the slope (0.96–1.01) and the intercept (-1.29–8.05) (Appendix D).

4. Discussion

We trialled two models of consumer-grade GoPros, for which a correlation test supported the hypothesis that these devices can be used as reliable tools to collect recordings for ecoacoustic indices in an underwater setting. However, when compared with recordings from the hydrophone, neither GoPro model passed the Passing-Bablok regression analysis with 90% confidence, suggesting that GoPros should not be used interchangeably with alternative recording devices.

Our results demonstrate that GoPros can be used to provide uncalibrated measures of selected ecoacoustic indices for marine soundscapes, and that these results can be reliably compared to results from other devices of the same model. The most suitable audio recordings on a GoPro in this study were collected using the 'raw' audio setting (enabled with the inbuilt 'Protune' setting), and the GoPro 7 outperformed the GoPro 5. However, our results do not support the interchangeable use of indices from GoPro and hydrophone recordings: within a study both types of device should not be used together to make recordings that will be compared against one another. This agrees with common good practice that relative (i.e. non-calibrated) sound measures from different devices should not be directly compared (Merchant et al., 2015). More insights on interpreting reliability and accuracy are provided in Appendix C.

To better understand the variation between devices we compared spectrograms and PSD plots of recordings of artificially generated signals recorded in a playback experiment as well as simultaneous recordings taken on the reef. These revealed consistent recording properties within models (5 and 7) and audio types (raw and video) (Appendix Fig. A.2). However, notable differences between these groups were observed, including average power in the normalised spectrograms (Fig. 3) which highlighted differing levels of overall gain applied by each device, including between GoPro models.

Information on the sensitivity and frequency response of most hydrophones is available to the user allowing the true acoustic signal to be determined. However, calibration is not performed during the manufacturing process of GoPros. This precludes the use of GoPros as absolute sound pressure sensors. However, our results confirm that non-calibrated devices can be used as relative sensors: each acoustic index used in this study assesses the sound recorded relative to itself so that the absolute amplitude of the signal does not change the result.

Spectrogram and PSD plots demonstrated that the hydrophone (SoundTrap) captured the full extent of the multi-tone signal with a uniform frequency response for the sinusoidal sweep. GoPro video audio exhibited a skewed response towards low frequencies and rolled down at higher frequencies (above 10–15 kHz). This asymmetry was much less pronounced for recordings taken with the 'raw' settings which could more effectively record across the full spectrum, especially for the GoPro 5. However, these plots reveal advantages of the GoPro 7 elsewhere, including strong peaks for a greater number of the multiple pure tones at higher frequencies in the PSD plots, and less variability in the sine sweep observable in the cross-spectrum and PSD plot. GoPro default settings (audio embedded in video) use automatic gain control, which auto-adjusts the gain based on how loud or quiet the input signal is, thus biasing the recordings and the estimation of indices. The frequency response of such a system is not only non-linear, but also variable depending on the input, making any comparison between recordings unreliable due to these inconsistencies. When uncalibrated, a device needs a flat response in the frequencies of interest. The 'raw' audio files generated by GoPro 5 and GoPro 7 deliver a flatter response than the video audio, highlighting the advantage of these recordings when using them as a tool for passive acoustic monitoring (PAM).

Our results support the use of GoPros for a range of underwater bioacoustics applications. The GoPros tested here record from 0–20 kHz, which covers the spectral range over which most known noises produced by reef organisms occur (Tricas & Boyle, 2009; Lillis & Mooney, 2016), and through analysis of acoustic indices derived from aquatic soundscapes within this range, has provided useful insights about underlying ecology (Kaplan & Mooney, 2016; Nedelec et al., 2016). AR, TV and ACI in both frequency bands, and H in the higher frequency band (1.5–20 kHz), calculated from GoPro 7 raw audio recordings, presented a satisfactory proportional bias (slope) and correlation. These indices have been shown previously to have a relationship with a number of marine ecosystem attributes (Bertucci, et al., 2016; Harris et al., 2016; Gordon et al., 2018b; Elise, Bailly, et al., 2019). Although the signal-to-noise ratio was significantly smaller for GoPros than for the SoundTraps, GoPros still provide sufficient sensitivity to act as an event detection tool, and could in help monitoring aquatic animal vocalisations, other acoustic events that consist of distinct specific sounds up to 20 kHz, including anthropogenic noise pollution, and for highlighting differences in soundscapes.

Commercially available low-cost acoustic monitoring devices have become frequently used in land-based PAM and soundscape ecology applications (e.g., AudioMoth (Hill et al., 2018), Solo (Whytock & Christie, 2017)), with some models built for specific taxonomic groups (e.g., bats: Peersonic Ltd (https://www.peersonic.co.uk/)). These devices generally come uncalibrated yet offer the necessary requirements to answer many questions about the soundscapes and animal vocalisations. Although underwater PAM and the study of marine mammals and fish communication are increasing (Lindseth & Lobel, 2018; Würsig et al., 2018), no such tools have not yet reached the underwater world. Action cameras (such as GoPros) are used widely both by the public for aquatic recreation activities, and by marine scientists to monitor animal behaviour or assess species abundance and biodiversity. Due to their low cost and high accessibility, GoPros present an opportunity to greatly expand the field of aquatic soundscape ecology. This includes use in new forms of citizen science projects, which could allow soundscape ecologists to increase their sampling strategy across previously impossible temporal and spatial scales, and enable practitioners already using these devices for capturing video to add an additional element to their investigations through combining audio and visual data. We encourage others to capitalise on this opportunity and contribute to the global exploration of marine and freshwater soundscapes where there remains so much to be discovered. Good practice should be employed through accounting for confounding variables typically considered in the marine environment (e.g., depth, habitat type) and others such as diel and lunar periods which can have strong influences on marine soundscape (Erica Staaterman et al., 2014; M. B. Kaplan, Mooney, Lammers, & Zang, 2016). Furthermore, it is clear from this study that comparisons of metrics from recordings using different recorders should be avoided unless the level of cross-device variation has been assessed (Merchant et al., 2015).

This study shows that sophisticated underwater acoustic sensors are not always necessary for collecting valuable ecoacoustic data for remote monitoring, as more accessible action cameras may be able to contribute. It also offers a methodological framework to assess and compare novel devices against hydrophones acting as a reference standard for comparisons, as recorder-specific attributes can influence the reliability and quantitative accuracy of the metrics derived, and also to test for within-model variation. As further advances in recording technology emerge and new equipment becomes available, we also encourage the testing of these against established hydrophones using a similar approach to the one presented here before employing them into large-scale collaborative aquatic soundscape monitoring programmes.

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Authors' contributions

Lucille Chapuis & Ben Williams: Conceptualization, Methodology, Investigation Formal analysis, Writing - Original draft, Reviewing and editing **Tim A. C. Gordon**: Investigation, Writing – Reviewing and editing **Stephen D. Simpson**: Conceptualization, Methodology, Supervision, Funding acquisition, Writing – Reviewing and editing.

Supporting Information

See attached Appendices A–D.

Data Availability

Raw audio and video data totals 2 TB and is stored on hard drives that can be made available upon reasonable request to Ben Williams (bw339@exeter.ac.uk).

References

Abu-Arafeh, A., Jordan, H., & Drummond, G, 2016. Reporting of method comparison studies: a review of advice, an assessment of current practice, and specific suggestions for future reports. *British Journal of Anaesthesia*, *117*, 569–575. doi:10.1093/bja/aew320

Bertucci, F., Parmentier, E., Lecellier, G., Hawkins, A. D., & Lecchini, D, 2016. Acoustic indices provide information on the status of coral reefs: An example from Moorea Island in the South Pacific. *Scientific Reports*, *6*, 1–9. doi:10.1038/srep33326

Bilic-Zulle, L, 2011. Lessons in biostatistics Comparison of methods : Passing and Bablok regression. *Biochemia Medica*, *21*, 49–52. doi: 10.11613/BM.2011.010

Bohnenstiehl, Delwayne R., Lillis, A., & Eggleston, D. B, 2016. The curious acoustic behavior of estuarine snapping shrimp: Temporal patterns of snapping shrimp sound in sub-tidal oyster reef habitat. *PLoS ONE*, *11*, 1–21. doi:10.1371/journal.pone.0143691

Bohnenstiehl, DelWayne R., Lyon, R. P., Caretti, O. N., Ricci, S. W., & Eggleston, D. B, 2018. Investigating the utility of ecoacoustic metrics in marine soundscapes. *Journal of Ecoacoustics*, *2*, R1156L. doi:10.22261/jea.r1156l

Bradfer-Lawrence, T., Gardner, N., Bunnefeld, L., Bunnefeld, N., Willis, S. G., & Dent, D. H, 2019. Guidelines for the use of acoustic indices in environmental research. *Methods in Ecology and Evolution*, *10*, 1796–1807. doi:10.1111/2041-210X.13254

Canada, A. R. C. of, Truax, B., & Project, W. S, 1978. *The world soundscape project's handbook for acoustic ecology*. ARC Publications: Aesthetic Research Centre: World Soundscape Project.

Carstensen, B, 2011. *Comparing Clinical Measurement Methods: A Practical Guide - Bendix Carstensen*. John Wiley & Sons. pp. 1-3.

Carstensen, B., Gurrin, L., Ekstrom, C., & Figurski, M, 2012. MethComp: functions for analysis of method comparison studies. *R Package Version*, *1*.

Chen, W, 2020. Align Wave. MATLAB Central File Exchange.

Coquereau, L., Grall, J., Chauvaud, · Laurent, Gervaise, C., Clavier, J., Aurélie Jolivet, ·, & Iorio, L. Di, 2016. Sound production and associated behaviours of benthic invertebrates from a coastal habitat in the north-east Atlantic. *Marine Biology*, *3*, 127. doi:10.1007/s00227-016-2902-2

de Virgilio, M., Cifarelli, S., de Gennaro, P., Garofoli, G., & Degryse, B, 2020. A first attempt of citizen science in the genetic monitoring of a *Posidonia oceanica* meadow in the Italian Southern Adriatic Sea. *Journal for Nature Conservation*, *56*, 125826. doi:10.1016/j.jnc.2020.125826

Depraetere, M., Pavoine, S., Jiguet, F., Gasc, A., Duvail, S., & Sueur, J, 2012. Monitoring animal diversity using acoustic indices: Implementation in a temperate woodland. *Ecological Indicators*, *13*(1), 46–54. doi:10.1016/j.ecolind.2011.05.006

Duarte, C. M., Chapuis, L., Collin, S. P., Costa, D. P., Devassy, R. P., Eguiluz, V. M., … Juanes, F, 2021, February 5. The soundscape of the Anthropocene ocean. *Science*. American Association for the Advancement of Science. doi:10.1126/science.aba4658

Elise, S., Bailly, A., Urbina-Barreto, I., Mou-Tham, G., Chiroleu, F., Vigliola, L., … Bruggemann, J. H, 2019. An optimised passive acoustic sampling scheme to discriminate among coral reefs' ecological states. *Ecological Indicators*, *107*, 105627. doi:10.1016/j.ecolind.2019.105627

Elise, S., Urbina-Barreto, I., Pinel, R., Mahamadaly, V., Bureau, S., Penin, L., … Bruggemann, J. H, 2019. Assessing key ecosystem functions through soundscapes: A new perspective from coral reefs. *Ecological Indicators*, *107*, 105623. doi:10.1016/j.ecolind.2019.105623

Erbe, C., Verma, A., McCauley, R., Gavrilov, A., & Parnum, I, 2015. The marine soundscape of the Perth Canyon. *Progress in Oceanography*, *137*, 38–51. doi: 10.1121/10.0001101

Florisson, J. H., Tweedley, J. R., Walker, T. H. E., & Chaplin, J. A, 2018. Reef vision: A citizen science program for monitoring the fish faunas of artificial reefs. *Fisheries Research*, *206*, 296–308. doi: 10.1016/j.fishres.2018.05.006

Ford, A. K., Eich, A., McAndrews, R. S., Mangubhai, S., Nugues, M. M., Bejarano, S., … Ferse, S. C. A, 2018. Evaluation of coral reef management effectiveness using conventional versus resilience-based metrics. *Ecological Indicators*, *85*, 308–317. doi: 10.1016/j.ecolind.2017.10.002

Gedamke, J., & Robinson, S. M, 2010. Acoustic survey for marine mammal occurrence and distribution off East Antarctica (30-80 E) in January-February 2006. *Deep Sea Research Part II: Topical Studies in Oceanography*, *57*, 968–981. doi: 10.1016/j.dsr2.2008.10.042

Gordon, T. A. C., Harding, H. R., Wong, K. E., Merchant, N. D., Meekan, M. G., McCormick, M. I., … Simpson, S. D, 2018a. Habitat degradation negatively affects auditory settlement behavior of coral reef fishes. *Proceedings of the National Academy of Sciences of the United States of America*, *115*, 5193–5198. doi:10.1073/pnas.1719291115

Gordon, T. A. C., Harding, H. R., Wong, K. E., Merchant, N. D., Meekan, M. G., McCormick, M. I., … Simpson, S. D, 2018b. Habitat degradation negatively affects auditory settlement behavior of coral reef fishes. *Proceedings of the National Academy of Sciences*, *115*, 5193–5198. doi:10.1073/pnas.1719291115

Harris, S. A., Shears, N. T., & Radford, C. A, 2016. Ecoacoustic indices as proxies for biodiversity on temperate reefs. *Methods in Ecology and Evolution*, *7*, 713–724. doi:10.1111/2041-210X.12527

Hill, A. P., Prince, P., Piña Covarrubias, E., Doncaster, C. P., Snaddon, J. L., & Rogers, A, 2018. AudioMoth: Evaluation of a smart open acoustic device for monitoring biodiversity and the environment. *Methods in Ecology and Evolution*, *9*, 1199–1211. doi:10.1111/2041-210X.12955

Kaplan, M. B., & Mooney, T. A, 2016. Coral reef soundscapes may not be detectable far from the reef. *Scientific Reports*, *6*, 1–10. doi:10.1038/srep31862

Kaplan, M. B., Mooney, T. A., Lammers, M. O., & Zang, E, 2016. Temporal and spatial variability in vessel noise on tropical coral reefs. *Proceedings of Meetings on Acoustics*, *27*(1. doi:10.1121/2.0000250

Kaplan, M., Mooney, T., Partan, J., & Solow, A, 2015. Coral reef species assemblages are associated with ambient soundscapes. *Marine Ecology Progress Series*, *533*, 93–107. doi:10.3354/meps11382

Kennedy, E. V., Holderied, M. W., Mair, J. M., Guzman, H. M., & Simpson, S. D, 2010. Spatial patterns in reef-generated noise relate to habitats and communities: Evidence from a Panamanian case study. *Journal of Experimental Marine Biology and Ecology*, *395*, 85–92. doi:10.1016/j.jembe.2010.08.017

Lau, S. T., Kwok, K. W., Chan, H. L. W., & Choy, C. L, 2002. Piezoelectric composite hydrophone array. *Sensors and Actuators A: Physical*, *96*, 14–20. https://doi.org/10.1016/S0924-4247(01)00757-9

Lefcheck, J. S., Innes-Gold, A. A., Brandl, S. J., Steneck, R. S., Torres, R. E., & Rasher, D. B, 2019. Tropical fish diversity enhances coral reef functioning across multiple scales. *Science Advances*, *5*, eaav6420. doi: 10.1126/sciadv.aav6420

Lillis, A., & Mooney, T. A, 2016. Loudly heard, little seen, and rarely understood: Spatiotemporal variation and environmental drivers of sound production by snapping shrimp. *Citation: Proceedings of Meetings on Acoustics*, *27*, 10017. doi:10.1121/2.0000270

Lindseth, A. V., & Lobel, P. S, 2018. Underwater soundscape monitoring and fish bioacoustics: A review. *Fishes*, *3*. doi:10.3390/fishes3030036

Magari, R. T, 2002. Statistics for laboratory method comparison studies. *BioPharm*, *15*, 28–32.

Merchant, N. D., Fristrup, K. M., Johnson, M. P., Tyack, P. L., Witt, M. J., Blondel, P., & Parks, S. E, 2015. Measuring acoustic habitats. *Methods in Ecology and Evolution*, *6*, 257–265. doi:10.1111/2041-210X.12330

Nedelec, S. L., Mills, S. C., Lecchini, D., Nedelec, B., Simpson, S. D., & Radford, A. N, 2016. Repeated exposure to noise increases tolerance in a coral reef fish. *Environmental Pollution*, *216*, 428–436. doi:10.1016/j.envpol.2016.05.058

Nedelec, S. L., Simpson, S. D., Holderied, M., Radford, A. N., Lecellier, G., Radford, C., & Lecchini, D, 2015. Soundscapes and living communities in coral reefs: Temporal and spatial variation. *Marine Ecology Progress Series*, *524*, 125–135. doi:10.3354/meps11175

Piercy, J. J. B., Codling, E. A., Hill, A. J., Smith, D. J., & Simpson, S. D, 2014. Habitat quality affects sound production and likely distance of detection on coral reefs. *Marine Ecology Progress Series*, *516*, 35–47.

Raoult, V., David, P. A., Dupont, S. F., Mathewson, C. P., O’Neill, S. J., Powell, N. N., & Williamson, J. E, 2016. GoPros™ as an underwater photogrammetry tool for citizen science. *PeerJ*, *4*, e1960. doi: 10.7717/peerj.1960

Sousa-Lima, R. S., Norris, T. F., Oswald, J. N., & Fernandes, D. P, 2013. A review and inventory of fixed autonomous recorders for passive acoustic monitoring of marine mammals. *Aquatic Mammals*, *39*. doi: 10.1109/RIOAcoustics.2013.6683984

Staaterman, E., Rice, A. N., Mann, D. A., & Paris, C. B, 2013. Soundscapes from a Tropical Eastern Pacific reef and a Caribbean Sea reef. *Coral Reefs*, *32*, 553–557. doi:10.1007/s00338-012-1007-8

Staaterman, Erica, Paris, C. B., DeFerrari, H. A., Mann, D. A., Rice, A. N., & D'Alessandro, E. K, 2014. Celestial patterns in marine soundscapes. *Marine Ecology Progress Series*, *508*, 17–32. doi:10.3354/meps10911

Sueur, J., 2018. Indices for Ecoacoustics. In *Sound Analysis and Synthesis with R* (pp. 479–519). Springer, Cham. doi:10.1007/978-3-319-77647-7_16

Sueur, J., Aubin, T., & Simonis, C, 2008. Equipment review: Seewave, a free modular tool for sound analysis and synthesis. *Bioacoustics*, *18*, 213–226. doi:10.1080/09524622.2008.9753600

Sueur, J., Farina, A., Gasc, A., Pieretti, N., & Pavoine, S, 2014. Acoustic indices for biodiversity assessment and landscape investigation. *Acta Acustica United with Acustica*, *100*, 772–781. doi:10.3813/AAA.918757

Tricas, T. C., & Boyle, K, 2009. Validated reef fish sound scans of passive acoustic monitors on Hawaiian coral reefs. *The Journal of the Acoustical Society of America*, *125*, 2589.

Villanueva-Rivera, L. J., Pijanowski, B. C., & Villanueva-Rivera, M. L. J, 2018. Package 'soundecology'.

Villon, S., Mouillot, D., Chaumont, M., Darling, E. S., Subsol, G., Claverie, T., & Villéger, S, 2018. A deep learning method for accurate and fast identification of coral reef fishes in underwater images. *Ecological Informatics*, *48*, 238–244.

Whytock, R. C., & Christie, J, 2017. Solo: an open source, customizable and inexpensive audio recorder for bioacoustic research. *Methods in Ecology and Evolution*, *8*, 308–312. doi:10.1111/2041-210X.12678

Würsig, B., Perrin, W. F., & Thewissen, J. G. M, 2018. History of Marine Mammal Research. In *Encyclopedia of Marine Mammals* (pp. 472–477). Elsevier. doi:10.1016/b978-0-12-804327-1.00150-3

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