inter.noise 2014
MELBOURNE AUSTRALIA
16-19 NOVEMBER

Marine Soundscape Ecology

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ABSTRACT

In the face of accelerated climate change, monitoring biodiversity has become a critical task for ecologists. Habitat loss is occurring at an alarming rate both in terrestrial and marine ecosystems, resulting in endangerment and extinction of species up to 1,000 times faster than natural rates. However, traditional biodiversity measurements are logistically and financially difficult, making biodiversity monitoring a challenging obstacle to conservation efforts. In terrestrial environments, "Soundscape Ecology" has recently emerged as a potential solution to these problems, providing a mechanism for measuring biodiversity at various temporal and spatial scales using acoustic signatures. Several acoustic diversity indices have proven to be useful indicators of biodiversity in a variety of landscapes. Thus far, this technique has not been extended to marine environments. What is known is that different marine habitats have distinct sound signatures both in temperate and tropical waters. For example, studies have shown that temperate reefs from within a marine reserve have a different spectral signature compared to reefs outside the reserve. Also, a fringing reef from a tropical island has a different spectral signature to those of the lagoon and back reefs. Here we highlight the research potential for using acoustics to monitor marine biodiversity and what is required for this field to progress.

Keywords: Sound, Soundscape, Soundscape Ecology, Biodiversity I-INCE Classification of Subjects Number(s): 03.9, 08.4, 13.5, 22, 54.3, 56.3

1. INTRODUCTION

1.1 Biodiversity

Monitoring biodiversity has become a global imperative as a result of broad-scale environmental degradation and climate change (1). Despite growing international conservation efforts, biodiversity continues to decline across the planet's varied ecosystems, posing a significant threat to the future stability of environmental as well as human welfare. To counteract the negative impacts of anthropogenic activities on global biodiversity levels, the United Nations Educational, Scientific and Cultural Organization (UNESCO) has launched a global-scale Biodiversity Initiative to support its signatory nations in reaching biodiversity and conservation targets

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(http://www.unesco.org/new/en/natural-sciences/special-themes/biodiversity-initiative). Twenty international targets for biodiversity were established in 2010 by the Convention on Biological Diversity (CBD), many of which require accurate and efficient monitoring to assess their progress and inform policy decisions (1).

However, there are numerous challenges associated with biodiversity measurement. Even in easy-to-access environments, recording biodiversity is time-consuming, labour-intensive, expensive, invasive and highly susceptible to human errors and biases. Often it involves the employment of trained specialists who must individually identify species within a given area by hand—a process that can take weeks or months to complete (2). Additionally, the physical presence of humans introduces uncertainty. Humans are visually biased towards larger, less-camouflaged species (3). Furthermore, interactions with animals in the field that skew results by attracting certain species and deterring others are unavoidable (2, 4). The difficulties inherent in measuring biodiversity generally result in an inability to conduct biodiversity-monitoring programs over large spatial or temporal scales. Unfortunately, global-scale biodiversity loss requires data at these scales to inform management and policy decisions.

Marine habitats are particularly difficult to access, increasing the challenges associated with biodiversity measurement in these locations. Biodiversity measures underwater require additional expensive equipment and often result in significantly biased results due to the influence of human presence on marine organisms (4, 5). Despite this, the ocean contains many of the world's most biologically diverse systems, and the need to monitor diversity within these systems is a high priority for conservation efforts (1). Coastal habitats are disappearing rapidly as human developments, destructive harvesting and fishery practices and reductions in water quality intensify, and structurally complex habitats, which are critical for maintaining biodiversity, are becoming increasingly rare (6). Coastal environments often contain irreplaceable natural resources, and the loss of natural habitat within these areas can result in permanent damage. It is therefore imperative that accurate, efficient and affordable mechanisms for marine biodiversity measurement are developed.

1.2 Soundscape Ecology

Promising improvements to biodiversity measurements have recently arisen within the context of an emerging field known as Soundscape Ecology. The foundational principles of Soundscape Ecology rely on the fact that sound is an integral part of nature and can provide valuable information about the environment within which it is produced. Pijanowski *et al.* (7) published the first comprehensive presentation of Soundscape Ecology, in which the soundscape is defined as "the collection of sounds that emanate from landscapes." These sounds include biological noises (biophony), geological noises (geophony), and anthropogenic noises (anthrophony). Together, the biophony, geophony and anthrophony comprise a unique acoustical signature that may vary over distinct spatial and temporal scales, providing invaluable information about its origin (7). Within the field of biological conservation, there is a growing recognition that "soundscapes possess both ecological and social value," and therefore that they should be conserved as natural resources (8).

Acoustic monitoring can allow for detailed progress reports on habitat health in real time. For instance, certain types of sound, whether natural or unnatural, may provide clues that help ecologists distinguish between healthy or deteriorating environments (7). Effects of anthropogenic activity, including habitat fragmentation; introduced diseases; population depletion through hunting; chemical pollution; noise pollution and many others may alter the status quo of animals' acoustic behaviour, thereby altering the overall acoustic signature of an area (9). Indeed, several studies show that variation in the soundscape can be "an early-warning indicator" of disturbances to the natural environment (9). Acoustic techniques are now employed in the tagging and tracking of populations or individuals; evaluations of the differences between populations and habitats; re-colonization of degraded environments through manipulation of settlement cues and estimations of population density or diversity (9).

Soundscape Ecology is a critical platform for using and expanding on these principles. Rather than recording specific species, Soundscape Ecology takes a holistic view of the entire sound-producing community of organisms (2). Within this framework, ecologists have developed several ways to use the acoustical patterns of a landscape as a biodiversity indicator in terrestrial environments. Biodiversity tracking in the context of Soundscape Ecology is faster than traditional methods because data can be collected and analyzed in real time (2). Moreover, it is less expensive as necessary field equipment is limited to microphones and often circumvents the necessity for trained specialists; and it is non-invasive, which minimises human errors and biases as well as environmental impacts (2). Soundscape Ecology enables access to a greater range of areas than traditional biodiversity sampling methods, and is more easily conducted over large spatial and temporal scales (2). Finally, there is the potential for increased amateur involvement in acoustic biodiversity monitoring, which allows for accelerated data collection and broader-scale habitat evaluation.

1.3 Sound in the Marine Environment

Acoustics has been studied in marine environments for decades and there is a broad body of existing knowledge on the subject. Cato's (10, 11) early work was the first to describe diurnal patterns of ambient sound in the marine environment around Australia. More recently, Radford *et al.* (12) described the diurnal, lunar and seasonal patterns of ambient sound from a temperate reef in New Zealand. The most intense noises produced by reefs occur at dawn and dusk, and are referred to as the morning and evening choruses (12). Typically, the evening chorus is the loudest. Over the course of a month, reef noise will vary significantly, with more intense sounds produced during the New Moon and the least intense sounds produced under the Full Moon (14). Finally, it is evident that overall sound intensity is higher during the summer than during the winter in coastal habitats (14), where the primary sources of sound are sea urchins and snapping shrimp, though several noise-producing fish and mammals also contribute to the soundscape (12, 13, 14).

In addition to temporal patterns in reef sounds, there is variation in marine soundscapes over changing habitats and locations, meaning that marine sounds carry unique information about the quality and conditions of the habitats in which they were produced (4, 15). Reef noises also play critical roles in navigation, larval recruitment and settlement for many fish and invertebrate species because of their location-dependent nature, making the preservation of diverse coastal marine soundscapes even more vitally important (16).

1.4 Marine Soundscape Ecology

A small number of studies have begun to investigate the possible application of Soundscape Ecology to the marine environment in the last few years. Lammers *et al.* (17) used equipment called Ecological Acoustic Recorders (EARs) to show that reef sounds should reflect changes in ecological conditions by demonstrating that observable patterns in acoustic activity are correlated with structural characteristics of the local environment. Parks *et al.* (18) investigated ocean basins using low-frequency noises made by three species of migratory whales to test the hypothesis that terrestrial acoustic diversity indices reflect biodiversity in marine environments. They used a noise-compensated entropy index, H_N, and found that it was reflective of the number of species-specific whale vocalizations present in recordings, displaying promise for the use of rapid acoustic assessment as an indicator of biodiversity and health in marine environments. Kennedy *et al.* (14) examined acoustic recordings from the Las Perlas Archipelago in Pacific Panama and concluded that a number of positive correlations were present between acoustic characteristics and the density, diversity and biomass of fish, benthic invertebrates and algae as well as physical reef structure and sea state. Finally, Lillis *et al.* (19) demonstrated that acoustic monitoring of oyster reefs reveals a relationship between benthic and acoustic characteristics in these settings.

These studies indicate that acoustic assessment of marine environments should yield valuable information on habitat health and biodiversity. However, their scope has been narrow and their conclusions limited. ~~Here we present the preliminary results from a broad-scale, multi-species study incorporating all trophic levels and investigating acoustical patterns over various spatial and temporal scales.~~

2. METHODS

The overall study consisted of nine temperate coastal reefs typical of northeastern New Zealand, selected based on their accessibility and habitat composition. Three of the sites were within the boundaries of the Goat Island Marine Reserve; three were within the Tāwharanui Marine Reserve and three were unprotected. ~~Here we will present the results of an example from one habitat within each location: Nordic Reef, a small unprotected reef adjacent to a busy commercial and recreational harbour, Pinnacle, a rocky reef on the edge of the Tāwharanui reserve, and OneSpot, a steep-sloping boulder landscape in the middle of the Cape Rodney Okakuri Point Marine Reserve (Fig. 1).~~

At each site, a SUDAR hydrophone (www.oceanacoustics.co.nz) was positioned 15 m from the outer edge of each reef on the seabed to record acoustic activity. It has recently been demonstrated that shallow reef habitats behave as extended sound sources, exhibiting a "reef effect" whereby sound intensity surrounding a reef does not decrease over a radial distance approximately equal to the length of the reef (20). Thus, all hydrophones were positioned within this reef effect zone to avoid signal degradation. Two-minute sound bites were recorded every 15 minutes at 144 kHz and 16 BITS. Preliminary data were taken over a three-day period from the 28 February to 02 March 2014, centered on the summer new moon. Sixty-second samples of each two-minute recording were used. Since relevant biological sound should not occur outside of the 50 Hz – 24 kHz frequency range, all recordings were subjected to a bandpass filter with these limits.

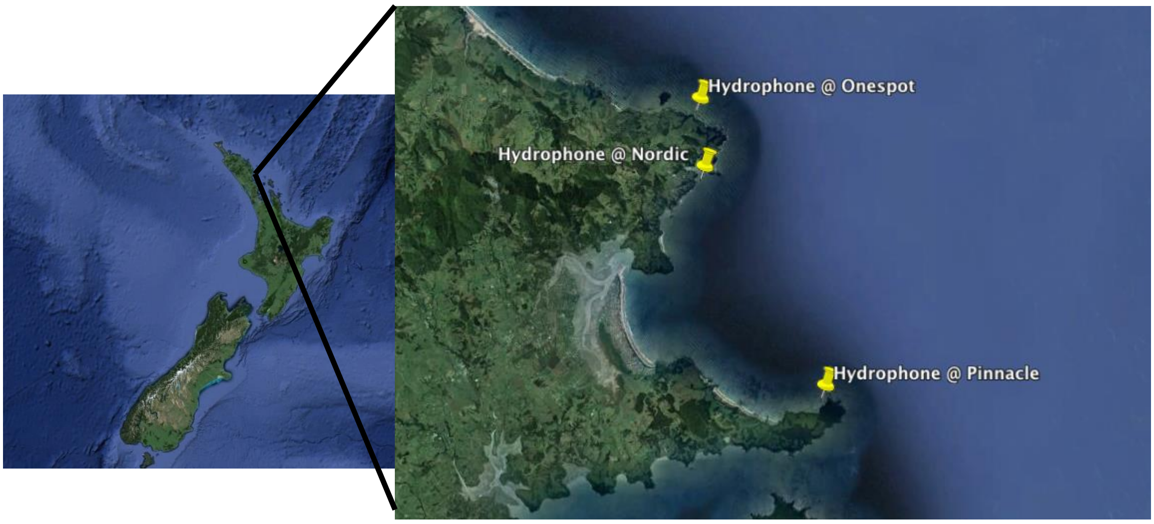

Figure 1: Map showing the locations of Nordic Reef, Pinnacle and OneSpot in northeastern New Zealand. Exact hydrophone deployment locations are marked with yellow pins.

A number of different acoustical indices have been developed as indicators of biodiversity. The underlying principle behind each of them is the same: the greater the acoustic diversity (the more variation there is in the components of the soundscape), the more diverse is the community of organisms that generated those sounds (2). It has been shown that various types of biodiversity (for instance, α or β indices) correspond to distinct components of the overall soundscape and to different acoustic indices (2, 21, 22).

Sueur *et al.* (2) developed the first acoustic biodiversity indices, including the Acoustic Entropy Index (H). H is a measure of alpha diversity, adapted from the Shannon Index and applied to both the temporal and spectral components of acoustic data to obtain measures of temporal entropy (H_t), and spectral entropy (H_f). The product of these components ($H_t \times H_f$) is the overall Acoustic Entropy (H). Essentially, H measures the evenness of the amplitude of sounds over time and across the full range of frequencies. Like the Shannon Index, H will increase from zero (for a pure tone) to one (for random noise) as the numbers of relevant frequency bands and amplitude modulations in a given signal increase (2).

The variability of the H index increases as the number of species decreases, meaning that more error is associated with calculations of acoustic diversity for communities with very few species (2). Additionally, local background noise has been found to significantly affect the H index (21). In an effort to mitigate these shortcomings, an Acoustic Richness Index (AR) was developed by Depraetere *et al.* (21). It weights the temporal entropy (H_t) as well as the amplitude of a signal by the median amplitude of the same signal to account for background noise (21).

Another acoustic index, the Acoustic Complexity Index (ACI), was developed for analyzing avian communities and measures the variation in intensity of a given recording over changing frequencies (22). ACI is particularly useful in areas affected by constant anthropogenic noise pollution, as it was developed specifically to identify diverse natural sounds despite the presence of human-generated background noise.

In this study, the Acoustic Complexity Index (ACI), Acoustic Entropy Index (H) and Acoustic Richness Index (AR) were calculated for Nordic Reef, Pinnacle and OneSpot (Fig. 1) and averaged by time of day over the three-day period surrounding the summer new moon. Calculations were made using the package Seewave, developed for the computing environment R, by Sueur *et al.* (2).

3. PRELIMINARY RESULTS AND DISCUSSION

Spectral analysis shows that there was the characteristic rise in power between 600 Hz and 2,000 Hz for each site at dusk (Fig. 2). At this time, both Nordic Reef (Fig. 2A) and OneSpot (Fig. 2B) have similar peaks at 70 Hz, 180 Hz, 200 Hz and 500-600 Hz, whereas Pinnacle (Fig. 2C) has several spurious peaks between 150 Hz and 200 Hz. All sites also show the acoustical activity expected of coastal reefs at dusk in the higher frequencies (2.5 kHz – 10 kHz), attributed to snapping shrimp. Additionally, at all three sites, high-frequency (> 700 Hz) sounds were consistently more intense at dusk than at midday. In the low-frequency (< 700 Hz) range, each site was distinct. At OneSpot, midday sounds were consistently quieter than dusk sounds; at Nordic Reef, a majority of the sounds at midday were less intense than those at dusk, with some notable exceptions centered around 100 Hz and 200 Hz; at Pinnacle, the opposite behaviour was evident: midday sounds appear to have consistently higher power levels than sounds during the dusk period. At Nordic Reef and OneSpot the power level at midday does not exhibit the same peaks as the power level at dusk, but rather shows a continuous increase in low-frequency (< 700 Hz) sound. ~~These data were consistent with what is known about temperate reef soundscapes (12, 13, 14), for which there is an increase in acoustical activity due to sea urchins and snapping shrimp at dusk (12, 13), and that different habitats have distinct sound signatures (14).~~

Each of the acoustic indices display some variability between sites (Fig. 3), especially the Acoustic Complexity Index (ACI) (Fig. 3A), supporting research that has shown different habitats to have unique acoustic characteristics (15). ACI appears to be the only index for which a consistent pattern exists between sites over an entire day, with the lowest ACI values occurring at dusk, during the hours just after sunset, and a second (smaller) decrease occurring at dawn. It is highly likely that these decreases in the ACI reflect the dawn and dusk choruses. A significant change in the ~~hour's~~ immediately following sunset was consistent with previous findings for reefs from northeastern New Zealand, which have shown that the dusk choruses occur during this time (12). In northeastern New Zealand the dusk chorus soundscape is dominated by two species, urchins and snapping shrimp, which could mask any potential fish vocalisations and therefore may register as less acoustically complex, resulting in decreased ACI values. There are also considerable differences in the ACI between the three sites, with Nordic Reef having the highest ACI and Pinnacle having the lowest. These distinctions are most pronounced at night, indicating a greater level of nocturnal acoustic activity at Nordic Reef. It is possible that Nordic Reef contains more nocturnal species due the heavy boat traffic and fishing activities that happen there during daylight hours.

The Acoustic Entropy Index (H) follows a relatively similar pattern to that of ACI, but has a more pronounced decrease during the dusk chorus (Fig. 3B). This may reflect the fact that in coastal marine settings, the dawn chorus is not as intense as the dusk chorus (12). It seems the H index was less sensitive than the ACI to this lesser increase in biotic activity. The distinction between H values at each of the three sites was also less pronounced than for ACI, suggesting that H is less sensitive to differences between habitats as well.

In contrast to both the ACI and the H indices, the Acoustic Richness Index (AR) significantly increases at dusk (Fig. 3C). Since AR is weighted by the median amplitude of each burst in order to account for volume changes, perhaps it is better suited to detect biological activity despite the loud dawn and dusk choruses. The increase at dusk, then, possibly reflects the increased activity of more than just snapping shrimp and sea urchins during this time. It has been suggested (21) that AR and ACI might be used as complementary indices because ACI has been correlated to the number of vocalisations from an acoustic community whereas AR is more directly correlated to alpha diversity. These preliminary findings confirm that the ACI and AR indices were registering different aspects of the soundscape, and that perhaps they can be used alongside one another to gain a more complete picture of habitat health and diversity.

Clearly, ecologists conducting acoustic diversity and habitat surveys will need to take care in selecting the appropriate time of day for extracting marine sound data as significant diurnal patterns exist for each index. It also seems that certain indices may be more valuable for different types of ecological information. ACI, for instance, was more sensitive to the differences between each of the three sites, and shows a consistent pattern irrespective of time of day. Thus, perhaps ACI is a more appropriate choice for between-site comparisons of acoustic activity levels. AR, on the other hand, was the only one of the three indices to reflect increased biological activity during the dusk chorus, suggesting that possibly it is the most appropriate choice for measuring alpha diversity. Since the differences between habitat types were variable over the course of a day, it would be crucial to keep time of day consistent if between-site comparisons were to be made with AR.

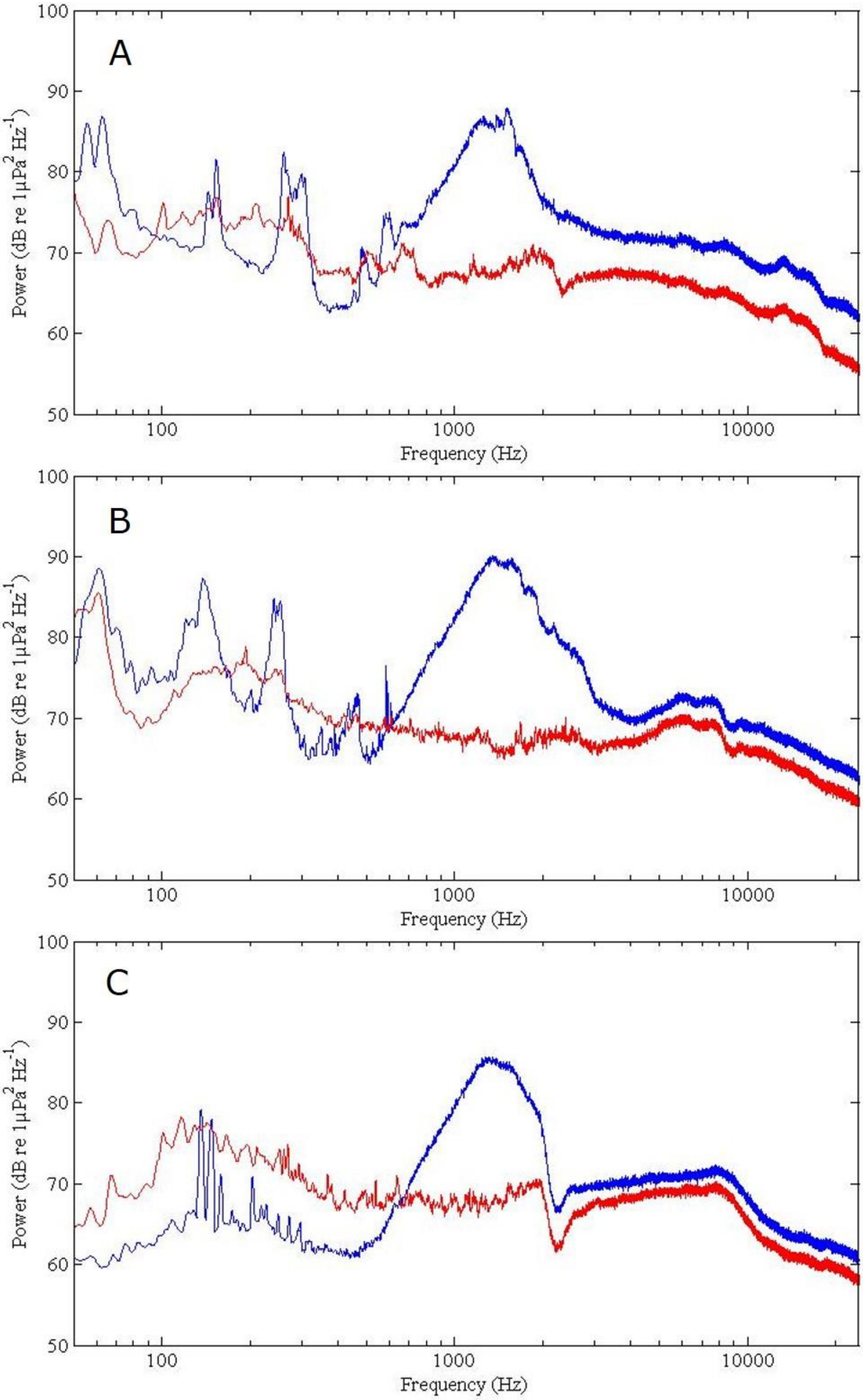

Figure 2: Spectra of midday (red) and dusk (blue) periods for A- Nordic Reef; B- Onespot; and C- Pinnacle.

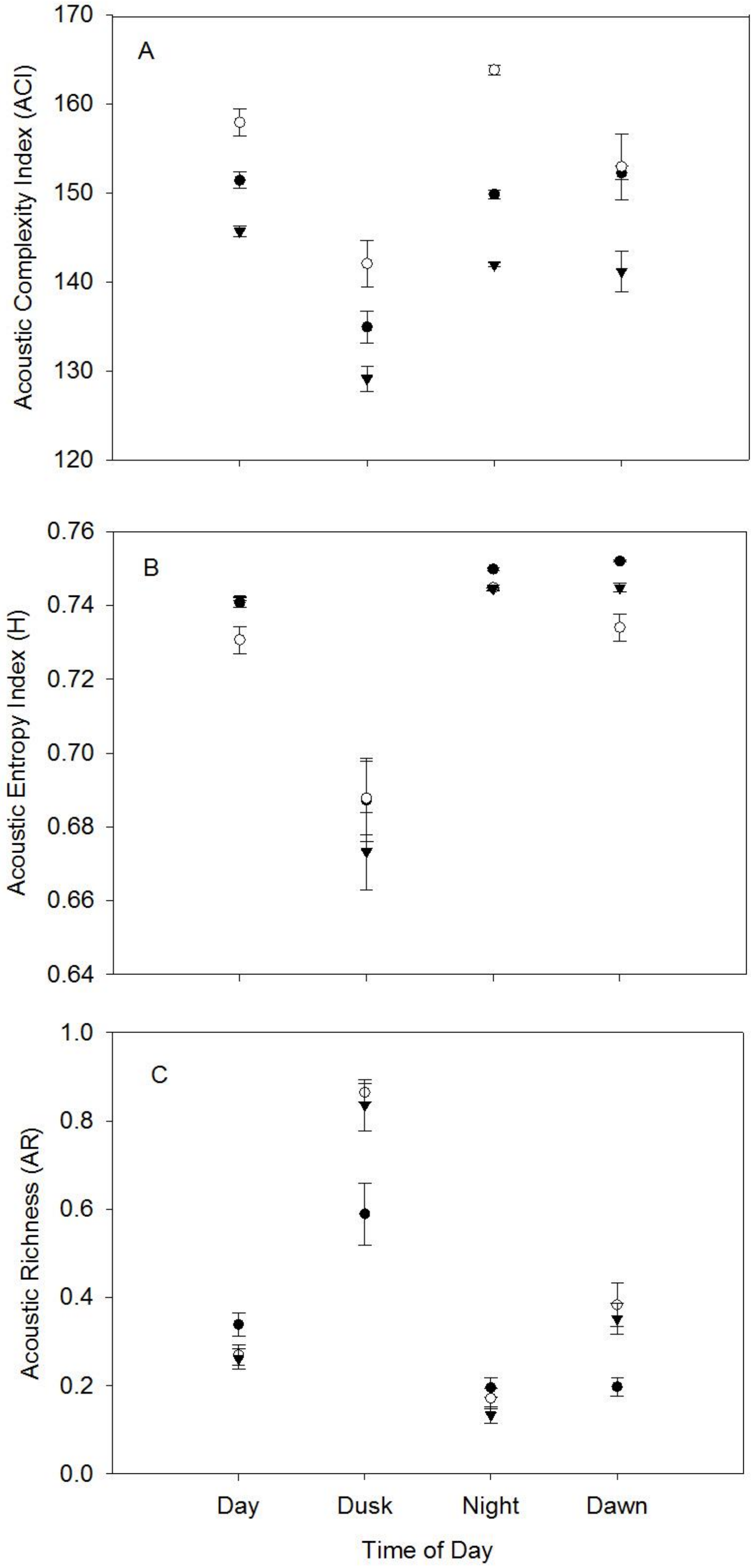

Figure 3: A - Acoustic Complexity Index (ACI); B - Acoustic Entropy Index (H); and C - Acoustic Richness Index (AR) for each site, averaged by time of day. ○ = Nordic Reef; ▼ = Pinnacle; ● = OneSpot. H and AR vary between 0 and 1, whereas ACI is typically in the 100s. All are unit-less numbers.

4. CONCLUSIONS

Marine soundscape ecology seems a promising new tool for tackling the challenges of diversity loss in today's changing climate, but much remains to be learned from acoustic biodiversity monitoring. In this preliminary study we have begun to explore some initial results. In the future, many more avenues must be investigated. Just as time of day influences acoustic index behaviour due to diurnal patterns in biological activity in reef environments, lunar and seasonal cycles are also expected to be relevant to acoustic monitoring. The comparisons presented in this paper will be expanded to all nine sites in northeastern New Zealand, and data covering the entire lunar cycle and changing seasons will be examined as well. Future studies to determine and standardise appropriate analytical methods for marine acoustic data would be extremely valuable. For instance, the window size and shape of the Fourier transform used to compute a spectrogram of each recording is likely to influence results and has not yet been explicitly tested. Efficient methods for handling background noise interference also need to be developed. Perhaps in the near future ecologists will even be able to create specialised diversity indices that are specifically suited to marine use.

ACKNOWLEDGEMENTS

Funding for this research was provided by the Royal Society of New Zealand Rutherford Discovery Fellowship (RDF-13-UOA-010) to CAR. SAH was funded by the Leigh Marine Laboratory.

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