



Advancing coral reef conservation through passive acoustic monitoring

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ABSTRACT

Passive acoustic monitoring (PAM) offers a cost-effective, non-invasive approach to studying coral reef ecosystems; habitats rich in biodiversity but increasingly under threat. Recent advances in acoustic technology and analysis have improved our ability to interpret coral reef soundscapes, revealing how biotic and abiotic processes shape acoustic patterns across space and time. In this synthesis, we provide an integrative overview of current approaches to understanding coral reef ecology through soundscapes, focusing on how commonly used acoustic metrics reflect ecological attributes at individual, population, and ecosystem levels. We explore how habitat structure, species composition, and ecological processes influence these metrics, and assess their validity as proxies for reef health and biodiversity. Drawing on case studies from Australian coral reef systems, we examine the ecological relevance of soundscape metrics by relating them to benthic cover and fish diversity and evaluate how species-specific signals (particularly snapping shrimp snaps and fish calls) shape spatial and temporal variability in the soundscape. We also identify key challenges in PAM interpretation, including signal overlap, propagation effects, and the need for sound source identification. While PAM holds promise as a complementary tool to traditional ecological monitoring, its effective application depends on metric standardisation, validation against ecological baselines, and integration with other datasets. We conclude with practical recommendations for improving the robustness and interpretability of PAM in coral reef conservation, including sensor deployment strategies and methodological harmonisation.

1 INTRODUCTION

Coral reefs are among the most biodiverse and dynamic ecosystems (Fisher et al. 2015) and support ecosystem services benefiting >1 billion people (Mumby et al. 2008). However, coral reefs are undergoing rapid degradation worldwide (Hughes et al. 2017). Traditional diver-based surveys provide only brief temporal snapshots, while satellite-based methods are limited by poor water-column penetration, restricting their ability to detect ecological change (Obura et al. 2019). Passive acoustic monitoring (PAM) provides a complementary approach that is scalable, continuous, and non-invasive, capturing biological, geophysical, and anthropogenic sounds that integrate ecosystem processes across space and time (Mooney et al. 2020).

Recent advances in recording technology and analytical capacity have accelerated reef soundscape studies (Sethi et al. 2018), but ecological interpretation remains inconsistent (Sethi et al. 2023). Many analyses rely on summarised acoustic indices or spectral averages that compress complex data and obscure biological meaning. The lack of causal linkage between acoustic metrics, biological sources, and habitat structure limits their utility for management.

Here, we aimed to establish an integrative approach to examine coral reef soundscape interpretation. Through complementary studies combining theoretical, methodological, and empirical approaches, we examined how reef soundscapes encode ecological information, how methodological choices influence outcomes and ecological interpretations, and how biologically validated signals can support the interpretation of soundscape analyses.

2 METHODS

2.1 Study systems and design

Research was conducted across different reef systems in Australia: Lizard Island on the Great Barrier Reef and Coral Bay at Ningaloo Reef. These sites encompass diverse benthic structures and community compositions, providing ideal settings for soundscape interpretation scrutiny.

2.2 Data acquisition and processing

Recordings were made using calibrated SoundTrap ST300/600 recorders, recording 5-min files every 15 min. Acoustic metrics were computed in MATLAB: 1) Soundscape Code (metrics of amplitude, impulsiveness, periodicity, and uniformity); 2) Standard acoustic indices (H, ACI, AEI, ADI, and NDSI). Fish calls detection, localisation, and motion classification were conducted in Python. Statistical analyses were computed in RStudio (NMDS, PERMANOVA, and Bayesian Models).

2.3 Multi-scale framework

2.3.1 Theoretical synthesis

We summarized sound sources and overall spatial-temporal patterns, ecoacoustic theory (morphological, acoustic adaptation, and acoustic niche hypotheses), current soundscape analyses, and the missing link between acoustic signals and the summarizing soundscape metrics. We propose an integrative framework to interpreting soundscapes without overviewing the compressed biologically meaningful information.

2.3.2 Ecological differentiation

Using the Soundscape Code, we analysed habitat differentiation across 25 simultaneous recordings from back, flat, and fore reef zones in Lizard Island. We explored the correlation between soundscape and the benthic cover and rugosity (3D photogrammetry) and the fish species composition (diver-operated videos).

2.3.3 Methodological calibration

We tested how the distance and orientation of an acoustic sensor relative to a target habitat affects the received soundscape within a spatial array of hydrophones at different distances (1 m, 2 m, 5 m) and orientations (vertical, horizontal) from a shallow coral reef in Coral Bay.

2.3.4 Parameterisation sensitivity

To evaluate the effects of spectrogram parameterisation on multivariate soundscape separation, we computed 432 spectrogram configurations per recording across five commonly acoustic indices, with two example environment comparisons: terrestrial (Bushland vs. Urban) from Western Australia and underwater (*Pocillopora* dominated vs. Non-*Pocillopora* dominated reefs) from Lizard Island.

2.3.5 Behavioural grounding

We compared the courtship call of two sympatric damselfish species in Coral Bay and Lizard Island by deploying portable audio-video arrays, enabling automated detection of pulse trains, 3D localisation, motion classification, and behavioural observations.

3 RESULTS

3.1 Theoretical synthesis

Our review revealed that many soundscape analyses implicitly assume a direct relationship between biodiversity and acoustic energy but rarely validate this link. In addition, most current analyses rely on the use of spectrogram information to visualize data and extract quantitative metrics or machine learning features. The potential biases of not considering the individual signals, parameterisation sensitivity, and sound propagation in the target soundscape is common.

3.2 Ecological differentiation

We found marked differences among nighttime soundscapes among the two types of reef, despite being separated by no more than 30 m. Sound pressure level (amplitude) and dissimilarity index (uniformity) distinguished the soundscapes, reflecting differences in benthic cover and faunistic composition (fish and snapping shrimps). This demonstrates that reef soundscapes reflect habitat structure and community composition, validating their use as ecological indicators.

3.3 Methodological calibration

Sensor orientation and distance influenced the received soundscape. Hydrophones pointing towards the reef displayed expected attenuation with distance, whereas up-ward-oriented sensors showed the opposite trend due

to the sensor directionality interacting with high frequency sounds. These results identify sensor directivity as a critical source of bias in PAM data.

3.4 Parameterisation sensitivity

Across terrestrial and marine datasets, spectrogram settings influenced the outcomes from commonly used acoustic indices. Higher NFFT values increased habitat separation in terrestrial soundscapes but decreased it in underwater environments, illustrating complex interactions between parameters and data-specific attributes. These findings emphasise the need for critical parameter selection and transparent reporting to ensure comparability.

3.5 Behavioural grounding

Audio–video arrays identified 659 pulse-train calls associated with male “signal-jump” courtship displays in two sympatric *Dascyllus* species. Call structures differed between species and even stronger effects by sites, suggesting environmental conditions can influence fish call production.

4 DISCUSSION AND CONCLUSIONS

Together, these studies highlight the importance of methodological rigour and biological validation in interpreting coral reef soundscapes. The consistent relationship between nocturnal acoustic patterns and benthic composition confirms that reef soundscapes can capture fine ecological gradients, reflecting both habitat structure and associated biological activity. This reinforces the potential of soundscape metrics as complementary indicators for ecological monitoring, particularly when traditional visual surveys are logistically constrained.

However, the results also demonstrate that the reliability of these interpretations depends heavily on the acoustic sampling design and spectrogram parameters. The experiment at Ningaloo Reef showed that hydrophone orientation and distance relative to the reef substantially influence the received soundscape. These findings underscore the need to account for sensor beam patterns and near-field propagation effects when comparing datasets. Similarly, the parameterisation sensitivity experiment revealed that choices in sampling frequency, NFFT, and window overlap can alter the outcome of multivariate soundscape analyses. Such interactions between signal properties and analysis settings can either enhance or obscure ecological separation, meaning that parameter transparency and critical experimental design are essential to ensure comparability among studies.

At the signal level, the behavioural analysis of *Dascyllus* courtship calls provided a biologically grounded link between individual acoustic events and community-level soundscapes. The observed interspecific and population-level variation in call structure illustrates how environmental factors shape acoustic signals. Integrating these verified biological signals with passive acoustic datasets will improve interpretation and facilitate the translation of soundscape metrics into ecologically meaningful indicators.

Collectively, these complementary studies contribute to bridge the gap between acoustic signals, soundscape metrics, and ecological interpretation. We show that passive acoustic monitoring is most powerful when supported by sensor calibration and deployment consistency, transparent parameterisation, and behavioural and ecological validation of sound sources. Establishing these principles will advance the reliability of reef soundscape interpretation and promote their adoption in large-scale monitoring frameworks. Ultimately, reef soundscapes are not merely auditory reflections of biodiversity but integrative measures of ecosystem function. With continued methodological refinement and standardisation, passive acoustic monitoring can become a central tool for assessing, managing, and restoring coral reef ecosystems under accelerating global change.

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