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ECHOES OF RENEWAL: THE SOUNDSCAPE OF A MALDIVIAN CORAL REEF

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Abstract

Coral reefs are increasingly threatened by climate change and human pressures, highlighting the need for effective monitoring tools. This study assesses whether underwater soundscape features reflect ecological conditions in a lagoon reef (Magoodhoo, Maldives) using Passive Acoustic Monitoring at a control site (coral rubble) and a treated site with a restoration structure; acoustic metrics (PSD, L5, L95) and ecoacoustic indices (ACI, ADI, DSC) were analyzed and compared across sites. The results show greater acoustic variability and more transient events (higher L5, ADI, DSC) at the treated site, while the control site exhibited more stable background noise (higher L95) and an overall similar ACI. These patterns align with ecological differences, indicating higher structural complexity and biological activity at the treated site, and more stable, less dynamic conditions at the rubble-dominated control site.

Keywords: *soundscape ecology, underwater acoustics, acoustic indexes, ecoacoustic indexes, coral reefs*

1. Introduction

Marine ecosystems provide essential ecological, social, and economic services, yet they are increasingly threatened by climate change and growing anthropogenic pressures. Among these systems, coral reefs represent biodiversity hotspots that support fisheries, provide coastal protection, and sustain tourism, with these functions largely dependent on their structural complexity and biological diversity [1]. However, over the past two decades, rising sea surface temperatures have driven recurrent mass bleaching events, resulting in widespread coral mortality and accelerating reef degradation [2]. As a consequence, there is an increasing need for effective and non-invasive tools to assess reef condition and monitor ecosystem changes over time.

An emerging, yet still underexplored, indicator of reef condition is the underwater soundscape [3,4]. The ensemble of sounds within a given environment constitutes its "acoustic climate," encompassing abiotic sources (e.g., wind, waves, and currents), biotic sources (generated by living organisms), and anthropogenic noise (originating from human activities), commonly termed geophony, biophony, and anthropophony, respectively. Temporal and spatial variations in this acoustic climate provide valuable insights into biological activity, environmental dynamics, and human disturbance.

Sound plays a critical role in the life history of many marine organisms, particularly in habitat selection and larval settlement [5]. Healthy coral reefs are typically characterized by complex and dynamic soundscapes reflecting high levels of biological activity and ecosystem functioning, whereas degraded reefs exhibit reduced acoustic diversity and intensity [6]. Despite growing interest, the link between soundscape features and reef condition in restoration contexts remains poorly understood.

In this study, we have used Passive Autonomous Monitoring (PAM) to study a coral restorative area [7]. Specifically, we aimed to: I. characterize the acoustic environment of the site; II. assess temporal patterns in soundscape composition; III. explore whether acoustic features can serve as proxies for ecological recovery and ecosystem functioning.

2. Material and Methods

2.1 Study area

Data collection took place on Magoodhoo Island in

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Faafu Atoll, Maldives. Sampling was conducted within the island lagoon, a semi-enclosed system bordered by coral reefs and connected to the open sea through a series of channels. The lagoon is significantly impacted by human activities, particularly tourism and fishing, making it a suitable context for assessing anthropogenic impacts on these fragile ecosystems.

2.2 Data collection

The study was conducted from 1 to 7 November 2024. Acoustic recordings (DJI Action 5 Pro) were collected between 06:15 and 07:30 AM local time (GMT +5), at a depth ranging from 8 to 10 m, and in water temperatures ranging from 28°C to 30°C.
Data was collected at two sites. The first, defined as the control site (Fig. 2A, C), consisted of a cubic metal frame and was primarily characterized by coral rubble with limited algal growth. The second, the treated site, had higher coral cover due to the presence of a PVC coral restoration structure and supported a rich fish community (Fig. 2B, D).

2.3 Data elaboration

Since acoustic recorders typically do not exhibit a flat frequency response, an equalization procedure was applied to improve the accuracy of the derived acoustic indices and ensure their comparability with those reported in other studies. Specifically, the frequency response of each recorder was aligned with that of a Class 1 reference sound level meter, enabling consistent estimation of sound levels and ecoacoustic indices [8,9]. The procedure comprised three steps: (i) simultaneous recording of a broadband white-noise signal using the reference meter and the tested devices; (ii) generation of a correction filter in the frequency domain based on the ratio of their Power Spectral Densities (PSDs); and (iii) application of this filter to all field recordings.

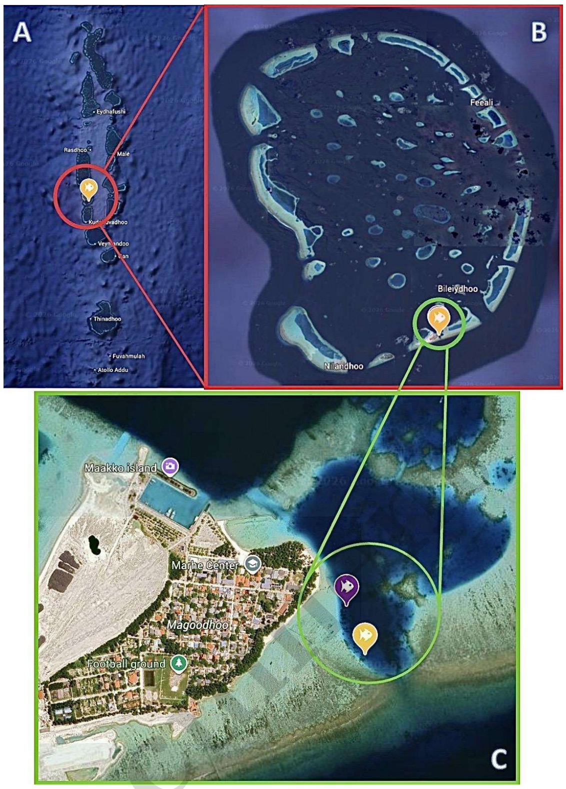

Figure 1. Study area in the Maldives. (A) Magoodhoo Island lagoon; (B) Faafu Atoll; and (C) detailed map of the lagoon showing the control site (purple) and the treated/restored site (yellow).

2.4 Analysis

After signal equalization and preprocessing, acoustic metrics and ecoacoustic indices were computed in the R environment using the tuneR, seewave, and soundecology packages to characterize the structural properties of the recorded soundscape. Spectral analyses were performed using a Fast Fourier Transform (FFT) with a window length of 2048 samples. First, acoustic metrics were derived, including the Power Spectral Density (PSD) and the standardized spectrum of sound levels across frequency [7]. Additionally, acoustic percentiles L5 and L95 were calculated, representing the sound levels exceeded for 5% and 95% of the measurement time, respectively [10]. These metrics provide a concise description of sound level variability, with L5 indicating higher and more transient sound levels, and L95 reflecting background or baseline acoustic conditions (Haver et al 2018). Subsequently, the following ecoacoustic indices were calculated: Acoustic Complexity Index (ACI), computed across frequency bands [11,12]; Acoustic Diversity Index (ADI; freq min= 100Hz, freq max = 12.000Hz; threshold = -30 dB) [13]; and Dynamic Spectral Centroid (DSC). Statistical analyses were conducted to assess differences only between sites. As the data did not meet normality assumptions, differences were evaluated using the non-parametric Kruskal-Wallis test.

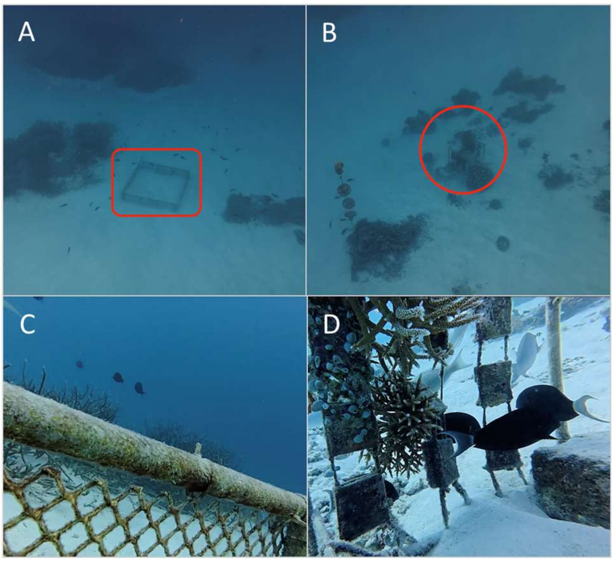

Figure 2. Control site (A, showing an anchor structure marked by a red square) and a close-up view (C, camera perspective). Treated site (B, showing a coral regeneration structure marked by a red circle) and a close-up view (D, camera perspective).

3. Results

Acoustic indexes

The power spectral density was consistently higher at the treated site relative to the control (Fig. 3a). Percentile analysis showed elevated L5 levels at the treated site (Fig. 3b), indicative of increased impulsive acoustic events. Conversely, L95 levels were markedly higher at the control site (Fig. 3c), reflecting a more continuous and homogeneous background noise environment. Within the overall signal, several peaks can be identified at different frequencies, attributable to boat passages that occurred on November 2, 4, and 6.

Ecoacoustic indexes

The results of the Acoustic Complexity Index (Figure 4,5) did not show overall differences between sites, except within the 1000–2000 Hz frequency band, where significantly higher values were observed at the control site ($\chi^2 = 340.8$, df = 1, $p < 0.001$). ADI exhibited significantly higher values at the treated site compared to the control (Figure 6) ($\chi^2 = 73.156$, df = 1, $p < 0.001$). Similarly, DSC values showed greater variability, with a tendency toward higher indices at the treated site relative to the control (Figure 7). Statistical analysis confirmed that these differences were also significant ($\chi^2 = 22.808$, df = 1, $p < 0.001$).

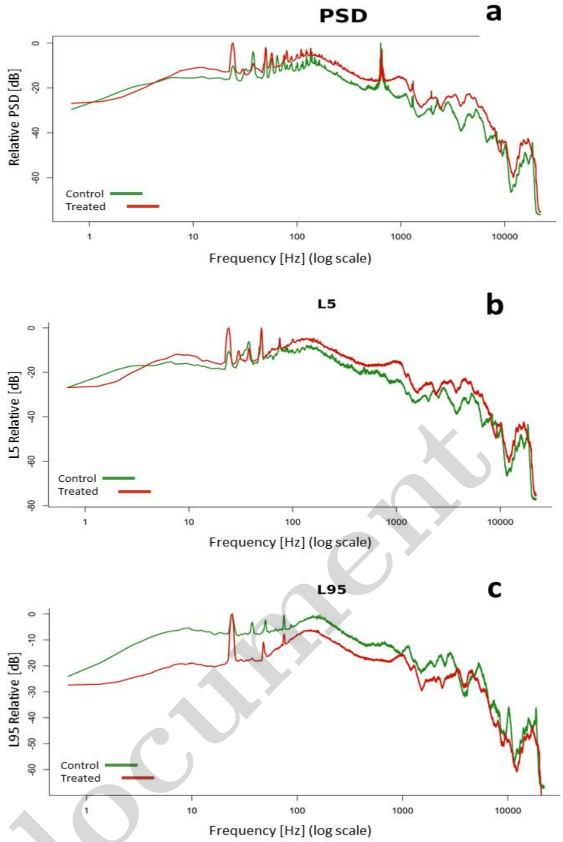

Figure 3. Relative power spectral density (a), and percentile noise levels: L5 (b) and L95 (c).

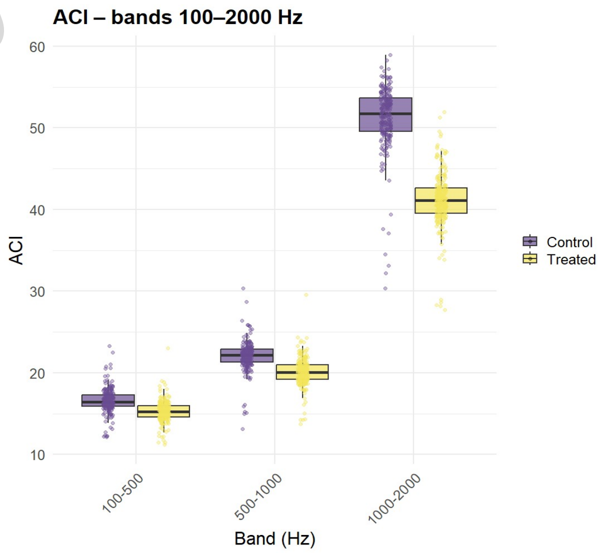

Figure 4. Acoustic Complexity Index (ACI) across different frequency bands. Significant differences between the control and treatment groups were observed exclusively within the 1000–2000 Hz frequency band.

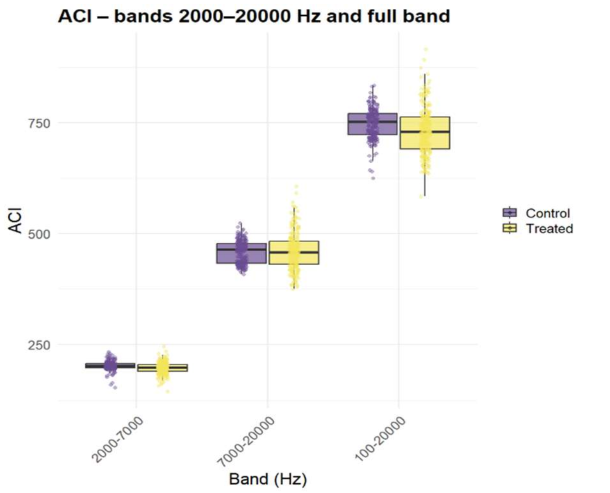

Figure 5. Acoustic Complexity Index (ACI) across different frequency bands. No differences were found for each frequency band between sites.

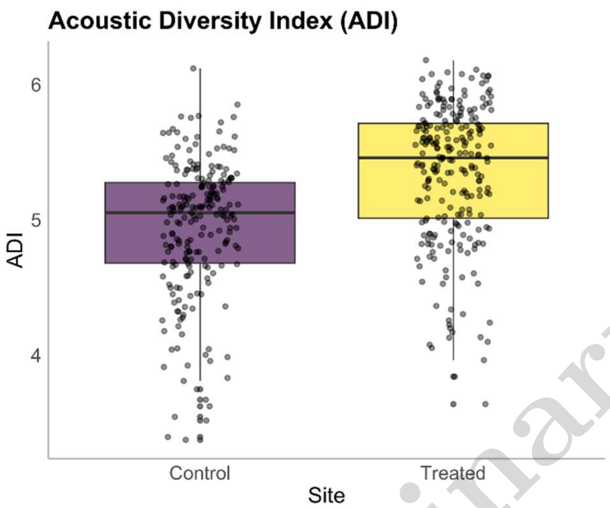

Figure 6. Acoustic Diversity Index (ADI) values differed significantly between the control and treatment sites.

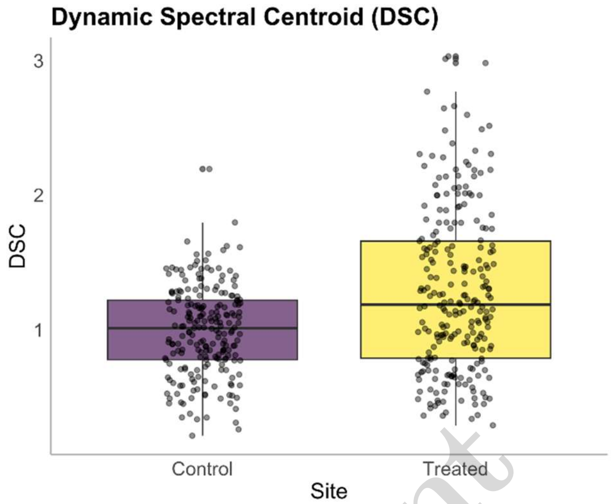

Figure 7. Dynamic Spectral Centroid (DSC) values differed significantly between the control and treatment sites.

4. Discussion

The observed acoustic differences between the control and treated sites are consistent with their contrasting ecological conditions. The treated site, located near an anthropogenic coral restoration structure, exhibits greater live coral cover and higher structural complexity. In contrast, the control site is largely composed of dead coral fragments (rubble) and presents a more homogeneous seabed [14,15].

These environmental differences are reflected in the acoustic metrics. Elevated L5 levels at the treated site indicate a higher occurrence of short, high-intensity acoustic events, potentially associated with increased biological activity. Conversely, the control site shows substantially higher L95 values, suggesting a more continuous and uniform ambient noise field. This pattern is likely linked to seabed composition: the dominance of coral rubble at the control site may generate persistent, low-level sounds through fragment movement and interaction, producing a stable acoustic background [16,17].

Further support for these patterns comes from acoustic diversity and variability indices. The higher Acoustic Diversity Index (ADI) at the treated site suggests a broader distribution of acoustic energy across frequency bands, often associated with higher acoustic heterogeneity and potentially greater biological diversity. Similarly, the elevated Dynamic Spectral Centroid (DSC) indicates increased temporal variability in acoustic energy, which may reflect more dynamic biological activity, including overlapping or intermittent signals from multiple taxa. Such variability is typically linked to ecologically active and structurally complex habitats. Importantly, the combined increase in ADI and DSC suggests not only a broader frequency occupation but also a more temporally dynamic acoustic environment, reinforcing the interpretation of a structurally and functionally more complex habitat.

This interpretation is reinforced by independent labeling results collected over the same monitoring period. A total of 561 acoustic events were identified at the treated site, compared to 385 at the control site, indicating greater variability and a higher occurrence of discrete sounds [18,7]. Field observations further support this finding, as small reef fish-likely belonging to the Pomacentridae family or the genus *Chromis*- were frequently observed around the restoration structure. These organisms are known to produce short, intermittent acoustic signals [14,18], consistent with the elevated L5 and PSD values recorded at the treated site.

In contrast, the Acoustic Complexity Index (ACI) showed higher values at the control site within the 1–2 kHz frequency band. The higher ACI values observed at the control site within the 1-2 kHz band may reflect a concentration of acoustic energy within a narrower frequency range, rather than greater overall acoustic complexity. This suggests that ACI, when analyzed in restricted frequency bands, may capture localized spectral dominance rather than broader ecological patterns. Localized abiotic noise, including water movement or resonance effects, may also contribute disproportionately to this band.

Alternatively, this pattern could reflect differences in community composition rather than overall ecological condition. The control site may be dominated by fewer but more consistently vocal species that concentrate acoustic energy within a narrow frequency range, thereby increasing ACI values. In contrast, the treated site may support a more diverse yet acoustically diffuse assemblage, consistent with the higher ADI and DSC observed.

5. Conclusion

Overall, the results indicate that the treated site supports a more acoustically dynamic and biologically active environment compared to the control site. Higher L5, ADI, and DSC values, together with the greater number of labeled acoustic events and field observations, suggest a more diverse and functionally complex soundscape associated with increased live coral cover and structural complexity. In contrast, the control site is characterized by a more homogeneous acoustic background, likely driven by abiotic processes related to coral rubble. These findings highlight that passive acoustic monitoring, combined with ecoacoustic indices, can effectively capture ecological differences between degraded and restored reef conditions. This approach provides a non-invasive and scalable tool to support the assessment and long-term monitoring of coral reef restoration efforts.

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