Journal of Animal Environment
(E-ISSN 2717-1396, ISSN 2717-1388)
Journal homepage: https://aejournals.org/

Original Research Paper

Passive Acoustic Monitoring to Assess Biodiversity Recovery in Tropical Rainforest Restoration Projects

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Key Words

Passive acoustic monitoring, Biodiversity recovery, Tropical rainforest, Restoration ecology, Acoustic diversity, Faunal recolonization, Soundscape ecology.

Abstract

Monitoring methods must be reliable, appropriate, and able to measure vegetation recovery, as well as the return of animal communities and ecological functions, in tropical rainforest restoration projects. This study compares the effectiveness of passive acoustic monitoring for assessing biodiversity recovery in restored rainforest plots, degraded control areas, and mature reference forest sites. Automated acoustic recorders were set up at fixed sampling points and set to record soundscapes at dawn, evening, and night, in both wet and dry seasons. The study was conducted on the acoustically active faunal groups, such as birds, frogs, insects, and selected mammals, because they are useful for reflecting the habitat quality, microclimatic stability, and ecological recovery. The acoustic data were processed using noise filtering, spectrogram inspection, species-level call identification, and the computation of the acoustic indices used: Acoustic Complexity Index, Acoustic Diversity Index, Bioacoustics Index, and Acoustic Entropy. There was a clear difference in results when considering habitat categories. Low species call richness and weak calling activity were observed at degraded control sites, in addition to low acoustic complexity. In restored rainforest areas, there was an increase in acoustic diversity, calling activity on the dawn chorus and at night, and species call richness, which suggests faunal recolonization was occurring. Mature and stable forest soundscapes were found in the reference forests with the highest acoustic values. Positive associations were detected between canopy cover, vegetation density, and acoustic diversity, with statistical analysis revealing significant differences between the habitat types. Results indicate that passive acoustic monitoring is a non-invasive, continuous, and practical tool for assessing the recovery of biodiversity in rainforest restoration initiatives. It can be used to monitor long-term conservation planning by identifying animal return, habitat improvement, and ecosystem functional recovery.

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Received: 25th May, 2026; Revised: 6th June, 2026; Accepted: 8th June, 2026; Available Online: 07th August, 2026
(DOI): 10.70102/AEJ.2026.18.3s.16

Introduction

Tropical rainforests are also home to a variety of birds, amphibians, insects, mammals, and reptiles. But these ecosystems are suffering due to deforestation, logging, encroaching agricultural activities, mining, road building, and climate change (Dixit & Raje, 2024). These pressures decrease canopy continuity, cause changes to the microclimatic environment, destroy habitat structure, and affect the inter-specific interactions. Concurrently, there is now a range of rainforest restoration projects occurring in many degraded landscapes to restore the structure of the rainforest, enhance habitat quality, and facilitate the re-establishment of native biodiversity (Poornimadarshini, 2025). However, measuring restoration success is still a challenging process, as recovery of ecosystems does not hinge on tree growth.

Canopy cover, plant density, survival of seedlings, and biomass gain are common vegetation-based indicators of restoration progress. These are crucial, but insufficient, indicators of ecological recovery. Although good vegetation growth occurs in a restored site, there may not be diverse animal communities. Animals have vital functions in pollination, seed dispersal, insect control, nutrient cycling, and stability of the food web. Thus, the diversity, abundance, and dynamics of animal communities are vital measures of whether or not a restored rainforest is a healthy ecosystem (Patil, 2018). In the tropics, there are many species that are hard to see in nature, either because they are nocturnal, seasonally migrating, or because of the dense vegetation, so monitoring faunal recovery is particularly critical.

Passive acoustic monitoring is one potential method that can be used in these systems to evaluate biodiversity recovery (Browning et al., 2017; Mauriño et al., 2026). This approach involves the use of automatic sound recorders to record the sounds of the surroundings continuously created by birds, frogs, insects, mammals, and other sound-producing species. Passive acoustic monitoring is a non-invasive, cost-effective, repeatable, and long-term ecological observation technique relative to traditional field surveys (Teixeira et al., 2024; Sugai et al., 2019; Ross et al., 2023). The presence of species, calling activity, daily activity patterns, and other soundscape characteristics can be inferred from acoustic data. In addition, acoustic indices like acoustic complexity, acoustic diversity, bioacoustic activity, and acoustic entropy can be employed to compare restored sites with degraded and reference forest habitats. The indicators are used to determine if the animal diversity and ecological function are being restored over time in restoration areas.

The goal of the present study is to evaluate the effectiveness of passively monitoring biodiversity recovery in tropical rainforest restoration projects. Consequently, the study is based on the acoustic indices and on the sound detections of species, making comparisons with degraded control areas and mature reference forests. The paper proposes a practical framework for assessing the success of habitat restoration and for guiding conservation planning based on supporting biodiversity by associating soundscape patterns with habitat recovery.

There are six main sections to the paper. Section I presents a discussion of the degradation of tropical rainforests, the importance of monitoring their restoration, and the capacity of passive acoustic monitoring to detect faunal recovery. The study area is described in Section II, along with the placement of the recorders, target faunal groups, processing of acoustic data, and statistical processing. The results are reported in Section III and compared between degraded, restored, and reference forest sites on acoustic indices, species call richness, and calling activity. In Section IV, acoustic complexity is discussed in relation to habitat quality, fauna recolonization, and restoration success. The conservation implications section ends with the recommendation of long-term acoustic stations, camera traps, vegetation surveys, and acoustic indicators for restoration planning.

Materials and Methods

Study Area

The study took place within a tropical rainforest restoration landscape comprising three habitat types: restored rainforest plots, degraded control areas, and mature reference forest sites. The restored plots were those areas that had been either planted with native trees, assisted natural regeneration, or cleared of invasive plants for ecological restoration purposes. The degraded control areas were made up of open or partially degraded forests with low canopy cover, low vegetation densities, and evidence of human disturbance. The reference forest sites were chosen in areas of relatively little human modification of the forest, including closed canopy, high site complexity, and minimal direct anthropogenic pressure. These three site types enabled the comparison of recovering, disturbed, and ecologically stable conditions in the rainforest.

Acoustic Recorder Placement and Sampling Design

All sites selected had automated passive acoustic recorders placed to record animal vocal activity and soundscape variation. Fixed sampling points were used in each plot with adequate separation between devices to minimize overlap of sounds. The recorders were installed on trees or stable supports at an average height of 1.5–2 m above ground level, away from streams, roads, and strong winds, whenever possible. To account for seasonal variation in calling behavior, sampling was done in both wet and dry seasons. Birds, frogs, insects, and nocturnal mammals are more acoustically active during key activity periods, such as the early morning, evening, and nighttime hours, and recordings were conducted during these times.

Recording Schedule and Environmental Conditions

The recording schedule was designed so as to record patterns of rainforest sounds on a daily and seasonal basis. At each location, recorders were set to capture sound samples at regular intervals (e.g., 10 minutes every hour for 24 hours a day) for several days in a row. Acoustic patterns were interpreted in the context of environmental variables, such as temperature, relative humidity, precipitation, canopy cover, vegetation density, and disturbance level. These variables were relevant since the weather, vegetation structure, and habitat quality have a significant effect on tropical rainforest sound activity. Detailed acoustic analysis was not performed on recordings that were affected by heavy rain, strong winds, or equipment disturbance.

Target Faunal Groups

Studies concentrated on groups of animals that are acoustically active and species that are indicators of rainforest recovery. Birds were deemed to be important daytime indicators as they respond to habitat structure, food availability, and nesting suitability. Frogs were added to the sample because their vocal activity is closely associated with moisture, microhabitat quality, and availability of freshwater environments. Crickets and cicadas were evaluated as soundscapes complexity and trophic activity indicators. Some mammals were also chosen (primates, bats, and small nocturnal mammals) when their vocal signals were identified. These groups together represented a wide spectrum of recovery of the animal biodiversity of restored rainforest habitats.

Acoustic Data Processing

The recording of all sounds was converted to a digital sound database and sorted into good and bad sounds before analysis. Files that were excessively noisy, equipment malfunction, or continual rainfall interference were removed. Low-frequency noises from wind and other non-biological sources were filtered to minimize the wind noise. The call patterns and sound frequency ranges were visually analyzed using spectrograms. The recordings were then divided into habitat category, date, time and site. This was an organization that allowed an objective comparison of acoustical responses to be made among restored, degraded, and reference forest sites.

Statistical Analysis

Acoustic biodiversity was compared between plots restored, between degraded control areas and between reference forest sites using statistical analysis. The number of species calling and the acoustic indices were tested for significant differences among habitat categories using one-way ANOVA. This was done by using correlation analysis to explore the relationships between acoustic measures and habitat variables (canopy cover, vegetation density, rainfall and disturbance level). Species richness, call abundance and acoustic index values were used for diversity comparison. Acoustic assessment of restored sites using restoration-status modeling was performed to determine if restored sites acoustically resembled degraded sites versus reference forests. A p value less than 0.05 was deemed statistically significant.

Results

Acoustic Differences among Habitat Categories

There were distinct differences between degraded control areas, forest areas being restored, and reference forest areas as revealed by the acoustic recordings. The acoustic complexity and call richness were found to be lower in degraded areas and dawn and night-time sound activity were weak. Characteristics of these patterns suggest low faunal activity and habitat suitability. The restored rainforest plots, on the other hand, exhibited moderate to high acoustic activity, indicating that activities were successful in improving habitat conditions for the vocal animal groups. The intensity of biological sound activity was higher at reference forest sites, which also exhibited the highest acoustic diversity, and were found to have a more stable and mature rainforest soundscape.

Acoustic Diversity and Species Call Richness

There was greater acoustic diversity in restored rainforest plots compared to the degraded control areas. Bird calls were more noticeable during dawn hours; frog and insect call during evening and night time. The number of bird, frog, and insect call types in the restored plots was also greater than in degraded plots, at the species level. However, reference forests exhibited the highest species call richness suggesting that sites that had been restored were moving towards recovery, but were not yet mature forest.

Table 1: Comparison of Acoustic Biodiversity Indicators Across Habitat Categories

Habitat Category	Acoustic Complexity Index	Acoustic Diversity Index	Bioacoustic Index	Acoustic Entropy	Species Call Richness	Mean Calling Activity
Degraded control sites	0.42 ± 0.06	0.48 ± 0.05	31.5 ± 4.2	0.51 ± 0.04	18 ± 3	Low
Restored rainforest plots	0.68 ± 0.07	0.71 ± 0.06	54.8 ± 5.6	0.73 ± 0.05	34 ± 4	Moderate to high
Reference forest sites	0.82 ± 0.05	0.86 ± 0.04	69.2 ± 6.1	0.88 ± 0.03	47 ± 5	High

Table 1 presents the results of the acoustic biodiversity assessment of the restored rainforest sites compared to degraded control sites. The rising complexity, diversity and entropy of sounds and the increasing number of species calling shows the progressive recovery of the animal communities that vocalize. The richest, most complex soundscapes are found in mature forest habitats, in reference forests.

Dawn and Night-Time Calling Activity

There was high variation in bird activity among the three habitat categories as revealed in dawn recordings. Degraded control areas were associated with fewer and shorter call sequences, with the restored plots associated with increased intensity of the dawn chorus. Reference forests had the highest dawn chorus with several species of birds calling at the same time. Significant more frogs and insects were also found in the restored forest and reference forest sites than in the degraded sites at night time recordings. This seems to indicate that re-established plots have improved microhabitat conditions, moisture, and vegetation structure for acoustically active fauna.

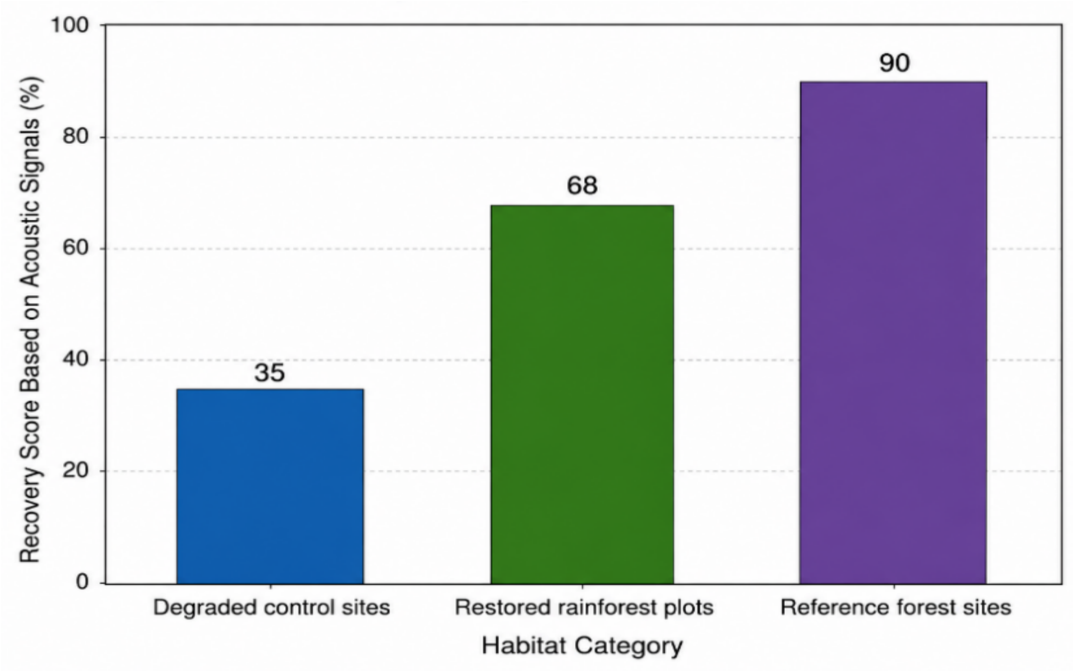

Figure 1: Biodiversity Recovery Trend Based on Acoustic Indicators

Figure 1 shows a progressive increase in acoustic biodiversity recovery from degraded control sites to restored rainforest plots and reference forest sites. The restored plots show a clear recovery trend, with acoustic scores closer to reference forest conditions than degraded sites. This confirms that passive acoustic signals can reflect faunal return and habitat improvement in rainforest restoration areas.

Relationship between Acoustic Signals and Faunal Recovery

The results show that the acoustic signals had a close relationship with faunal recovery. More species call richness was related to higher acoustic complexity and bioacoustic activity, particularly for birds, frogs and insects. Acoustic structure was improved in restored plots, indicating that suitable acoustic conditions for animal recolonisation were provided by the vegetation recovery. The higher levels of sound activity at both the morning and evening times were also a sign of restored areas producing both diurnal and nocturnal faunal groups. In general, PAC was a successful tool for capturing patterns of biodiversity recovery which are not necessarily apparent from vegetation assessment alone.

Statistical Interpretation

The differences between the acoustic indices at degraded, restored and reference sites were statistically significant in the one-way ANOVA analysis. In all cases, the number of species calls per minute, Bioacoustic Index, Acoustic Diversity Index, and Acoustic Complexity Index was significantly higher at restored and reference forest sites than at degraded control areas. Canopy cover, vegetation density, and acoustic diversity were found to be correlated and were positively related. The results indicate that habitat restoration has the potential to enhance soundscape complexity and to contribute to the progressive recovery of the rainforest community of animals. Plots that have been restored did not completely resemble reference forests, but the acoustic profile suggested an ecologic recovery that was meaningful.

Discussion

Interpretation of Acoustic Findings

The findings indicate that passive acoustic monitoring is an effective method for assessing biodiversity recovery in tropical rainforest restoration projects (Ribeiro et al., 2017; de Almeida et al., 2025; Metcalf et al., 2022). Restored rainforest plots showed higher acoustic diversity, greater species call richness, and stronger dawn and night-time calling activity than degraded control areas. This suggests that restoration activities improved habitat conditions and supported the gradual return of vocal animal communities. In degraded areas, low acoustic complexity reflected reduced faunal presence, poor vegetation structure, and limited microhabitat availability. In contrast, restored plots produced richer soundscapes, showing that faunal recovery was progressing along with vegetation restoration.

Acoustic Complexity and Habitat Quality

A more complex acoustics in forest sites that have been restored and reference forest sites are used to assess habitat quality and the ecological functioning. When more than one vocal species is present, there will typically be an abundance of different sounds in the calls cape, with each species employing a different region of the spectrum and a distinct calling time. In rehabilitated plots, the presence of more complexity in the soundscape implied recolonization of birds, amphibians, insects, and some mammals. These results suggest that there are other aspects of the restoration besides tree growth or canopy development that should be considered as an indicator of success. Direct evidence is the activity of animals, and they are now doing things that make the restored habitat more suitable for feeding, breeding, shelter and movement.

Comparison Among Restored, Degraded, and Reference Forest Sites

The highest acoustic diversity and species call richness were found in the reference forest sites, revealing the soundscapes structure of a mature and stable rainforest environment (Müller et al., 2023). This suggests that restored rainforest plots were intermediate in their acoustic values, but did not yet reach the level of reference forest. This indicates that restored rainforest areas had intermediate acoustic values compared to degraded control areas, but not yet the reference forest (Vega-Hidalgo et al., 2021). This indicates that there is a trend towards improving biodiversity with restoration, but full ecological recovery might take longer. The sound activity was lowest in degraded control areas, suggesting that faunal use is lower in areas with habitat disturbance and minimizes biological interactions. Therefore, restored sites can be considered as recovering systems moving towards reference forest conditions.

Ecological Importance of Soundscape Indicator Groups

Soundscape indicators were important and included birds, amphibians, and insects. Birds were well represented in dawn recordings and were linked to canopy structure, food availability, and habitat connectivity. Amphibian activity occurred more during the evening and nighttime, suggesting moisture availability, microhabitat stability, and quality of aquatic or semi-aquatic habitat. Insects added to the background sound activity and indicated trophic interactions, vegetation density, and seasonal productivity. These groups were combined to give a wide ecological overview of rainforest recovery. They were able to determine whether or not sites were being restored to support different functional groups, not just individual species, through their calls.

Conservation and Restoration Significance

The findings point to the importance of acoustic monitoring in restoration planning and conservation of biodiversity (Ramesh et al., 2023; Riede & Balakrishnan, 2025). Passive acoustic monitoring can be used to observe changes in faunal activity without disturbing wildlife (Zwerts et al., 2021; Appel et al., 2025). It also affords repeated and long-term observation, useful in dense tropical forests, where visual surveys cannot be conducted. Conservation managers can use acoustic indicators to determine if the restored site is doing better, or if it is getting worse or not improving for animals to recolonise. This approach may also inform adaptive restoration practices, such as enhancing canopy connectivity, water body protection, human disturbance, and retaining habitat patches for vocal species.

Conclusion

Passive acoustic monitoring is a useful and effective tool for assessing biodiversity recovery in tropical rainforest restoration initiatives. This study demonstrates the potential of using acoustic signals to detect ecological changes that would not adequately be identified by an assessment based on vegetation alone. Acoustic complexity, acoustic diversity, bioacoustic activity, acoustic entropy, and species call richness were found to be higher in restored rainforest plots than in degraded control sites. These results suggest a progressive recovery of vocal animal communities (birds, amphibians, insects, and some mammals) that benefited from the restoration efforts. There were also higher levels of dawn chorus activity and night-time calling, reflecting increases in habitat quality, microhabitat quality, and ecological functioning. Despite the fact that the richest and most stable soundscape was found in reference forests, a trend toward recovery was also observed in restored plots, thus reflecting faunal recolonization and habitat improvement as a possible indicator of making use of passive acoustic monitoring. Acoustic monitoring should be incorporated in long-term rainforest restoration programs from a conservation point of view. Continuous evidence of return of animals, improvement of habitat quality, and functional recovery of the ecosystem can be obtained through permanent or seasonal acoustic stations. Passive acoustic monitoring can be paired with camera trapping, vegetation surveys, field observation, and remote sensing for a more comprehensive evaluation of the success of a restoration. Community-based acoustic monitoring can also enhance local involvement and monitoring costs. Acoustic biodiversity indicators can be used for restoration planning to define areas that are recovering well, areas that need more restoration work, and areas that need protection from disturbances. Passive acoustic monitoring is a non-invasive, repeatable, and conservation-driven method that can inform tropical rainforest restoration with a focus on enhancing biodiversity recovery results.

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