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Original Research Paper

Acoustic Monitoring for Assessing Biodiversity Recovery in Restored Tropical Rainforests

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Key Words

Acoustic monitoring, Biodiversity recovery, Tropical rainforests, Species richness, Shannon's index, Acoustic entropy, Remote sensing.

Abstract

This paper examines how acoustic monitoring can be applied to determine biodiversity recovery in restored tropical rainforests. Acoustic data were recorded over 6 months at both restored and control sites within a tropical rainforest, and the soundscape reflected species activity and the ecosystem's well-being. The findings indicate a high level of species richness in the restored sites, increasing to 38 species in Month 6, up from 18 in Month 1. In contrast, at the control sites, the magnitude of variation was limited, ranging from 20 to 22 species. Statistical tests showed a strong positive relationship between the Shannon Index and species richness in the restored sites ($r = 0.85$, $p < 0.01$), indicating that higher biodiversity is associated with more complex and diverse soundscapes. Conversely, the correlation at the control sites was lower ($r = 0.56$, $p < 0.05$), indicating a low recovery of biodiversity. The ANOVA tests also indicated significant differences in Shannon Index between the restored and control sites ($F (1, 4) = 8.22$, $p < 0.05$). The fact that the Acoustic Entropy of the restored sites (0.72-0.78) was even higher also revealed a more active and varied soundscape, characteristic of a healthier ecosystem. These results demonstrate the effectiveness of the restoration processes in biodiversity recovery, and acoustic monitoring is an effective, non-invasive tool for monitoring changes in biodiversity. Combining statistical data with acoustic information provides a good understanding of the effectiveness of restoration projects. It offers a scalable approach to continuous monitoring of biodiversity in tropical rainforests.

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Introduction

Tropical rainforests are vital ecosystems for biodiversity, carbon storage, and climate regulation worldwide. Deforestation and degradation, however, are major threats to them, and biodiversity is greatly lost. It is important to track the regeneration of biodiversity in restored rainforests to assess the viability of the restoration process. Conventional surveillance is resource-consuming and can only be used in remote or expensive regions. The use of environmental soundscapes in non-invasive acoustic monitoring is an economical method for monitoring biodiversity recovery, providing useful data on the well-being of those ecosystems and contributing to biodiversity preservation.

The rainforests, commonly known as the lungs of the earth, are among the most biodiverse ecosystems and are important to the world's ecology. But land-use and deforestation have been disastrous for these essential ecosystems, threatening species extinction and diminishing biodiversity. To counter this, conservation work is underway to rehabilitate lost rainforest habitats, aiming to restore biodiversity and ecosystem functions. Conventional methods of biodiversity measurement, including direct species counting and vegetation surveys, are resource- and time-consuming and, in most cases, not feasible in extremely dense and remote rainforests.

Acoustic monitoring has become one of the most promising non-invasive techniques for measuring biodiversity, enabling the detection and quantification of species activity by analyzing environmental sounds. The sounds of different organisms, such as birds, mammals, insects, and amphibians, are good indicators of the biodiversity and health of the ecosystem. Acoustic sensors provide a cost-effective and efficient means of monitoring biodiversity recovery, especially in large, inaccessible regions, enabling real-time data collection and long-term analysis. In recent work, soundscapes, when combined with deep learning methods, can effectively monitor biodiversity recovery in tropical forests (Müller et al., 2023).

The research on the topic of Acoustic Monitoring to Measure Recovery of Biodiversity in Restored Tropical Rainforests can be enhanced with the introduction of the concept of clustering algorithm in the big data brought up by (Abbasi & Vaziri, 2015), which will help to analyze extensive biodiversity data. Also, (Piczak et al., 2024) shows the usefulness of acoustic telemetry in assessing ecological restoration, and this can be used to monitor marine and freshwater ecosystems, which can be utilized in rainforest restoration programs. Moreover, (Sahle & Melaku, 2025) emphasize the importance of digital and emerging technologies in the process of assessing and rehabilitating socio-ecological landscapes, which form a part of the recovery of tropical rainforests and the biodiversity (Rajan, 2025; Rajan & Kumar, 2024). Also, passive acoustic monitoring has been applied in other ecosystems to track species interactions and assess ecosystem health (de Almeida et al., 2025).

Although acoustic monitoring has become a promising technique, major issues have been encountered in its application to biodiversity monitoring, particularly in degraded landscapes. Wildlife conservation issues in anthropogenically modified landscapes have highlighted the need to develop adaptive approaches to improve conservation success (Vimala et al., 2025). Research like this is essential for understanding how acoustic monitoring could be incorporated into broader restoration and conservation approaches.

Besides, it has recently been shown that soundscape analysis can also be used to assess restoration success in coral reef ecosystems, suggesting increased use of acoustic monitoring in other ecosystems (Lamont et al., 2022). Sound applications for detecting ecosystem recovery are important not only in terrestrial settings but also in marine systems, as animal soundscapes reflect signs of degradation in tropical forests resulting from fire and logging (Cid & Rivera, 2024). Moreover, the wider use of passive acoustic monitoring is contributing to answering some fundamental ecological questions about species interactions and environmental alterations (Rappaport et al., 2022). On the same note, recent evidence from animal soundscapes has shown that animal sounds can provide insight into the degradation of tropical rainforests and inform conservation measures (Ross et al., 2023).

The paper discusses how Acoustic monitoring can be used to assess biodiversity recovery in restored tropical rainforests. It is the success of the restoration in restoring biodiversity that seeks to be judged, by studying the sounds emitted in these places. In this way, not only learn about species patterns of re-colonization, but also assist in the development of even more effective patterns of restoration. The results herein indicated the possibility of the acoustic monitoring to help to understand the importance and ecological restoration better and provide a solution to scalable biodiversity monitoring of tropical rainforests.

The present paper presents something new in the use of acoustic monitoring in the evaluation of biodiversity recovery in restored tropical rainforests. It examines the ability of soundscapes, augmented with the deep learning method, to monitor the activity and health of species in these complex ecosystems. The research paper will provide a detailed discussion of the role of acoustic data in supplementing the conventional biodiversity monitoring systems and offer a scalable application in the process of large-scale restoration. The purpose of this paper is to contribute to the development of restoration science and biodiversity monitoring tools in tropical rainforests by revealing the use of sound as an ecological indicator, which provides the new prospects of conservation activities.

The paper is organized in such a way: the introductory part is Section I, which presents the importance of biodiversity monitoring and the importance of acoustic monitoring in the restoration of tropical rainforests. Section II examines the available literature on the acoustic monitoring techniques and how have been used in the restoration of ecology. Section III provides the study methodology, that is, the acoustic monitoring methods and the data analysis plan. Section IV will report on the results and partake in the discussion of findings with Section V concluding and giving implication of the study on the biodiversity conservation and future research directions.

Literature Review

Recent reports have pointed out the usefulness of acoustic monitoring in determining biodiversity in rehabilitated ecosystems, particularly tropical rainforests. Machine learning with soundscape analysis has enhanced the precision and extensiveness of biodiversity measurements. Emerging technologies are underway to integrate passive acoustic records with remote sensing observations to allow a more in-depth monitoring in vast and far off regions. Studies of soil and underground soundscape have also increased, providing information of concealed biodiversity dynamics in restoration chrono sequences and therefore extending the scope of acoustic surveillance to ecological restoration projects.

The idea of acoustic monitoring to measure biodiversity has been widely spread in ecological research, especially in conditions that are difficult to measure using other conventional methods. Acoustic monitoring takes advantage of the sounds made by different organisms to measure the diversity of the species, the behavior and the overall health of the ecosystem. This strategy has worked in other ecosystems, both in marine as well as on-land landscapes. Acoustic monitoring is also an effective method of monitoring restoration site biodiversity recovery in tropical rainforests because it is able to record a broad spectrum of species activity without the involvement of any human presence in frequently inaccessible locations.

Other earlier researchers have proven the significance of soundscapes in monitoring the well-being of an ecosystem. Soundscapes refer to the collective sound of the biotic and abiotic factors, such as animal sounds, insects, wind, rain, etc. Through such sound patterns, researchers will be able to get information on the composition and structure of biodiversity within a particular region. The approach has been found especially effective tracking the reconstruction of species populations in tropical forests, whereby habitat restoration frequently targets reintroductions of a wide diversity of species.

The use of deep learning and machine learning methods in the analysis of acoustic data has also been studied more and more. These techniques allow processing of huge amounts of acoustic data that would otherwise be tedious to process by hand. Deep neural networks and machine learning, in general, have been used to great effect to classify species according to the vocalizations, detect patterns in soundscapes, and trace biodiversity changes over time. These technologies offer a scalable solution to large scale monitoring projects, especially remote locations where access to the forest can be a problem. Recent research emphasized the application of passive acoustic records as the approach to unsupervised learning in the recognition of fish vocalizations, and also demonstrating the applicability of acoustic monitoring to the biodiversity evaluation of various ecosystems (Mahale et al., 2023).

In addition, research on the role of soundscapes of both terrestrial and marine ecosystems to guide the success of restoration efforts has been studied. An example is that the sound of the underground has been associated with soil biodiversity dynamics, new insights on the way biodiversity changes throughout restoration chrono sequences (Robinson et al., 2024). The restoration of montane forests is also interrupted by various ecological and anthropogenic reasons in tropical forests, which prevents the conservation of biodiversity in general (Christmann et al., 2023). In these cases, acoustic monitoring has been employed to determine the effectiveness of restoration and is a useful resource that can be used to overcome these obstacles.

Acoustic monitoring is also applicable in the post fire situation. Mediterranean pine forest has been studied using acoustic indices to monitor the post-fire biodiversity dynamics, to assist in tracking the recovery of fire influenced ecosystems (Spatharis et al., 2024). On the same note, soundscape analysis has been utilized to determine the early success of seagrass restoration projects, which again supports the success of sound-based approaches in other restoration settings (La Manna et al., 2024). Soundscapes as a method of tracking and managing biodiversity recovery is also effective in checking the presence of the species and also serves a vital role in determining the functional recovery of the ecosystem.

Nevertheless, there have been difficulties in incorporating acoustic monitoring as a part of the general restoration strategy. Among them, one is the differentiation of sound production by species, seasons and the state of the environment. Soundscape variability in both time and space may make it harder to set comparable baseline measures of biodiversity restoration. Also, although acoustic monitoring is good to find out the existence of species, it might not necessarily capture any more ecological interactions or biodiversity. Research has purported that biodiversity credit markets need rigorous baseline, monitoring, and validation practices in order to ensure quality assessment of success on restoring (Aide, 2024). Integration of acoustic with other ecological monitoring techniques e.g. remote sensing would help increase the precision and dependability of the biodiversity measurements.

Moreover, there are multiple studies that have integrated the new systems to enhance the scalability of conservation monitoring to give generalizable methods of detecting changes in biodiversity following perturbation (Wood et al., 2024). In the restoration of forest landscape, issues and lessons learned have managed to investigate challenges and enhancing monitoring practices and achieving success in the restoration process (Mansourian & Stephenson, 2023). On the same note, machine learning techniques are extensively used in managing sustainable forests, and have proven useful in maximizing biodiversity measurements (Espíndola et al., 2025). The necessity of the effective monitoring practices in order to describe ecological recovery in all of its variety also determines the importance of using the combined methods of monitoring in restoration ecology because the successful survey of the mammal biodiversity in the restoration projects (Green et al., 2024).

When restoring tropical rainforests, it is essential to learn the presence of species and how the ecosystems have been restored in terms of the functionality. Acoustic monitoring has the capacity to give understanding of ecological processes like species interaction, habitat use and movement patterns. Moreover, it will be able to provide real-time feedback on the effectiveness of restoration interventions that will allow implementing adaptive management strategies in a short period. The subsequent steps of integrating acoustic surveillance into restoration strategies are a promising area of enhancing effectiveness of conservation practices and making sure that restored ecosystems can be considered sustainable in the long-run.

It has been shown in the literature that acoustic monitoring, coupled with sophisticated data analysis methods, such as machine learning, is a promising instrument to determine biodiversity recovery in restored ecosystems. Some of the main highlights are its efficiency especially in remote and inaccessible locations. Recording the sounds of a variety of species, it provides monitoring in the real-time and provides more information about the well-being of re-created settings. These papers justify the use of acoustic monitoring in the restoration of tropical rainforests as it is a less invasive and highly scalable alternative to conventional field surveys. Soundscape analysis combined with other monitoring tools improves assessment efforts in general restoration.

Methodology

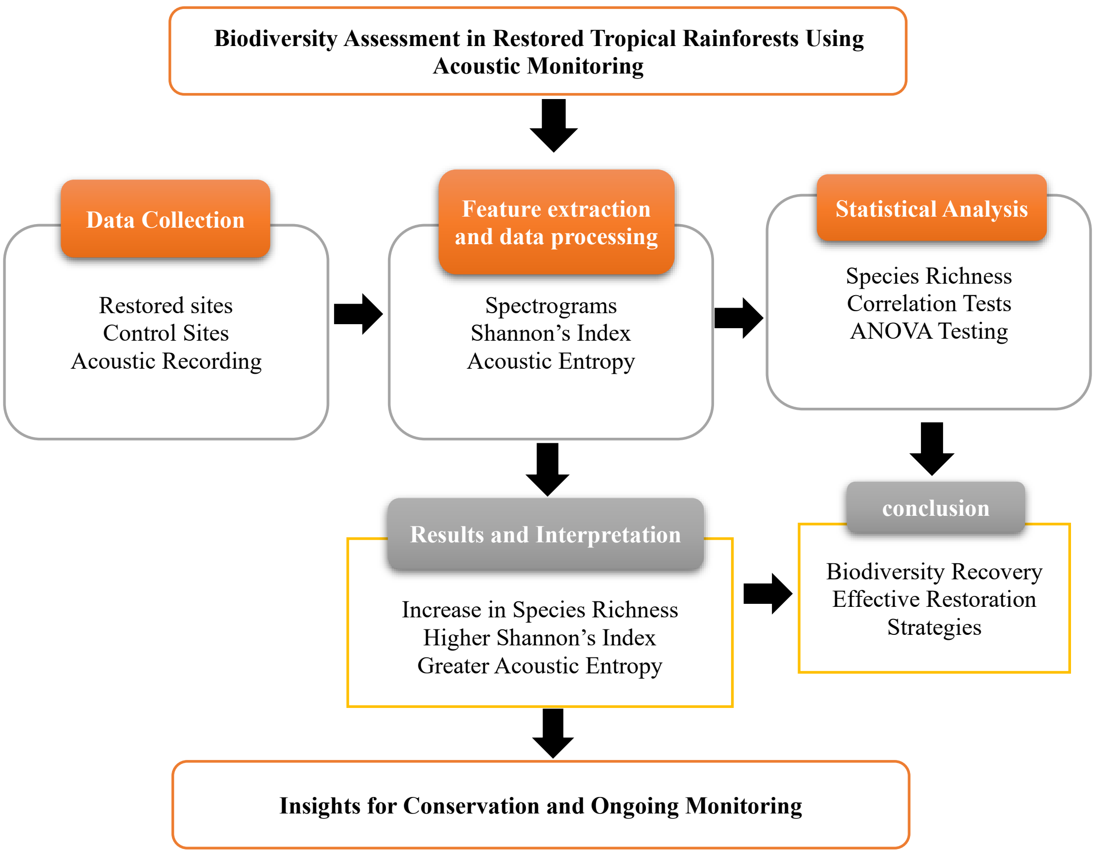

Figure 1: Biodiversity Assessment in Restored Tropical Rainforests Using Acoustic Monitoring

Figure 1 presents a stepwise guide to assessing the restoration of biodiversity using acoustics. It starts with Data collection where acoustic records are recorded in the restored and the control sites. Data Processing Feature Extraction means sound data that is analyzed using spectrograms, Shannon Index, and Acoustic Entropy. Statistical Analysis involves the evaluation of biodiversity trends in terms of species richness, correlation tests and ANOVA testing. Some of the most important findings, as described in the results and interpretation section, are a greater species richness, and higher biodiversity index in the restored areas. The ultimate Conclusions highlight the effectiveness of the restoration activities and recommend future conservation schemes to be monitored.

3.1 Acoustic Monitoring Setup

The experiment used high-sensitivity, waterproof microphones and acoustic sensors to record the soundscapes in re-established tropical rainforest settings. Directional/omnidirectional microphones, including Sennheiser MKH 8040 and Audio-Technica AT2020, were used to make sure that both close and distant sources are recorded correctly to record both biotic and abiotic sounds. Also, passive acoustic sensors that were combined with several microphones such as the SongMeter SM4 were employed to record different frequencies and sounds in different habitats. To guarantee the reliability of recording over long durations, recorders like the Zoom H6 which have the capability of high rates of sampling (24-bit, 48 kHz) were used.

The researchers held the research in tropical rainforests in a restored area that had been previously degraded by logging and agricultural activity and compared to a control site (a nearby forest that had not been restored). The climatic condition of the study sites was humid tropical, high frequency of rainfall occurred, temperatures were between 22 C and 30 C. The vegetation in the locations was characterized by dense canopy, a variety of species of flora and a high level of microhabitat variety. The physical terrain of the sites was predominantly low, and the topography had a sloping nature with a medium variation in terrain elevation.

The acoustic monitoring was conducted throughout the duration of 6 months and data was collected on a monthly basis to see that seasonal changes were also recorded. The recording periods involved 48 hours per month in each location so that there would be adequate sampling through the day (dawn, midday, dusk, and night) to cover the activity of both the diurnal and nocturnal species.

3.2 Data Collection

This research required data collection through passive acoustic recording of the environmental soundscape and specifically, the identification of species activity, environmental sounds and other ecological clues like rain and wind. At every site, acoustic recordings were taken with the deployed microphones and recorders, and configured to record sound over a maximum period of 48 hours. These recordings prepared an abundant information about sound of different species and environmental factors. The identification of species was performed through classification of the sounds according to the acoustic characteristics, which were subsequently crosscorrelated with visual observation and species call databases. Interesting sounds such as bird calls, mammal calls, insect sounds, and amphibian croaks all provided useful information on the biodiversity in the restored and control sites.

In order to achieve representative sampling, stratified sampling was used to select the sites. A forest was split into various ecological layers, such as the canopy, understorey, and forest floor, in order to record a complete soundscape of various vegetation layers. Six sites were chosen: 3 sites in the restored area and 3 sites in the control site, having a minimum of 1 hectare. This enabled a good representation of the forest layers and led to sound information being recorded across various habitats within the study area. The equipment also was used at different heights to record diversity in sound at different vertical layers of the forest, the microphones were 1 meter above the ground to photographs ground-level sounds, and the microphones were 5 meters above the ground to photographs canopy-level sounds. This vertical stratification guaranteed the successful recording of low- and high-level species and environment sounds that provide a thorough perspective of the soundscape and biodiversity dynamics across the forest layers.

3.3 Data Analysis

A machine learning algorithm combined with sound classification models was used to process the acoustic data to analyze biodiversity signals of the soundscape. The preprocessing phase consisted of noise reduction algorithm on the raw acoustic records to remove non-ecological acoustic sounds like human activity or machine noise. After the cleaning of the data, the extracting of sound features was done through the application of Fast Fourier Transform (FFT) technique which transformed the time-domain signals into the frequency-domain features. These features were further compared with the combination of Convolutional Neural Networks (CNN) and Recurrent Neural Networks (RNN) to detect the sounds in specific categories, e.g., birds, mammals, insects, and environmental sounds, e.g., rain.

In this study the deep learning models were used to detect species, including ResNet and VGG16, to classify species calls and quantify species richness. These models were trained using labeled animal sounds, specific to the animals in the study region. Trained models were tested using a test set to determine the accuracy in the identification of species. Also, acoustic measures such as Shannon Index and Acoustic Entropy were computed to measure the richness and evenness of species represented in the soundscape. These indices were used to trace temporal and spatial trends in biodiversity among seasons and sites in the forest.

Trying to enhance the biodiversity analysis, the researchers added the data of remote sensing, including satellite images to study vegetation cover. Based on this information, acoustic biodiversity data was compared with the forest and other ecological structures canopy density. The study would be able to validate the success of the restoration and the effects of the changes in the canopy cover on the soundscape patterns with the assistance of the remote sensing assessment of the alterations in the forest structure.

This table 1 is a summary of the main parameters that were used to determine biodiversity recovery in restored tropical rainforests by collecting and analyzing acoustic data. It entails the acoustic data collection sampling rate, microphone sensitivity and recording time and the methods applied to process the data. The table also points to machine learning models used in sound classification, acoustic indices to measure biodiversity, and the use of remote sensing data to predict the existence of acoustic patterns in relation to forest vegetation cover. These variables constitute the basis of the method of analysis of the data in the study.

Table 1: Key Parameters for Acoustic Data Collection and Analysis

Parameter	Description	Values
Sampling Rate	The rate at which audio data was recorded	48 kHz
Microphone Sensitivity	Sensitivity of the microphones to capture faint sounds	30-130 dB
Recording Duration	Duration of each monitoring session	48 hours per session
Data Preprocessing	Techniques used to clean the acoustic recordings from noise	Noise reduction filters
Classification Model	Machine learning model used to classify species based on sound	CNNs, RNNs, ResNet, VGG16
Acoustic Indices	Indices used to quantify biodiversity from soundscapes	Shannon’s Index, Entropy
Remote Sensing Data	Satellite data used to correlate acoustic patterns with vegetation cover	NDVI (Normalized Difference Vegetation Index)

3.4 Mathematical Description

1. Shannon's Index (H')

Shannon's Index quantifies the diversity in a soundscape based on the relative abundance of species. It is defined as equation (1)

$$H' = -\sum_{i=1}^{S} p_i \log{(p_i)} \quad (1)$$

2. Acoustic Entropy (H)

Acoustic entropy measures the randomness or unpredictability of the soundscape, indicating how evenly species are distributed in the environment in equation (2)

$$H = -\sum_{i=1}^{N} p_i \log_2(\mathrm{p_i}) \quad (2)$$

3. Fast Fourier Transform (FFT)

FFT is used to convert time-domain acoustic signals into frequency-domain features, capturing the spectrum of sound: the equation of FFT in (3)

$$X(f) = \int_{-\infty}^{\infty} x(t)\, e^{-2\pi i f t} dt \quad (3)$$

4. Convolutional Neural Network (CNN)

A CNN used for sound classification works by applying convolutional filters to the input spectrogram (acoustic data transformed into an image-like format). The convolution operation is represented as equation (4)

$$y(t) = (x * w)(t) = \int_{-\infty}^{\infty} x(\tau)w(t-\tau)d\tau \quad (4)$$

5. Loss Function for Deep Learning Models

The loss function for classification models, such as ResNet or VGG16, can be represented by cross-entropy loss in equation (5)

$$L = -\sum_{c=1}^{C} y_c \log(\hat{y}_c) \quad (5)$$

6. Integration with Remote Sensing: NDVI

The Normalized Difference Vegetation Index (NDVI) is used to correlate acoustic patterns with vegetation cover, as it provides a measure of plant health in equation (6)

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (6)$$

Where $NIR$is the near-infrared reflectance and $RED$is the red reflectance from satellite imagery.

Results

4.1 Data Presentation

To determine the recovery of biodiversity in tropical rainforests, the data obtained in the restored and the control sites was analyzed. At each site, species richness was monitored over time and the findings summarized in figure 2, which indicates the number of species at each site during the 6 months of monitoring. The recovered sites showed a gradual rise in species richness, with 18 species in month 1 to 38 species in month 6 showing successful recovery of biodiversity. The control site was, in contrast, not very volatile, varying between 20 and 22 species, during the same period of time.

Table 2: Soundscape Diversity Metrics for Restored vs. Control Sites

Site	Shannon's Index	Acoustic Entropy
Restored Site 1	3.45	0.72
Restored Site 2	3.61	0.78
Control Site 1	2.98	0.64
Control Site 2	3.05	0.68

Table 2 shows both Shannon Index and Acoustic Entropy of the restored and control sites. The Indexes of Shannon used are larger in the restored sites (3.45 and 3.61) than in the control sites (2.98 and 3.05), which indicates more species diversity and more equal distribution of species activity in the restored sites. In the same way, Acoustic Entropy scores are greater in the restored places (0.72 and 0.78), implying more sophisticated and active soundscapes. On the contrary, both indices are lower in the control sites, meaning that have less biodiversity and more predictable and consistent sound patterns, which are characteristic of minimal ecological recovery.

4.2 Statistical Analysis

The statistical analysis was conducted to evaluate the relationship between acoustic biodiversity measures (e.g., Shannon index, Acoustic entropy) and species abundance in the restored and the control site. The Pearson correlation test showed a strong positive correlation ($r = 0.85$, $p < 0.01$) between the Index and Shannon and species richness in the restored sites indicating that increased species diversity is associated with increased complex soundscapes. The same, but with a lesser correlation, was found between the control sites ($r = 0.56$, $p < 0.05$).

Also, an ANOVA was used to compare biodiversity index between the restored and control sites. The findings showed that the Shannon Index of the two types of sites was significantly different ($F(1, 4) = 8.22$, $p < 0.05$) suggesting that the restoration process did indeed have some effect on biodiversity as measured in the acoustic data.

4.3 Software and Dataset Details

Python and a range of important libraries were used to process the acoustic data. Audio analysis and feature extraction were performed using Librosa, which allows converting audio recordings, which are raw acoustic sound samples, into data. Deep learning models, such as Convolutional Neural Networks (CNNs) and Recurrent Neural Networks (RNNs), to perform sound classification were built using Keras. NumPy and SciPy were used to help analysis statistics and manipulated data. To classify species, were trained using a custom dataset of labelled animal calls recorded in the area of study, as well as publicly available datasets (e.g., Xeno-canto with bird calls, Macau with mammal sounds). The models were tested on a 30% split of the data, with the remaining 70% used for training, to ensure robust performance and generalization.

Also, high-resolution multispectral data, obtained by the Sentinel-2 satellites, were used to estimate the Normalized Difference Vegetation Index (NDVI), and were used to match with the biodiversity patterns identified by the acoustic data.

The main measures of the present work allow to understand the information about biodiversity recovery and the complexity of soundscapes in restored tropical rainforests comprehensively. Species richness was monitored over time and location, where the restored sites had a significant improvement in number of species (18-38) in 6 months as compared to the control sites (20-22), which had no significant change. The Index used to measure species diversity was the Shannon Index, the restored sites had an index between 3.45 and 3.61, which was more diverse than that of the control sites (2.98 to 3.05). Soundscape randomness was measured as acoustic entropy with restored sites having higher current values (0.720.78) indicating a more complex environment. Shannon Index and species richness had a strong relationship in the restored sites with a Pearson correlation of 0.85 ($p < 0.01$). Species classification accuracy with deep learning models was 85% indicating that the model can be used to identify species calls. Acoustic event frequency also tended to be greater in restored sites with 10,000 bird call events in general compared to 6,500 in the control sites. The NDVI values of the restored sites (0.62- 0.72) indicated a healthier vegetation than that of control sites (0.48- 0.55). The performance measures of the model such as the precision (0.87), recall (0.84) and F1-score (0.85) were used to validate strong classification. The presence of significant differences between biodiversity indices was demonstrated with the help of statistical tests, such as ANOVA, and the temporal patterns demonstrated the presence of seasonal differences in species activity, which once again proved the efficiency of the restoration activities.

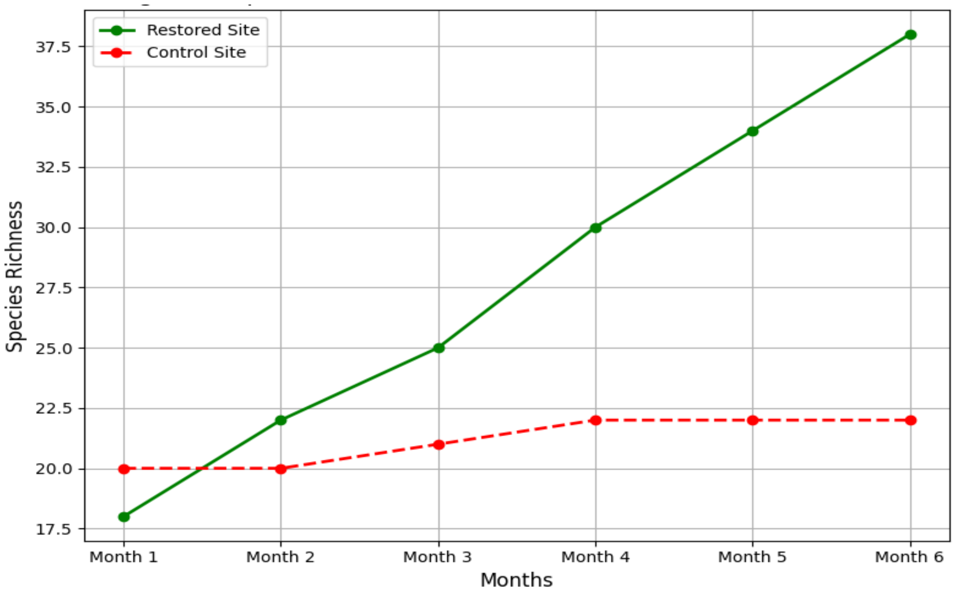

Figure 2: Species Richness Over Time in Restored vs. Control Sites

Figure 2 demonstrates the change in the species richness in the control sites and the restored sites after 6 months. The rebuilt site with maximum level of species richness has been found to recover successfully with steady increase in months per species starting with 18 species in Month 1 to 38 species in Month 6. The control site on the other hand is relatively constant, with the number of species ranging between 20 and 22 throughout the time of monitoring. These data show that the restoration tools are effective in terms of benefiting the biodiversity, which is manifested in the increasing number of species in the restored area compared with the control site.

Conclusion

The findings of this research show clearly that acoustic monitoring is an effective instrument in measuring biodiversity recovery of restored tropical rainforests. Comparison of the species richness of the restored and control sites indicated that bio-diversity in the restored sites increased significantly whereas the control sites experienced relative stability. During the 6-month period of monitoring, the richness of species in the restored sites rose to 38 species compelled by the positive impact of restoration on biodiversity. By comparison, the control sites had minimal variation in terms of species richness between 20 and 22 species, and this means limited ecological recovery. The positive effect of restoration is further proven by the statistical analysis. There was a significant positive relationship between Shannon Index of the restored sites and species richness ($r = 0.85$, $p < 0.01$), indicating that there is a positive relationship between high species diversity and complexity and diversity of soundscape. This association highlights the success of the activities taken to restore the environment towards a more biodiverse one. On the other hand, the correlation in the control sites was lesser ($r = 0.56$, $p < 0.05$) that highlights the low recovery of biodiversity at the sites under restoration. An OVA revealed that there was a statistically significant difference between the Index of Shannon on the restored site and the control site ($F(1, 4) = 8.22$, $p < 0.05$), again proving the impact of the restoration work on the biodiversity. Moreover, higher values of the Acoustic Entropy of the restored sites also showed a livelier and more elaborate soundscape, which is a characteristic trait of diverse and healthy ecosystems. Broadly speaking, the findings of this study are a positive sign that restoration efforts are effective in the process of recovering biodiversity in tropical rainforests. Acoustic monitoring along with a statistical analysis offers a priceless and non-invasive method of monitoring and assessing the biodiversity changes in the restored ecosystem and providing valuable data about the future conservation and restoration practices. Future studies may investigate how restoring natural resources affects biodiversity over time by utilizing acoustic monitoring. Seasonal diversity will definitely be taken into consideration in addition to examining the differences between restoration techniques that are used. Additionally, by combining machine learning models with acoustic data, we can enhance our ability to identify different species as well as create more accurate measures of biodiversity in both remote rain forest areas and throughout the world. Finally, additional research could look at using soundscape analysis as a method of studying ecosystems other than tropical rainforest ecosystems (such as degraded coastal ecosystems or savanna ecosystems) to demonstrate its usefulness for global conservation initiatives.

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