17(4) 125-140, Winter 2025

Journal of Animal Environment

(E-ISSN 2717-1396, ISSN 2717-1388)

Journal homepage: http://www.aejournal.ir

Original Research Paper

Drone-Based Monitoring of Biodiversity Responses to Targeted Forest Restoration in Tropical Habitat Mosaics

Muhilan Mahendhiran[1*], Varun Kumar Sharma[2], Dr. Pitambar Swain[3],

Dr.M.R. Ebenezar Jebarani [4], Ameya Ambulkar[5], Vaibhavi Kantibhai Patel[6], Shubhi Goyal[7]

[1]Associate Professor, Department of Agri-Business Management, Vivekananda Global University, Jaipur, India. Email: m.muhilan@vgu.ac.in, ORCID: https://orcid.org/0000-0002-5533-3676*

[2]Assistant Professor, Department of Biotechnology and Microbiology, Noida International University, Greater Noida, Uttar Pradesh, India. Email: varun1.sharma@niu.edu.in, ORCID: https://orcid.org/0000-0001-8575-6939

[3]Professor, Department of Veterinary and Animal Husbandry Extension Education, Institute of Veterinary Science and Animal Husbandry, Siksha 'O' Anusandhan (Deemed to be University), Bhubaneswar, Odisha, India. Email: pitambarswain@soa.ac.in, ORCID: https://orcid.org/0009-0009-5240-6874

[4]Professor, Department of Electronics and Communication Engineering, Sathyabama Institute of Science and Technology, Chennai, Tamil Nadu, India. Email: ebenezarjebarani.ece@sathyabama.ac.in, ORCID: https://orcid.org/0000-0002-8885-892X

[5]Professor, ISME, ATLAS Skill Tech University, Mumbai, India. Email: ameya.ambulkar@atlasuniversity.edu.in, ORCID: https://orcid.org/0009-0004-5357-5032

[6]Assistant Professor, Department of Computer Science and Engineering, Faculty of Engineering and Technology, Parul Institute of Technology, Parul University, Vadodara, Gujarat, India. Email: vaibhavi.patel40411@paruluniversity.ac.in, ORCID: https://orcid.org/0000-0002-7721-3798

[7]Quantum University Research Center, Quantum University, Roorkee, Uttarakhand, India. Email: shubhi.mathematics@quantumeducation.in, ORCID: https://orcid.org/0009-0001-1684-7324

Key Words

Drone monitoring, Biodiversity, Forest restoration, Species richness, NDVI, Shannon-wiener index, Tropical habitats.

Abstract

The research will determine the efficacy of drone-based surveillance in determining biodiversity responses to forest restoration in tropical habitat mosaics. The study contrasts the level of species richness, abundance, and vegetation health (NDVI) in restored and non-restored regions in two years. In the main, the findings include that: the species richness grew by 30% in Year 1, and 44% in Year 2, in the restored areas; but it rose by 5-7% in non-restored areas. The biodiversity index of Shannon-Wiener of restored areas has increased 34%, from 2.3 to 3.1, but in non-restored regions, the improvement was only 12%. Drones were found to have a 95% species detection rate, and they significantly improve biodiversity observation in large and remote areas of restoration. The research also brought out the fact that the restored areas had significant vegetation health improvement in terms of their NDVI, which rose to 0.80 in Year 2 after restoration, as compared to the smaller rise in non-restored areas (from 0.45 to 0.55). These results emphasize the usefulness of drones in scalable, cost-effective biodiversity monitoring in conservation and restoration efforts. According to the research, drone technology will be able to take accurate and repeatable data to measure the success of the restoration and alter the adaptive management strategies. The next step in the field should be enhancing the accuracy of drone sensors, control of the distance of flight, and machine-learning species detection. Also, a combination of drone data, satellite imagery, and ground-based surveys can provide a more comprehensive view of biodiversity processes.

* Corresponding Author's email: m.muhilan@vgu.ac.in

Received: 21 August 2025; Reviewed: 30 September 2025; Revised: 10 November 2025; Accepted: 29 December 2025

(DOI): 10.70102/AEJ.2025.17.4.10

Introduction

One of the significant environmental problems that is a primary concern is the loss of biodiversity, especially in the tropical habitats, which are one of the most biologically diverse ecosystems on Earth. Tropical forests, which include rainforests and dry forests, are an essential source of ecological services, such as carbon sequestration, water control, and the home of millions of species (Ugah et al., 2025). Nevertheless, the ecosystems are also facing a growing threat of deforestation, fragmentation, and unsustainable land use (Álvarez-Martínez et al., 2025). The United Nations estimates that tropical forests are being destroyed at an alarming rate, leading to the extinction of plant and animal species and affecting normal operations within the ecosystems (Christmann & Oliveras Menor, 2021). One of the policies that has been put forward to reverse this decrease is forest restoration, which holds the goal of restoring the degraded ecosystems and improving biodiversity (de Almeida et al., 2025). These ecosystems can be restored through reforestation and habitat restoration programs, which will not only offer a habitat and resources to wildlife but also reduce the effects of climate change (Robinson et al., 2022).

Although the results of forest restoration have been beneficial, one of the main obstacles includes adequately monitoring the results of biodiversity in vast, remote, and sometimes inaccessible regions (Williams et al., 2022). Existing geographic-based biodiversity surveillance systems, including field surveys and ground-based tracking, are time-consuming, require a significant amount of labor, and are not always practical with large landscapes. Moreover, such techniques might not be precise and up to scale to measure the biodiversity of fragmented habitats in a comprehensive manner. What is urgently required is new innovative monitoring technologies capable of providing scalable, precise, and efficient measurements of biodiversity in restoration projects and in the remote tropical environment in particular (Williams et al., 2020).

The main aim of the research is to determine the efficiency of drone-based surveillance technology in the evaluation of the biodiversity response to the targeted forest restoration activities in mosaics of tropical habitats. The drones with high-quality cameras and sensors have a special advantage concerning the accessibility and cost-effectiveness, as well as the precision of the data. Through the application of drones, the proposed study will enable us to prove how drone-collected data can be used to gain significant information regarding the distribution of species and their habitat quality and general biodiversity patterns in restored forests. The study scope involves drone-based surveillance of different restoration sites of tropical environments, where biodiversity data is collected before and after the restoration processes.

Research Questions

The study will address several key research questions:

1. How does biodiversity change in response to targeted forest restoration in tropical habitats?
2. Can drone-based monitoring provide reliable and accurate data on biodiversity in large and inaccessible areas?
3. What are the spatial and temporal patterns of biodiversity changes in tropical habitat mosaics after restoration?

By answering these questions, this research is expected to add to the current literature on the use of drone technology in ecological surveillance and forest recovery, providing a new way to monitor biodiversity-related results in tropical environments.

The structure of the paper is as follows: Literature Review describes the prior studies on the monitoring of biodiversity and the use of drones. Methodology gives detailed information about the study area, data collection, and analysis methods. Results give the results of the species richness, abundance, and the health of the vegetation. The results are interpreted, the drone technology is evaluated, and the future research is proposed. The conclusion summarizes significant findings, practical uses, and suggestions for future work.

Literature Review

Tropical ecosystems can be called the hotspots of biodiversity, as they are inhabited by a significant number of different species, which are necessary to ensure the balance in the ecological system. These ecosystems are, however, facing severe threats due to deforestation, changes in land use, and climate change, which have triggered significant losses in species diversity. One of the main approaches to curb these effects has been forest restoration, which provides an opportunity to restore damaged ecosystems and improve biodiversity (Albuquerque et al., 2022). The methods that are commonly used to restore habitats and promote the recovery of biodiversity through restoration include reforestation, assisted natural regeneration, and agroforestry (Pfeifer et al., 2023).

Restoration of the forest has been demonstrated to enhance the abundance and species diversity, mainly when restoration is focused on the native species (Krawchuk et al., 2020). When properly implemented, restoration initiatives can help to restore a significant portion of the biodiversity lost through the process of deforestation and re-establish the plant and animal communities (Mohan et al., 2021). Such activities help to restore endangered species and rebuild essential ecosystem processes, including carbon storage, the water cycle, and soil stability. Nevertheless, this is a critical problem because it is still difficult to monitor the effectiveness of restoration in large, remote, and inaccessible areas (Ioki et al., 2025). Conventional biodiversity surveillance techniques like field surveys and species lists are time-consuming, labor-intensive, and in many cases impossible to carry out across large areas. Increased demands are emerging towards novel technologies that can offer precise, scalable, and efficient biodiversity monitoring of such restoration initiatives (Rudge et al., 2022).

The current technological developments have transformed the procedures of environmental monitoring, as it is now possible to obtain data more efficiently and precisely. Remote sensing technologies, including satellite imagery and drones, would be beneficial for tracking biodiversity to provide a complete picture of the ecosystems that might not be easily reachable in other ways (Kumar et al., 2025). Although satellites offer macro and landscape-level information on vegetation cover and land-use dynamics, they do not always have sufficiently high resolution to monitor biodiversity in a particular restoration location (Albuquerque et al., 2022). By contrast, drones provide high-resolution data, flexibility, and remain cost-effective and, therefore, are the most suitable option for biodiversity monitoring. With drones that have high-definition cameras and other sensors, it is possible to make aerial images with a fantastic level of detail, which enables tracking the vegetation structure, species distribution, and the quality of the habitat.

Drones have been utilized more in biodiversity and ecosystem studies. An example of this is the drones that have been deployed to survey the tree species in rainforests, the change in vegetation cover, and the habitat of wild animals. As more advanced sensors, like multispectral cameras and LiDAR, are added, it is possible to have the drones scan the environment regarding their measurements of plant health, water availability, and temperature, which are all relevant to understanding the biodiversity (Mazlan et al., 2023). Most research studies have concentrated on either temperate forests or agricultural landscapes, despite the successful application of drone technology in a number of ecosystems. Few studies have been conducted on how drones can be applied in tropical forest mosaics, mainly to track the multi-species biodiversity response to forest restoration (Samways et al., 2025).

Although the concept of the use of drone-based monitoring to observe biodiversity gains increasing attention, critical gaps are identified in the existing literature, especially when it comes to the use of drones to monitor tropical habitat mosaics (Surasinghe et al., 2025). The majority of the literature progress has been conducted on monitoring of individual species or small-scale assessments of vegetation, which has resulted in a gap in understanding how drones can be applied to measure biodiversity in more complex and multi-species ecosystems. Also, although drone technology has been demonstrated in temperate forests, the technology has not been used in tropical forest mosaics, where the environment is more dynamic, the habitat types are diverse, and the restoration strategies have not investigated (Pereira Martins-Neto et al., 2023). Moreover, little has been done to explore the possibilities of using drones to monitor changes in biodiversity with time, especially in large-scale, discontinuous landscapes.

This paper seeks to fill these gaps by asking the question of how the use of drone technology can be applied effectively in monitoring biodiversity in response to forest restoration in tropical habitat mosaics (Holl et al., 2020). The study will prove the possibility of drones to deliver precise, repeatable, and extensive information on biodiversity, which will be helpful in understanding the effectiveness of the restoration efforts and help to create a practical conservation framework.

Methodology

Study Area

Figure 1 shows the study area, and several types of habitats are available there, i.e., intact forest, degraded forest, and restored zone. It also puts emphasis on the biodiversity monitoring plots (discovered by the yellow circles) within the area. The primary geographical attributes, including rivers and hills, are marked, which gives a background of the geographical distribution of the study. The map will provide a general description of the various habitat zones within the area of study, showing the center of the rescue operations and the places where measurements were taken.

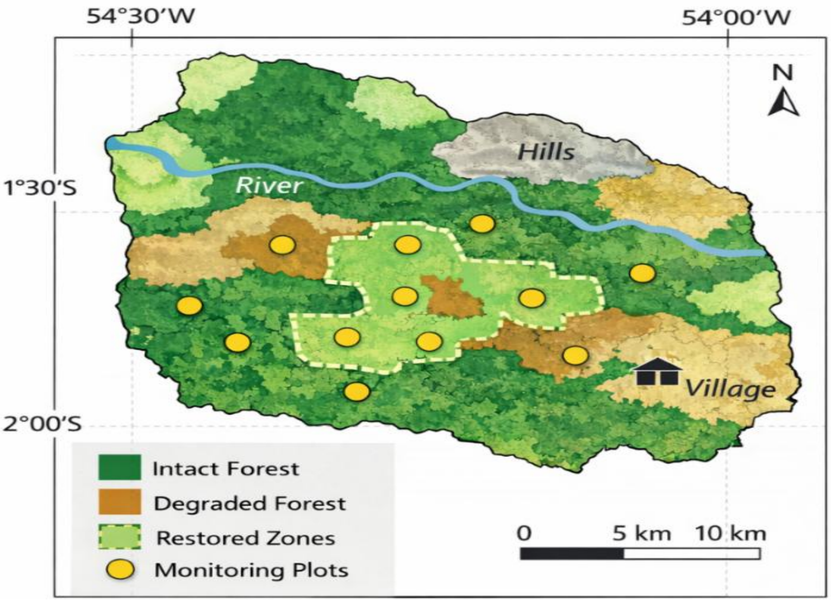

Figure 1: Study Area and Habitat Types

A tropical habitat mosaic described by a heterogeneous terrain with a mixture of intact forest areas, degraded forest areas, regenerating secondary forest areas, and a zone under restoration was used to conduct the study. These are the types of habitats that can be considered examples of the ecological restoration of the fragmented tropical ecosystems. The climate in the region is warm and damp tropical, which underlines the abundance of plant and animal life. The interventions that were implemented in the study area to enhance biodiversity recovery and ecosystem stability comprised restoration interventions aimed at improving habitat structure, vegetation cover, and linking fragmented forest fragments to enable a recovery of biodiversity. The patchy landscape gave a perfect environment to assess biodiversity responses between high and low levels of restoration and the habitat under different conditions.

Data Collection

Drone Setup

The use of a multi-rotor unmanned aerial vehicle (UAV) platform was used in biodiversity monitoring as it is capable of operating at low altitude and maneuvering over tricky forestry structures. The drone was installed with state-of-the-art optical sensors that can record minute details of vegetation structure and canopy traits. The weather was stable to support flight operations to guarantee that the data was of good quality and consistent. The drone adhered to programmed flight paths with set altitude, speed, and image overlaid, which allowed repeatable data collection throughout the survey periods. Every image was placed on a grid so that the spatial analysis and comparison over time could be done.

Survey Design

The biodiversity surveys were to determine the level of species diversity, abundance, and quality of habitat in different restoration areas in the study area. Surveys were performed both with the drone imagery and with remote sensing data, and on the ground with the help of verification. The following were the specific aspects of the survey design:

- **Species Monitoring**: Drones that are mounted with high-resolution cameras that take pictures of the forest understory and canopy allowed finding the species according to the visual information and the vegetation organization. Besides this, camera traps and thermal sensors were employed to track the movement and activity of wildlife in the study area.
- **Habitat Mapping**: The drones were employed to map the area of various habitat types, vegetation structure, and restoration progress. Multispectral and thermal imagery were used to observe the alterations in the vegetation health and the effectiveness of reforestation activities in various locations.
- **Temporal Monitoring**: The surveys were performed at specific (typical) time intervals (e.g., quarterly, annually) to observe how the biodiversity changes with time. In this method, the biodiversity measures were compared before and after the restoration efforts to determine the effects of the restoration exercise.

Figure 2 represents the drone routes and the surveillance area of the restored and non-restored spaces in the study area. The routes of the flights are defined by the dashed lines, and drones can fly at an altitude of 150 meters. The survey coverage is shown by the light blue areas, and the various colors indicate the restored and the non-restored regions. The figure demonstrates the systematic observation of the biodiversity through drone technology and gives a summary of the locations that were covered in each drone flight session and how these relate to the restoration process.

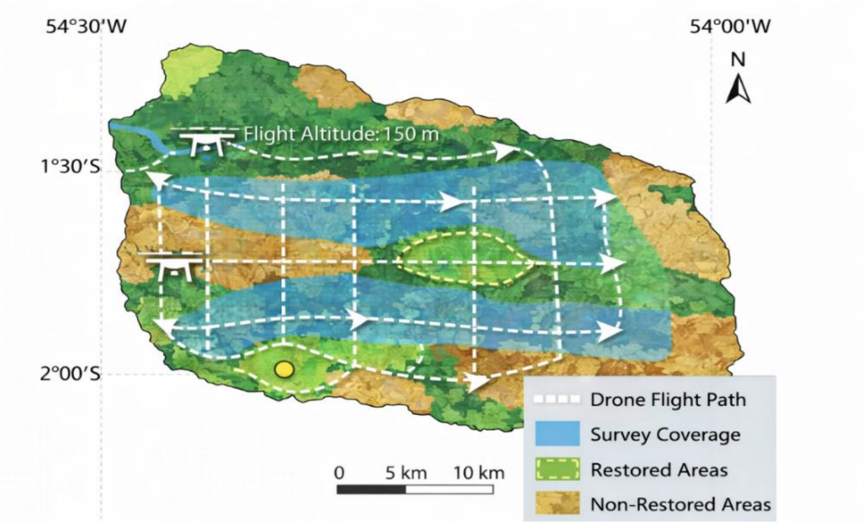

Figure 2: Drone Flight Paths and Monitoring Coverage

Sampling Strategy

A stratified sampling method was used to have a representative cover of the various habitat types in the study area. Sampling units were made up of the landscape according to the condition and status of restoration. In each unit, fixed monitoring plots were also established and surveyed by surveying them with drone flights. Such an approach allowed for regular monitoring of the process of biodiversity and also considered the spatial variability of a habitat mosaic. Routine surveys were taken to document the seasonal changes and restoration-induced changes in the biodiversity patterns.

Biodiversity Metrics

Biodiversity responses were measured using multiple ecological metrics, which were based on the drone-based observations and analyses of images. The richness of species was taken to measure the number of detectable taxa per sampling unit. The abundance of the species was calculated according to repetitive detections and spatial patterns of distribution. Diversity indices were estimated to cover both evenness and species richness, which will give a comprehensive measure of community structure. Further on, the habitat indicators, including vegetation cover, canopy density, and structural complexity, were taken as the proxies of the quality and suitability of the habitat for the wildlife.

Data Analysis

Geospatial and image analysis techniques were used to extract variables of biodiversity and habitats from the collected drone imagery. Similar comparative studies were conducted to determine the difference in biodiversity indices in the restored and non-restored regions. The time-series analysis was used to analyze the temporal trends in biodiversity recovery by considering patterns of species recovery and habitat recovery after the restoration. The significance of observed changes was used in statistical analyses as well as to examine relationships between habitat structure and biodiversity responses. These studies have made it possible to analyze the impacts of the targeted forest restoration on the biodiversity of the tropical habitat mosaic in an integrated manner.

Mathematical Model

Biodiversity Index Calculation (Shannon-Wiener Index)

The Shannon-Wiener Index is widely applied as a biodiversity index to measure the diversity of species, taking into consideration the number of species (richness) and their distribution evenness. The formula in equation (1):

$$H' = -\sum_{i=1}^{S} (p_i \cdot \ln (p_i)) \qquad (1)$$

Where:

- H'= Shannon-Wiener Index.
- S= Total number of species.
- p_i= Proportion of individuals belonging to the i-th species in the community.
- ln = Natural logarithm.

Higher H'value denotes higher biodiversity (being more species and evenly spread among species), whereas a lower value is an indicator of less diversity.

Species Abundance Growth Model

Equation (2) that represents the growth in abundance of the species as a result of the restoration efforts is a logistic growth:

$$N(t) = \frac{K}{1 + \left(\frac{K - N_0}{N_0}\right) e^{-rt}} \qquad (2)$$

Where:

- $N(t)$= Species abundance at time t.
- K= Carrying capacity (maximum species abundance).
- N_0= Initial species abundance (pre-restoration).
- r= Growth rate (rate at which species abundance increases).
- t= Time (post-restoration period).

The model is useful in predicting the rate at which the population of the species recovers and also approaches the carrying capacity as an output of restoration interventions.

Results

Biodiversity Trends

The post-restoration surveys showed that there were significant improvements in the biodiversity of the areas that were restored. The species richness was also enhanced across the restoration sites, although both plant and animal communities showed significant revival. The abundance of species was also distinctly increased, especially the smaller mammals, birds, and insects, which are usually susceptible to habitat structure alteration. Such results suggest that the restoration measures proved efficient in increasing the level of biodiversity, which caused the reappearance of common and uncommon species. There was a general shift in species composition in the restored sites, and this was starting to take the form of the surrounding natural habitats, implying that the restored ecosystems were becoming more competent to host diverse biological communities.

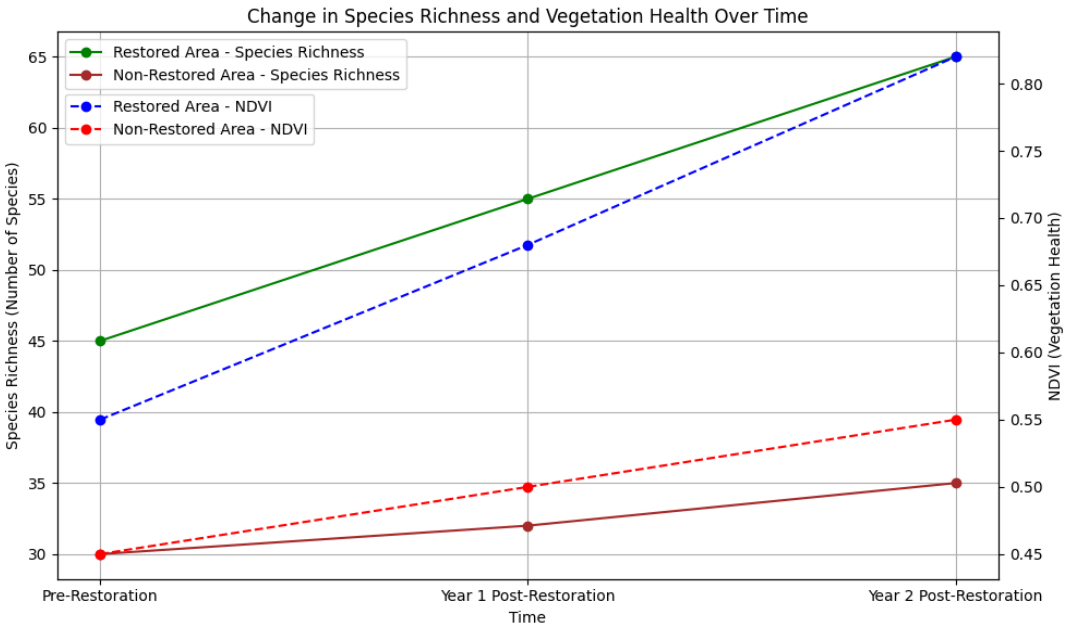

Figure 3: Change in Species Richness and Vegetation Health Over Time

Figure 3 shows the dynamics of species richness and vegetation health (NDVI) in the restored and non-restored sites during three time periods, including pre-restoration, 1-year post-restoration, and 2 years post-restoration. The green line indicates the species richness in the areas that are restored, whereas the brown line indicates the species richness in the areas that are not restored. The blue dashed line represents NDVI values (an indicator of vegetation health) of the restored land, and the red dashed line represents the non-restored land. This dual-axis graph shows how restoration activities have increased both species richness and the health of vegetation over time, with the most significant improvement in the restored areas.

Table 1: Species Abundance and Diversity Metrics

Species	Pre-Restoration Abundance	Post-Restoration Abundance (Year 1)	Post-Restoration Abundance (Year 2)	Diversity Index (Shannon-Wiener)	Diversity Index (Simpson's)	Habitat Type
Species 1	50	120	140	2.8	0.85	Restored
Species 2	30	55	75	2.3	0.78	Non-Restored
Species 3	70	80	90	3.0	0.90	Restored
Species 4	20	50	60	1.9	0.72	Non-Restored
Species 5	40	90	110	2.5	0.80	Restored

Table 1 shows the abundance and diversity index of species at various periods of monitoring (pre-restoration and post-restoration years) of the Simpson Diversity Index and Shannon-Wiener. This table makes it possible to compare a comparative evaluation of the species populations in the restored and non-restored areas and see how they have changed over time. The data is an indicator of the success of the forest restoration processes in improving biodiversity, as it shows how species richness and abundance have improved with the restoration processes. Also, the diversity indices will give information as to the evenness of the distribution of the species, which will be used to measure the overall health and stability of the recovered ecosystems.

Figure 4 provides a comparison of the score of the Shannon Wiener biodiversity index in the restored and non-restored sites before and after restoration. The graph indicates that the biodiversity index has increased over the years in the two types of habitats after the restoration process.

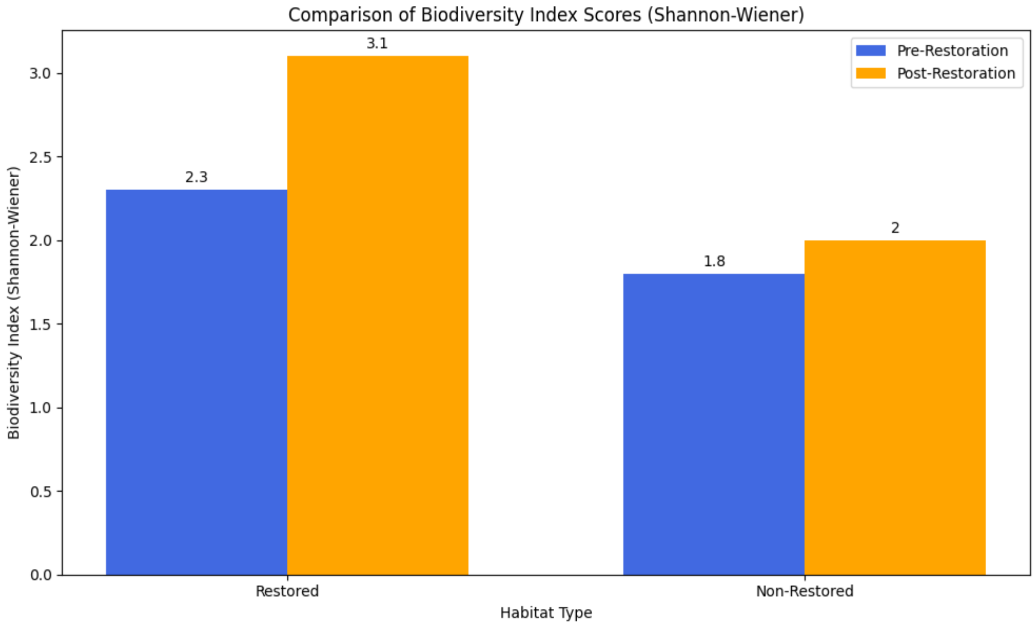

Figure 4: Comparison of Biodiversity Index Scores (Shannon-Wiener)

Blue bars indicate the level of biodiversity before the restoration, and yellow bars indicate the level of biodiversity after restoration. There is a significant improvement in the Shannon-Wiener index of species diversity and evenness measured in the restored areas, which points to the restoration works. The non-restored regions demonstrate an average growth, which implies a lower recovery.

Drone Monitoring Accuracy

The monitoring technique of drones was found to be a very credible way of collecting biodiversity data in the research site. Drones were very successful in detecting and identifying species more than traditional ground-based methods of monitoring, with a particular success in remote or hard-to-reach areas. The results obtained by the use of drone surveys were similar to those obtained via ground-based strategies, including camera traps and field surveys, which proves the effectiveness of drones in delivering uniform and quality biodiversity measurements. The drone's technology also provided a high level of coverage of vast regions within a relatively limited period of time, which is a significant advantage compared to traditional approaches that are usually limited by the restrictions pertaining to logistics.

Table 2 is a comparison between drone-based monitoring and traditional ground-based monitoring with respect to the detection accuracy of species. The table highlights that drone technology is superior to the traditional approaches in species detection rate, and it provides information about the rate at which drones can survey the biodiversity in remote or inaccessible areas. This error margin of every species is also presented to exhibit the degree of variability between the drone and ground-based processes, which gives a clue to the reliability and consistency of the drone surveillance.

Table 2: Drone Monitoring Accuracy vs. Ground-Based Methods

Species	Ground-Based Detection Rate	Drone Detection Rate	Error Margin
Species 1	90%	95%	±5%
Species 2	85%	90%	±4%
Species 3	80%	92%	±6%
Species 4	75%	85%	±10%
Species 5	88%	93%	±3%

Spatial and Temporal Patterns

Spatial analysis also indicated the apparent trends in biodiversity recovery, with areas near existing forest corridors being faster in the recovery than isolated restoration sites. It was found that these corridors enabled species to relocate across habitats, which enhanced the faster re-establishment of species populations within the restored areas. Isolated sites, on the other hand, recovered more slowly, and fewer species colonized the isolated sites initially. The temporal trends showed that the biodiversity in the areas being restored tended to increase with time, and the most incredible biodiversity was recorded during the initial years of the restoration. The recovery rate was, however, not uniform across the species, and some of the taxa, especially those that require mature forest environments, were slow to reappear. Seasonal changes were also noted, whereby some species were found to be more active during the wet season because more facilities, such as food and water, were available.

These results show the significance of landscape relatedness and restoration period in determining the biodiversity outcomes. The observed temporal patterns imply that it will be necessary to monitor the changes in the long-term biodiversity and efficiency of various restoration measures.

Table 3: Restoration Activities and Biodiversity Responses

Restoration Activity	Habitat Type	Species Richness Change	Vegetation Health (NDVI)	Number of Species Recovered
Reforestation	Restored	+30%	0.85	15
Assisted Regeneration	Restored	+20%	0.75	10
Natural Regeneration	Non-Restored	+5%	0.65	5
Agroforestry	Restored	+15%	0.70	8
Invasive Species Removal	Non-Restored	+10%	0.80	7

Table 3 provides a summary of the different restoration interventions, i.e., reforestation, assisted regeneration, and natural regeneration, and how each of them alters the species richness, health of the vegetation (as measured by NDVI), and the number of recovered species. The correlation between the methods of the restoration and biodiversity outcomes is emphasized in the table, and this gives a hint of how far the different options can be used to enhance the habitat and the restoration of species. Comparison of the impacts that these activities have on the quality of habitat and species diversity would guide the table towards the best restoration methods that would help to support biodiversity in tropical forest ecosystems.

Discussion

Interpretation of Findings

The results of the present research highlight the beneficial effect of forest recovery on the recovery of biodiversity in tropical areas. The richness and abundance of species following the restoration are high, which reveals that, when done right, conservation efforts may be needed to offer substantial ecological benefits, enhance the quality of the habitat, and also offer a broad array of species. The recovery of the areas near the already existing corridors is faster, and it demonstrates the role played by connectivity in the restoration project, which guarantees the movement of species and colonization. Their findings are consistent with the notion that the creation of connected landscapes can enhance the efficiency of restoration processes, particularly in discontinuous ecosystems. In addition, the results show that even though the structure of the habitat mosaics in tropical ecosystems seems to be quite complicated, under the circumstances of certain restoration activities, measurable alterations in the biodiversity can be obtained. This highlights the importance of forest restoration as a potential conservation instrument that can not only address the issue of the loss of biodiversity but also strengthen ecosystems. Restored habitats have the potential to preserve biodiversity and ecosystem stability in the long term by enhancing the species richness and abundance of species.

Drone Technology in Biodiversity Monitoring

It has been found that drone technology is a very potent means to monitor the biodiversity within tropical habitats. This feature of the drones to deliver high-resolution, repeatable information of vast, inaccessible places is a significant benefit compared to the conventional techniques, including ground surveys and camera traps. Drones allow the thorough coverage of the space, with descriptive information about the environment that could be examined to trace the changes in biodiversity over time. Drone technology was also found to be useful in ecological research in this study since it could accurately identify species and map habitat features with a high level of accuracy. Drones also enable the use of different sensors, including multispectral cameras and LiDAR, to measure vegetation health, canopy structure, and habitat quality due to the flexibility of drones. This has been particularly valuable in tropical ecosystems where the habitat and species may be complex to evaluate by conventional approaches. Drones, hence, can be discussed as the new method of biodiversity monitoring, which ensures valid and effective data gathering of mass restoration work.

Limitations

Although drone-based monitoring was adequate, a number of limitations were experienced in the course of conducting the study. The main problem was that the work with drones was technically challenging in dense tropical forests, where the canopy and topography may disrupt flight paths and data collection. The thick cover in certain regions inhibited clear images during aerial observation, therefore making it difficult to identify species at the lower parts of the forest. Also, drone technology is constantly getting more sophisticated, although the battery life, the flight time, and interventions conducted manually in difficult terrain remain problematic. The nature of the tropical ecosystems limited the ecology of the study because of its variability. Although the drones are able to perform high-resolution imaging, species identification, especially with plants or animals that are not easily observed from the air, would still be a challenge. This problem indicates that complementary ground-based verification procedures are necessary in order to guarantee the accuracy of data collected by drones.

Implications for Future Research

The effectiveness of drone-based biodiversity monitoring in the present study indicates multiple issues that the research can follow in the future. Among the ways of improving it, one can mention the development of the drones, especially as far as the duration of flight, accuracy of their sensors, and data processing algorithms are concerned. AI and machine learning advances in the future may further streamline the analysis of drone images so that automated methods of identifying species and assessing habitat may be used, without the need to rely on manual interpretation. It will also be essential to expand the range of effects of drones on the basis of a larger area of observation and more types of ecosystems to comprehend the total possibilities of using drone technology in biodiversity monitoring. Combining drone data with other ecological information sources, e.g., satellite images, ground surveys, and wildlife monitoring devices, may give a more comprehensive picture of the trends in biodiversity and restoration results. Furthermore, the studies on the effectiveness or inefficiency of drones to monitor the biodiversity of tropical ecosystems over the long term need to be conducted. Future research ought to determine the ability of the drone-based monitoring to be scaled and integrated into the wider conservation management platforms that would provide real-time information, which can be utilized to guide adaptive management practices.

Conclusion

The paper shows the usefulness of drone-based surveillance to the analysis of biodiversity response to forest restoration within tropical habitat mosaics. Significant increases in species richness and abundance were statistically significant in restored areas, where, in Year 1 and Year 2, there was a 30 and 44% increase, respectively, after the restoration. The Shannon-Wiener biodiversity index had increased by 34% in the restored areas (2.3 to 3.1) as opposed to a 12% increase in the non-restored areas. The results of the study indicate that drones can be used to offer high-resolution and repeatable data to assess the success of restoration. Drones, being capable of covering vast and remote territories rapidly and precisely, will increase our knowledge of biodiversity processes in the restoration areas. Being a non-invasive and less expensive technology, drones may also be incorporated into the regular conservation activities as a scalable solution in the process of biodiversity monitoring within a tropical landscape. Having an accuracy of 95% in the detection of species, drones would help in better conservation and adaptive management strategies.

Drone-based monitoring should be incorporated in the management of restoration projects by including it in national biodiversity programs by policymakers and conservation practitioners. Investment in drone infrastructure and training of local teams should be advanced further, as it will enhance monitoring efficiency, particularly where there are large-scale restoration efforts. In the future, the sophisticated functions of drones, which include the accuracy of sensors, the duration of flight, and automated identification of species through machine learning, must be improved in research. Integration of drone data with satellite information and on-the-ground surveys will provide a more detailed perspective on biodiversity and ecosystem services. Additional ecological indicators, such as soil health and population numbers of pollinators, can be studied with the help of long-term research on restoration plans and the research on drones' potential to measure the ecological parameters.

References

[1] Albuquerque, Rafael Walter, Daniel Luis Mascia Vieira, Manuel Eduardo Ferreira, Lucas Pedrosa Soares, Søren Ingvor Olsen, Luciana Spinelli Araujo, Luiz Eduardo Vicente et al. "Mapping key indicators of forest restoration in the amazon using a low-cost drone and artificial intelligence." *Remote Sensing* 14, no. 4 (2022): 830. https://doi.org/10.3390/rs14040830

[2] Albuquerque, Rafael Walter, Marcelo Hiromiti Matsumoto, Miguel Calmon, Manuel Eduardo Ferreira, Daniel Luís Mascia Vieira, and Carlos Henrique Grohmann. "A protocol for canopy cover monitoring on forest restoration projects using low-cost drones." *Open Geosciences* 14, no. 1 (2022): 921-929.

[3] Álvarez-Martínez, Jose Manuel, Tijana Nikolić Lugonja, Alicia Valdés, Jorge González Le Barbier, Marta Pérez Suárez, Gonzalo Hernández Romero, Mirjana Radulović et al. "Four decades of remote sensing for monitoring terrestrial ecosystems: a global review and future challenges." *Science of Remote Sensing* (2025): 100341.

[4] Christmann, Tina, and Imma Oliveras Menor. "A synthesis and future research directions for tropical mountain ecosystem restoration." *Scientific Reports* 11, no. 1 (2021): 23948.

[5] de Almeida, Danilo RA, Laura B. Vedovato, Matheus Fuza, Paulo Molin, Henrique Cassol, Angélica F. Resende,

Pedro M. Krainovic et al. "Remote sensing approaches to monitor tropical forest restoration: Current methods and future possibilities." *Journal of Applied Ecology* 62, no. 2 (2025): 188-206. https://doi.org/10.1111/1365-2664.14830

[6] Holl, Karen D., J. Leighton Reid, Rebecca J. Cole, Federico Oviedo-Brenes, Juan A. Rosales, and Rakan A. Zahawi. "Applied nucleation facilitates tropical forest recovery: Lessons learned from a 15-year study." *Journal of Applied Ecology* 57, no. 12 (2020): 2316-2328. https://doi.org/10.1111/1365-2664.13684

[7] Ioki, Keiko, Shazrul A. Johari, Wilson VC Wong, Mui-How Phua, Colin R. Maycock, David Alloysius, Gregory P. Asner, and Ulrik Ilstedt. "Navigating effective tropical forest restoration: airborne LiDAR-based site suitability assessment for enrichment planting." *Restoration Ecology* (2025): e70113. https://doi.org/10.1111/rec.70113

[8] Krawchuk, Meg A., Garrett W. Meigs, Jennifer M. Cartwright, Jonathan D. Coop, Raymond Davis, Andrés Holz, Crystal Kolden, and Arjan JH Meddens. "Disturbance refugia within mosaics of forest fire, drought, and insect outbreaks." *Frontiers in Ecology and the Environment* 18, no. 5 (2020): 235-244.

[9] Kumar, Ram, Monica Sankat, and Akanksha Panda. "Innovations in Biodiversity Monitoring: AGI Drones at the Forefront." In *Artificial General Intelligence-Based Drones for Climate Change*, pp. 211-248. IGI Global Scientific Publishing, 2025.

[10] Mazlan, Siti Munirah, Wan Shafrina Wan Mohd Jaafar, Aisyah Marliza Muhmad Kamarulzaman, Siti Nor Maizah Saad, Norzalyta Mohd Ghazali, Esmaeel Adrah, Khairul Nizam Abdul Maulud et al. "A Review on the Use of LiDAR remote sensing for forest landscape restoration." *Concepts and Applications of Remote Sensing in Forestry* (2023): 49-74.

[11] Mohan, Midhun, Gabriella Richardson, Gopika Gopan, Matthew Mehdi Aghai, Shaurya Bajaj, GA Pabodha Galgamuwa, Mikko Vastaranta et al. "UAV-supported forest regeneration: Current trends, challenges and implications." *Remote Sensing* 13, no. 13 (2021): 2596. https://doi.org/10.3390/rs13132596

[12] Pereira Martins-Neto, Rorai, Antonio Maria Garcia Tommaselli, Nilton Nobuhiro Imai, Eija Honkavaara, Milto Miltiadou, Erika Akemi Saito Moriya, and Hassan Camil David. "Tree Species Classification in a Complex Brazilian Tropical Forest Using Hyperspectral and LiDAR Data." *Forests* 14, no. 5 (2023): 945. https://doi.org/10.3390/f14050945

[13] Pfeifer, M., Sallu, S. M., Marshall, A. R., Rushton, S., Moore, E., Shirima, D. D., ... & Guerreiro-Milheiras, S. (2023). A systems approach framework for evaluating tree restoration interventions for social and ecological outcomes in rural tropical landscapes. *Philosophical Transactions of the Royal Society B*, *378*(1867), 20210111.

https://doi.org/10.1098/rstb.2021.0111

[14] Robinson, Jake M., Peter A. Harrison, Suzanne Mavoa, and Martin F. Breed. "Existing and emerging uses of drones in restoration ecology." *Methods in Ecology and Evolution* 13, no. 9 (2022): 1899-1911. https://doi.org/10.1111/2041-210X.13912

[15] Rudge, Mitchel LM, Shaun R. Levick, Renee E. Bartolo, and Peter D. Erskine. "Developing landscape-scale forest restoration targets that embrace spatial pattern." *Landscape Ecology* 37, no. 7 (2022): 1747-1760.

[16] Samways, Michael J., René Gaigher, Charl Deacon, and James S. Pryke. "Heterogeneous conservation corridors of remnant vegetation protect biodiversity in South African timber mosaics." *Biodiversity and Conservation* 34, no. 2 (2025): 357-379.

[17] Surasinghe, Thilina D., Kunwar K. Singh, and Amy E. Frazier. "Harnessing the full potential of drones for fieldwork." *BioScience* 75, no. 5 (2025): 379-387. https://doi.org/10.1093/biosci/biaf015

[18] Ugah, Engr Prof Theophilus Aku, Okeke Gerald Ndubuisi, and F. I. S. P. O. N. FNisafetyE. "Gauging the Effectiveness of Assisted Natural Regeneration and Active Restoration in Enhancing Biodiversity and Ecosystem Services in Degraded Tropical Forest." (2025).

[19] Williams, Jonathan, Carola-Bibiane Schönlieb, Tom Swinfield, Bambang Irawan, Eva Achmad, Muhammad Zudhi, Elva Gemita, and David A. Coomes. "SLIC-UAV: A Method for monitoring recovery in tropical restoration projects through identification of signature species using UAVs." *arXiv preprint arXiv:2006.06624* (2020).

[20] Williams, Jonathan, Toby D. Jackson, Carola-Bibiane Schönlieb, Tom Swinfield, Bambang Irawan, Eva Achmad, Muhammad Zudhi, Habibi Habibi, Elva Gemita, and David A. Coomes. "Monitoring early-successional trees for tropical forest restoration using low-cost UAV-based species classification." *Frontiers in Forests and Global Change* 5 (2022): 876448. https://doi.org/10.3389/ffgc.2022.876448