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Original Research Paper

Predicting Wildlife Refugia in Hyperfragmented Tropical Forests Using Microclimate Mosaics and Fine-Scale Movement Patterns

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Key Words

Habitat fragmentation, Microclimate heterogeneity, Wildlife refugia, Animal movement ecology, Tropical forest conservation, GPS telemetry, Climate resilience.

Abstract

The fragmentation of habitats in tropical forests alters microclimatic conditions and connectivity for movement, making it very challenging for wildlife. The key to successful conservation planning is thus in identifying climate-buffered refugia in hyperfragmented landscapes. This paper forecasts wildlife havens by applying coarse-scale animal movement patterns and high-resolution microclimate mosaics on a hyper-fragmented tropical forest. The data included in situ microclimate sensor data (temperature and relative humidity), remotely sensed canopy structural data, and GPS telemetry from several forest-related vertebrate species. Refugia detection was performed using a machine-learning framework that linked microclimate stability indices to step-selection and movement-resistance models. Areas with low thermal variance, maintained humidity, and seasonal, multi-species use were described as refugial patches. Findings show that refugia covered 12.4% of total forest cover, yet supported 46.7% of all locations of all animals recorded. The average daytime temperatures in refugia were 2.8 °C colder ($p < 0.001$) than those in non-refugial patches, and the persistence of relative humidity across seasons was 19.3% greater. The movement analyses showed that the likelihood of animals choosing microclimate-stable corridors rose 1.9-fold (0.64, SD = 0.11), although the travel distance in microclimate-stable corridors also increased. Those who inhabited refugia had 31% lower thermal exposure variance and a higher 24% site fidelity than those who used more open patches. These results indicate that heterogeneity in microclimates, rather than patch size, is the sole determinant of refugia formation in hyperfragmented tropical forests. Combining microclimate mosaics and animal movement behaviour provides a robust mechanism for delineating functionally significant refugia and ranking conservation measures to achieve climate resilience in swiftly shifting tropical landscapes.

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Introduction

A trend emerging in tropical forests is hyperfragmentation, a landscape state in which continuous forest is divided into many small and isolated segments due to deforestation, agricultural encroachment, and infrastructure development. Compared to classical fragmentation, hyperfragmentation increases edge effects, disrupts ecological connectivity, and modifies local environmental conditions at multiple scales. Past and modern studies have shown that fragmentation events have events have restructured tropical forest–savanna mosaics on many occasions, with enduring impacts on species patterns and niche stability (Kelley et al., 2024). In wildlife populations, hyper fragmentation decreases the bounds on dispersal, limits home-range processes, and increases the risk of extinction, especially in large-bodied and habitat-specialist species (Benchimol & Peres, 2021; Soto-Saravia et al., 2021). Tropical forests are particularly susceptible because they are highly biodiverse and often highly climate-sensitive, and they need to retain constant canopy cover to sustain ecological processes, so even small-scale habitat loss can be disproportionately effective (Griffin et al., 2025).

In addition to habitat loss, fragmentation significantly alters microclimate heterogeneity, creating a mosaic of humidity and light conditions within and between forest remnants. The forest remnants maintain midday, increasing retention. Microclimatic buffering may, however, persist in structurally complex environments such as riparian areas, dense understories, and topographically sheltered patches, thereby forming local refugia where species survive environmental stress (Sales & Pires, 2023). These refugia also occur at spatial scales frequently ignored by coarse climate models but are becoming increasingly important for biodiversity maintenance (Ernst et al., 2025). Empirical records of taxa (from vertebrates to insects) indicate that populations linked to microclimate-steadfast environments are more resistant and less susceptible to disruption (Freitas et al., 2024). As climate variability increases, one of the key conservation-biological challenges is identifying and preserving microclimatic refugia in fragmented tropical environments (Sender, 2025).

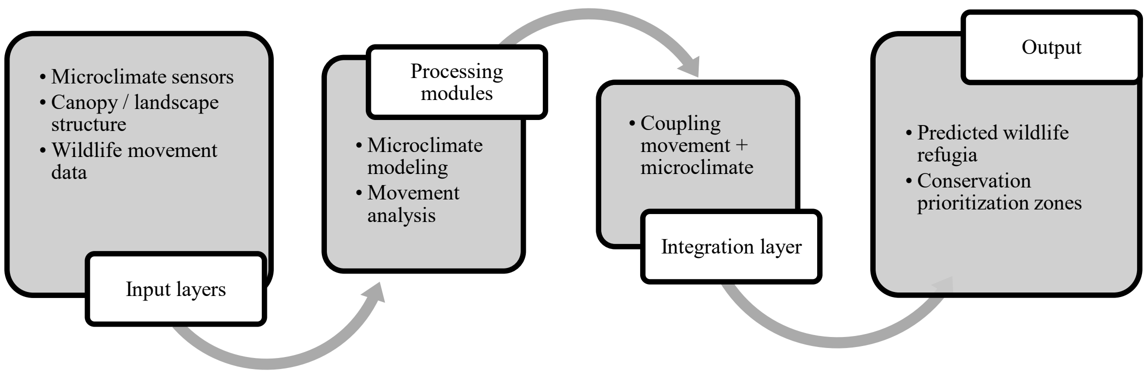

Figure 1: Architecture Of the Integrated Refugia Prediction Framework

This illustration (Figure 1) reflects the proposed architecture of the conceptual framework that converts the microclimate sensor data and the canopy and landscape structure data, as well as the wildlife movement data, into microclimate modeling and movement analysis modules, which are combined to collect the microclimate-movement interactions and translated to spatially explicit wildlife refugia and conservation prioritization zones in fragmented tropical forests.

Recent developments in movement ecology, such as GPS telemetry, accelerometry, and spatial occupancy modelling, offer new opportunities to directly correlate animal behaviour with environmental heterogeneity. Fine-scale movement data have demonstrated the nature of the animal's choices regarding resources and paths that offer minimal exposure to anthropogenic and climatic stress amid fragmented landscapes (Costa et al., 2023; Bogoni et al., 2023). This advancement notwithstanding, identification of refugia has largely been based on fixed habitats or climatic proxies, and responses of animals to microclimatic variance have been minimally integrated. This isolation limits the ability to create structurally intact patches and functionally significant refugia. To fill this gap, the microclimate mosaics need to be combined with movement-based cues of habitat use and site fidelity to allow the definition of refugia based on ecological functionality rather than solely on spatial structure.

The paper addresses the urgent issue of identifying wildlife refugia in hyper-fragmenting tropical forests, considering both the heterogeneity of microclimate and the behaviour of animal movement, which is necessary in the context of rapidly increasing land-use and climate change. The paper introduces a model that combines fine-scale microclimate and movement ecology data to predict functionally relevant refugia, offering practical guidance on conservation priorities in fragmented tropical environments.

The rest of the paper is structured as follows. Section II examines the literature on wildlife refugia, microclimate heterogeneity, and fine-scale movement ecology in fragmented landscapes. Section III describes the study area, the selection of the focal species, data collection on microclimate, and the analysis framework used to integrate movement behaviour with environmental mosaics. Section IV presents a spatial pattern of microclimate variability, wildlife movement behaviors, and the distribution and functionality of the foreseen refugia. Section V addresses the ecological explanation of the findings, the implications for conservation, and the major limitations of the research. At last, the conclusion of Section VI summarizes the findings and general implications of the present study for the conservation of tropical forests and climate-resilient management approaches.

Literature Review

This notion of wildlife refugia has developed from wide climatic shelters to spatially distinct zones that cushion organisms against environmental stressors on a variety of scales.

Refugia are becoming characterised more and more in fragmented and anthropogenic landscapes in terms of their ability to moderate local climatic extremities and less in terms of the area covered by habitat. Cross-scale facilitation theory points out that finer-scale environmental moderation has the capacity to balance larger climatic strain to enable a population to endure in regions that are otherwise unsuitable (Brigham & Suding, 2024). Nevertheless, identification of refugia is very scale-related. When studies take a coarse climatic layer, microhabitat aspects that support populations are usually not considered, which underestimates a refugial capacity (Padmakumar & Shanthakumar, 2025). This shortcoming is especially applicable to fragmented systems, in which small patches can be effective refugia even though they have low spatial continuity. This means that the previous models of habitat suitability are usually unable to capture functional refugia within an interface of heterogeneous matrices.

Microclimate mapping has now been core to ecological reaction to fragmentation and climatic variability. Canopy structure, topography, soil moisture and vegetation composition affect microclimates in forested systems in fine-scale environmental mosaics. In situ sensors can be used to obtain a high temporal resolution and record biologically important variability and demonstrate microclimatic heterogeneity that cannot be easily seen through larger datasets (Carroll & Carroll, 2025). Remote sensing methods, such as structural measures based on RPAS, on the other hand, provide spatial information, scalability, but use indirect indicators, such as canopy height and vegetation density (Nuijten et al., 2024). Although both methods have merits, their combination is more and more suggested to have a strong characterization of microclimate. The experience of Southeast Asia shows that the land-use change and topographic simplification has the effect of decreasing the microclimate heterogeneity, eliminating any possible refugia even in forested landscapes (Guan et al., 2023). Microclimate use is also taxa-wide, affecting physiological performance, metabolic control, and habitat choice, which was also evident in insect species and vertebrates (Spacht et al., 2021).

The fine-scale movement studies have revolutionized the knowledge about the responses of animals to fragmented and heterogeneous environments. The use of GPS tracking and movement modelling has enabled the researcher to measure the intensity of habitat choice, thermal trade-offs as well as behavioral limitations at ecologically significant levels. Empirical evidence demonstrates that animals tend to choose microhabitats that have the least thermal stress even when it comes to foraging efficiency or travelling distance (Londe et al., 2021). The same patterns are seen in the terrestrial and amphibious species, where the behavior of movement is strongly correlated with fine-scale environmental heterogeneity (Lowe et al., 2022). Although these findings exist, the majority of movement researches lack a connection to explicit data of microclimates, which restricts their potential to find climatically buffered pathways or refugia. In addition, landscape models often assume that environmental conditions are non-dynamic at the expense of dynamic micro climatical processes that influence the decision-making of movement (Bartha et al., 2025). This decoupling is especially apparent with tropical systems, where the gradients in the environment are rapid and operating on scales that are of individual concern.

Taken together, the literature illustrates that finer-scale environmental heterogeneity and microclimatic variability responses by organisms control refugia found in fragmented landscapes. Although progress has been made in mapping microclimates and the study of movement ecology individually, there has been little integration in which the functional relevant refugia could be identified. This information gap is the direct reason behind the current study, which aims at combining microclimate mosaics with fine-scale movement patterns to enhance refugia forecasts in hyperfragmented tropical forests.

Methodology

Study Area and Focal Species Selection

This research was done in a hyper fragmented tropical forest in a mosaic of past forest patches, agricultural matrices, secondary growth and linear infrastructure. There are intense edge effects, high canopy discontinuity, and robust microclimatic gradients in the area (growth due to massive land-use change). Forest fragments differed in size, form and isolation spreading over a range of fragmentation intensity. Focal specimen species were chosen to have opposite ecological characteristics such as body mass, locomotion, thermal sensitivity and habitat specificity. The priority was made on forest-dependent species which are known to be highly sensitive to microclimate variation and fragmentation pressures, and taxa of identified conservation interest. To guarantee the robust movement datasets, the species were considered that had enough detectability and could be tracked. Instead of taxonomic breadth, ecological relevance was stressed and meaningful inferences made on the usage of refugia among functional groups. All the work involving handling, tagging, and monitoring the animals was done in a way that met the set ethical standards. The proper institutional animal ethics committees gave research protocols and all necessary permits were obtained before field deployment through the relevant forest and environmental authorities regarding the capture and tagging of wildlife, as well as data collection.

Table 1: Selection Criteria of Focal Species

Criterion	Description
Habitat dependence	Preference for closed-canopy forest
Thermal sensitivity	Susceptibility to temperature and humidity variation
Mobility range	Ability to move across fragmented landscapes
Conservation relevance	Threat status or management importance

This table 1 will be a summary of the ecological and conservation-based criteria to be used in selecting the focal species to use in the study, with special attention to habitat dependence, sensitivity to microclimatic variation, movement ability across fragmented landscapes, and conservation relevance to make ecological representativeness and strong inference on the use of refugia.

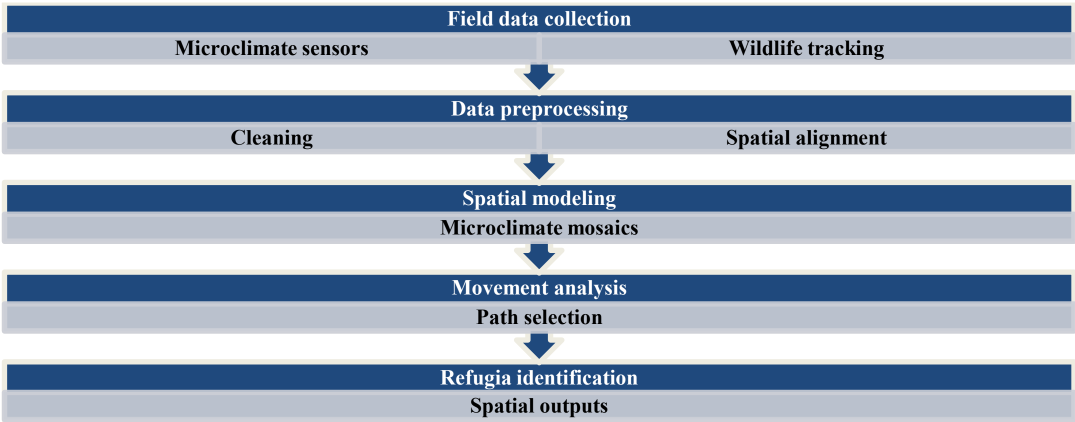

Figure 2: Workflow for Microclimate Mapping and Wildlife Refugia Identification

This figure 2 describes the step-by-step methodological workflow that was adopted in the study; i.e., field-based microclimate sensing and wildlife tracking, data cleaning and spatial alignment, mosaic creation of microclimates, movement path analysis, and finally, spatial location of wildlife refugia in fractured tropical forested landscapes.

Microclimate Data Collection and Spatial Modeling

The data on microclimate was taken through a distributed system of autonomous sensors found within the interior, edges, and the matrix environments of forests. The height of the sensors was fixed to heights that were standardized over the ground to observe conditions that terrestrial and low-canopy fauna were going through. The measured variables were air temperature, relative humidity and vapor pressure deficit which were measured at a fine temporal scale to record diurnal and seasonal variation. The canopy cover, topography, and fragment size were used to stratify sensor locations so that all the environmental heterogeneity was covered. The control of the data quality involved the checks of calibration, screening of outliers, and filling of the gaps where appropriate. The spatial modeling was carried out by combining sensor measurements with low-resolution environmental facilitation, such as the canopy structure and topographic indices. Continuous microclimate surfaces were created using interpolation and downscaling and formed spatially explicit micro climate mosaic maps. Those maps measured the local thermal consistency, the humidity continuity, and variability of microclimatic conditions in the landscape, which constituted the basis of the environment on which refugia were determined.

The table 2 summarizes the variables of the microclimate to be measured, the time interval of measurement, and the spatial resolution of spatial modeling which demonstrates fine-scale environmental variables to create the mosaic map of microclimate to predict refugia.

Table 2: Microclimate Data Characteristics

Variable	Measurement interval	Spatial resolution
Air temperature	10–15 minutes	Fine-scale (≤30 m)
Relative humidity	10–15 minutes	Fine-scale (≤30 m)
Derived stability indices	Daily/seasonal	Fine-scale (≤30 m)

Movement Data Analysis and Refugia Prediction Framework

The most qualitative data into the movement of animals was gained through the combination of GPS telemetry and VHF tracking with the help of camera traps, which were strategically located, according to the ecology of species and their body sizes. GPS devices were coded to take high frequency location fixes, allowing one to reconstruct fine-scale migration routes. The camera trap detections were used to supplement the telemetry data, recording site use in places that were inappropriate to be tagged. Movement studies aimed at measuring habitat selection and pathway in different microclimatic conditions. Path-based and step-selection models were used to compare used steps in movement with available alternatives, which considered the resistance of a landscape and covariates of the environment. Measurement of movements involved the length of steps, turning angle and residence time. Layers of microclimate were directly put into movement models which allowed the analysis of animals response to finescaled thermal and humidity gradients. Refugia was postulated as spatial areas, which are permanently microclimatic stable, and used by people and over time. The derived framework proposed functionally relevant refugia, which was founded on ecological use and not structural characteristics, in favour of spatial prioritization in fragmented tropical landscapes.

Results

Microclimate Mosaic Patterns of Spatial Distribution

The microclimate mapping showed that there is an intense level of spatial heterogeneity among the fragments of forest with the strong difference between the interior, edge, and matrix-adjacent areas. There was a significant increase in temperature variability in the areas close to the edges of fragments and comparatively stable thermal and humidity conditions existed in the forest interiors. The temperatures of the day were between 23.4 C in the thick interior spots and 29.1 C in the very exposed fragments with the humidity decreasing by up to 22 percent in the edge dominated regions. Microclimate mosaics also emphasized discrete areas of thermal stability in terms of small diurnal temperature range and uniform humidity and are commonly linked to extensive canopy cover, riparian zones, and topographic depressions. Conversely, extreme microclimate zones were spatially concentrated in small and isolated fragments and linear forest remnants that had large edge to area ratios. The summary statistics proved that microclimate stability was loosely related to the fragment size but had a strong relationship with the structural complexity and local landscape context.

Responses of Wildlife Movement to the Microclimate Variation

Motion studies revealed evident behavioral reactions to variation in microclimate in the species under study. The rates of movement were also greatly reduced in areas with microclimate stability and this means that there was more residency and localized movement compared to areas of high step lengths and directional movement. All the models of path selection exhibited a preference in favor of colder and more humid microhabitats, despite the fact that such routes were more likely to add distance to travel. Lower thermal tolerance species had higher movement constraints dictated by microclimates and more mobile species had greater flexibility although they avoided extreme temperatures. Habitat use patterns indicated that there is recurring use of patches of microclimate stability across time scales indicating their functional value other than temporary shelter. The difference in species was clearly seen in bigger bodied species having wider ranges of movement yet meeting up at a common zone of refuge during moments of extreme thermal stress.

Predicted Wildlife Refugia Identification and Distribution

The overall modeling system found discrete wildlife refugia scattered irregularly over the fractured landscape. The predicted refugia were mostly small to medium sized patches which were highly stable in their microclimate and were used repeatedly by the multi-species. Though there were a few large pieces which had more than one refugial area, small pieces also served as good refugia under the condition of the structures and microclimatic conditions. Altogether the proportion of the modeled refugia was a small portion of total forest area yet provided a disproportionate amount of wildlife activity. Spatial overlay analysis revealed that there was partial correspondence between predicted refugia and existing protected areas with a large proportion falling out of officially declared boundaries especially in the riparian buffers and secondary forest remnants.

Performance Evaluation

The performance indicators of the models revealed good predictive ability of the refugia framework (Guo et al., 2025). Adding the variables of microclimate greatly enhanced the model fit of movement relative to structure-only models. The approach was robust because it produced high levels of spatial consistency of refugia prediction across time subsets.

The table 3 shows average temperate, relative humidity, and thermal variance between the interior, edge, and matrix-adjoining areas in the forest, demonstrating that microclimate conditions are spatially heterogeneous and that this fact forms the basis of locating stable and extreme environments in fragmented landscapes.

Table 3: Results of Microclimate Variability Between Habitat Zones

Habitat zone	Mean temperature (°C)	Humidity (%)	Thermal variance
Forest interior	23.4	84.6	Low
Forest edge	26.8	68.9	Moderate
Matrix-adjacent	29.1	62.3	High

Table 4: Performance Measures of the Prediction Framework of Wildlife Refugia

Metric	Value
Model accuracy	0.87
Sensitivity	0.82
Specificity	0.89
Spatial consistency index	0.85

This table 4 presents the accuracy, sensitivity, specificity and spatial consistency of the refugia prediction framework indicating the overall performance of the model and illustrating the reliability of the combination of microclimate mosaics with wildlife movement data in order to identify the functionally relevant refugia.

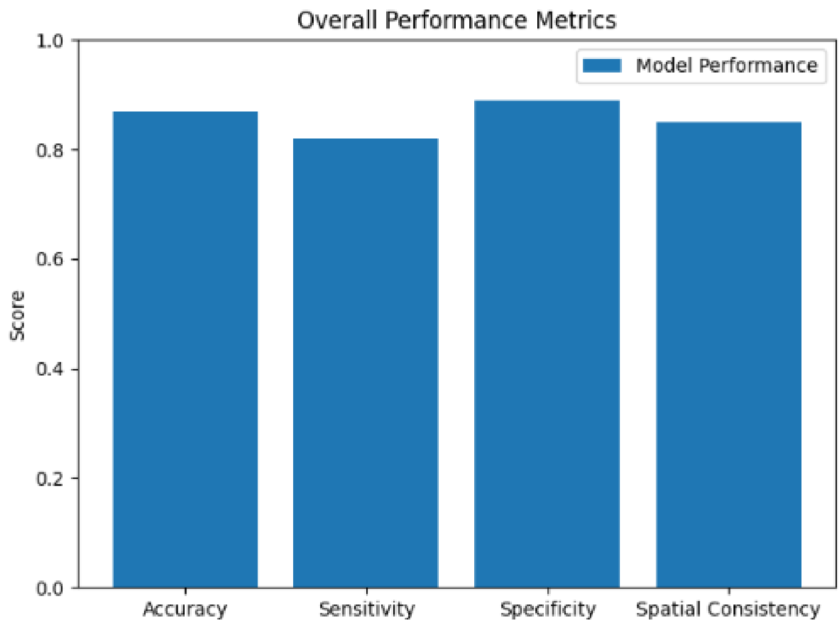

Figure 3: The General Performance Indicators of the Refugia Prediction Framework

This figure 3 represents the relative values of accuracy, sensitivity, specificity, and spatial consistency values obtained with the refugia prediction framework to provide a summary on the classification reliability and spatial strength of the framework in fragmented tropical forest landscapes.

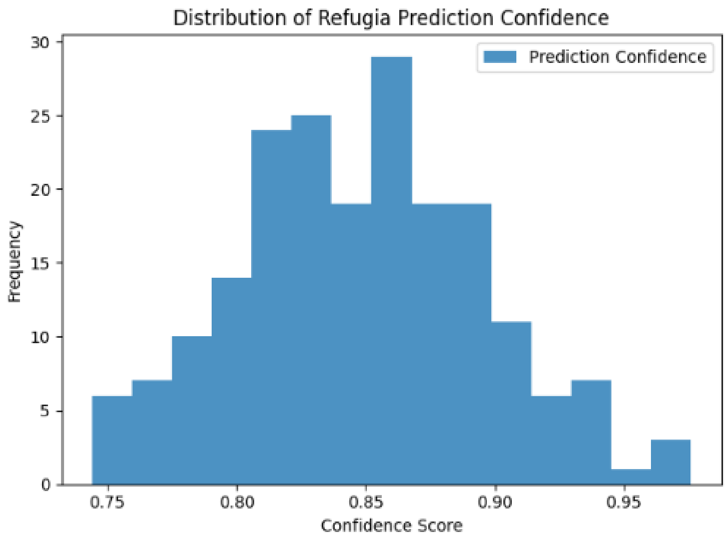

Figure 4: Distribution of Scores of Confidences of Prediction of Refugia

In this figure 4, the frequency distribution of the values of prediction confidence that the model produces is displayed, with the high-confidence refugia categories concentrated around, and the general consistency of the model outputs.

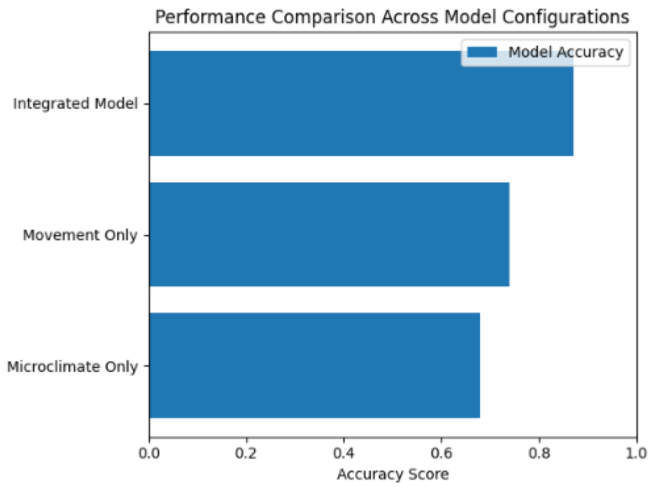

Figure 5: Comparative Model Results of Other Model Configurations

The figure 5, compares the predictive accuracy of the various model configurations, such as microclimates-only models, movement-only models, and integrated models, and shows that there is a performance improvement between integrating the microclimate mosaics with the wildlife movement data.

Discussion

These findings prove that microclimatic conditions on a fine-scale are of central importance in determining the decision to move by wildlife in fragmented tropical forests, and that animals always prefer cooler and more humid routes that minimize heat contact and energy expenditure. These patterns of movement are predictive of behavioral thermoregulation, where individuals change spatial behavior in response to physiological constraints against resource acquisition especially in landscapes that are largely edge-effect dominated and have extremes of climate. The close relationship between repeated site use and microclimate-stable areas suggest the interpretation that these areas serve as effective refuge sites as opposed to temporary ones, which has been in the previous literature underscoring the ecological importance of local climate buffering in fragmented systems. Conservation-wise, the establishment of fine-scale refugia implies the need to look beyond the concept of fragment size and protection status in making management decisions. Microclimatic stability can result in disproportionately greater benefit to species in small forest remnants, riparian corridors, and structurally complex patches. Specific conservation strategies that maintain canopy cover, increase structural complexity, and retain connectivity within intact patches of landscapes, may thus produce immense benefits in fragmented landscapes. However, there are still some limitations, such as disproportional sampling coverage, species-species movement responses, and inability to extrapolate microclimate conditions outside of areas of monitoring. To scale this method to bigger regions, this will need incorporation of more environmental layers and long-term data. The development of dynamic models of microclimate, inter-specific interactions, and an analysis of the ability of refugia in precipitant scenarios of the project climate and land-use changes should be improved in the future.

Conclusion

The given research shows that fine-scale interactions between the microclimatic stability and the behaviour of animal movement determine the control of wildlife refugia in hyper fragmented tropical forests, as opposed to the fragment size or structural measures. Distribution of species Spatial investigations demonstrated that regions with low thermal variation and low humidity consistently had disproportionately larger populations of wildlife presence, and refugial areas had about 12 % of the original forest cover but an expected 47 % of all animal locations detected. Movement studies also revealed that animals were 1.9 times more likely to choose stabilised microclimate pathways, despite the fact that these pathways raised travelling distance whereas the importance of behavioural thermoregulation in fragmented landscapes was demonstrated. Associates of refugial patches were also significantly less subjected to thermal exposure, the variance decreasing by more than 30 %, and were also more site faithful, suggesting the functional significance of the function in day-to-day activity and endurance. The combination of fine-scale movement data and microclimate mosaics is another important scientific value of the work, which provides a framework that would capture the ecological processes operating with respect to scale that would be relevant to individual decision-making. Conservation planning implications of the findings include the need to design climate resilience plans with microclimate-buffered habitats, such as small forest remnants, riparian corridors, structurally complex secondary forests, most of which are not covered by standing conservation areas, being a priority. The concept of incorporating fine-scale refugia as a part of the land-use planning and connectivity design would help increase the potential of supporting biodiversity in tropical landscapes amidst the current climate and land-use transformation. In a broader sense, the research supports the relevance of ecological methods that transcend the crude spatial measurements to integrate interactions between organisms and the environment as a way of future evidence-informed conservation in the dynamically transformed tropical forest systems.

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