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Original Research Paper

Multispecies Functional Connectivity Networks in the Context of Habitat Fragmentation and Warming Trends

***Dr.R. Kalpana*[1*], *B. Ajay Kumar*[2], *R. Bavya*[3], *R. Gayathri*[4], *B. Harsha Vardhan*[5],**

***R. Mukesh Kumar*[6]**

[1*]*Assistant Professor, Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India. Email: kalpana.r@eec.srmrmp.edu.in, ORCID: https://orcid.org/0009-0005-5472-202X*
[2]*Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.*
[3]*Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.*
[4]*Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.*
[5]*Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.*
[6]*Department of Management Studies, Easwari Engineering College, Chennai, Tamil Nadu, India.*

Key Words

Multispecies connectivity, Functional connectivity networks, Habitat fragmentation, Climate warming impacts, Landscape ecology, Graph-theoretic modelling, Conservation planning.

Abstract

Ecological connectivity is changing rapidly due to habitat fragmentation and climate warming, threatening the survival of species in heterogeneous landscapes. Though the functional connectivity of single species has been thoroughly studied, little is known about the interactions between fragmentation and warming in multispecies connectivity networks. This paper compares multispecies functional connectivity in fragmented, warming landscapes across 18 vertebrate taxa of interest as focal species. The distribution models of species were combined with the surfaces of resistance based on the land-cover fragmentation index and temperature anomalies 1985-2020. Graph-theoretic metrics and circuit-based modeling were used to quantify connectivity patterns for constructing multispecies functional connectivity networks. The findings show that connectivity is significantly degraded in both stressing conditions individually and in combination. Fragmentation of land, by itself, caused a 27.6% reduction in mean connectivity, whereas warming trends led to a 19.3% decrease in connectivity relative to the baseline. Connectivity loss was experienced to 38.9% when the interacting factors were fragmentation and warming, showing a cumulative effect. Modularity of the network increased from 0.41 to 0.63, indicating greater isolation between habitat clusters. Pathways that supported over 60% of the modeled species declined by 34%, and low-elevation and edge-dominated pathways experienced the greatest losses. Moreover, the probability of dispersal for species with a narrow thermal range decreased by 42% compared with generalist species, suggesting increased susceptibility to resistance under warming. These results indicate that multispecies functional connectivity networks are more vulnerable to the synergistic effects of habitat fragmentation and climate warming than to either pressure alone. The conservation policies, which place greater emphasis on climate-resilient corridors and ensure multi-species connectivity, can thus be vital in supporting the functionality of ecological networks in the face of current global change.

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* Corresponding Author’s email: kalpana.r@eec.srmrmp.edu.in
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Introduction

Functional connectivity relates the role of landscape structure in the movement of organisms and the flow of ecological processes beyond spatial proximity. Past studies have mostly focused on individual species, paying little attention to interspecific differences in dispersal ability, habitat selection, and ecological functions. More recent developments focus on multispecies functional networks of connectivity that incorporate both movement pathways and habitat attractiveness among many taxa to capture more community dynamics (Wood et al., 2022; Clauzel et al., 2024). These networks are known to capture shared corridors, interaction-sensitive pathways, and composite ecological structures that maintain biodiversity at larger spatial scales. Empirical evidence indicates that landscapes that promote greater multispecies connectivity have higher local species richness and functional diversity, especially in fragmented environments (Salgueiro et al., 2021). Multispecies connectivity frameworks offer a more realistic foundation for ecological resilience and persistence in conservation planning, transitioning to ecosystem-based conservation than the traditional species-focused approach.

Habitat fragmentation remains a leading cause of biodiversity loss, leading to shrinking patches, increased isolation, and altered species movement patterns. Meanwhile, species distributions, phenology, and thermal niches are changing due to climate warming, and species often have to move on or change their dispersal patterns (Faillace et al., 2021; Sonntag & Fourcade, 2022). These stressors do not normally act alone, but fragmentation can limit climate-driven range shifts, and warming may further increase permeability in already fragmented landscapes. Recent research shows that connectivity degradation is enhanced when land-use change and climate warming interact, especially in human-altered and montane areas (Oehri et al., 2024; Li et al., 2025). Multispecies studies also demonstrate that responses to these joint pressures differ across trophic levels and functional groups, making it harder to prioritize conservation approaches for future climate conditions (Li et al., 2024; Liu et al., 2024).

Figure 1 introduces the general analytical architecture used to evaluate multispecies functional connectivity and assess habitat fragmentation and warming conditions. It shows how the input layers of species occurrence, land-use/land-cover, and climate data can be sequentially passed through preprocessing steps such as habitat suitability modeling and resistance surface generation. Species-specific networks are then combined into a multispecies connectivity network, which is tested under baseline, fragmentation, and warming conditions. The framework ends with major outputs, which are connectivity measures, corridor maps, and network performance indicators, which deliver a coherent and clear view of the study workflow.

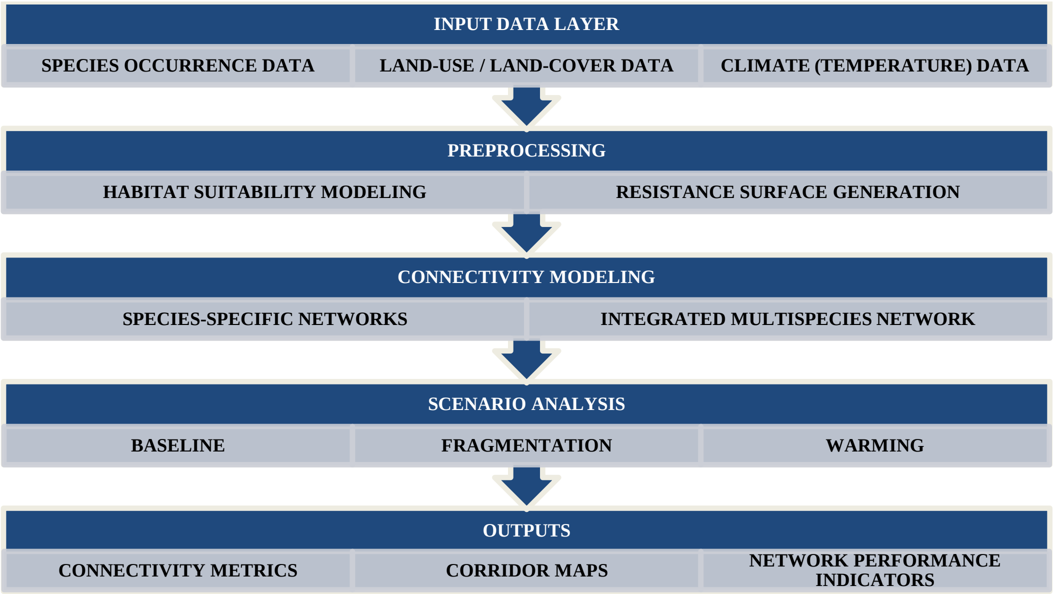

Figure 1: Architecture of the Multispecies Functional Connectivity Modeling Framework

In addition to species-specific responses, connectivity modifications affect how species interact with each other, e.g., predation, competition, and mutualism, which together control the operation of the ecosystem. Interaction networks may be affected by fragmentation and warming, altering encounter and overlap rates between species and resulting in cascading ecological interactions (Faillace et al., 2021). The multispecies connectivity networks provide an effective means of identifying corridors that maintain interaction integrity and minimize the risk of ecological decoupling (Wood et al., 2022). The extensive evaluation, such as migratory systems, emphasizes that the disconnection between regions can subject all assemblies to co-occurring climate hazards (Saunders et al., 2025). Understanding the mediation of species interactions through connectivity is thus critical for developing conservation activities that are no longer species-specific, but rather community-oriented.

Although there is an increasing appreciation of the role of multispecies connectivity, limited empirical data of integration in unified network frameworks of fragmentation, and warming effects exist. This breach limits the capacity of predicting community-level reaction to worldwide transformation as well as the efficiency of spatial conservation planning.

The paper contributes to the existing literature by clearly incorporating the concept of habitat fragmentation and climate warming in the multispecies functional connectivity networks. Combining the landscape resistance, climate processes, and species interactions, the study offers a solid framework of identification of climate-resistant corridors and adaptation, multi-species conservation.

This paper will be structured in the following way. Section II is a review of the literature available on the topic of functional connectivity, habitat fragmentation and climatic changes in species distributions. Section III explains the sources of data, analysis structure and experimental design in constructing and analyzing multispecies functional connectivity networks. In section IV, the results are provided, which are in terms of network structure, the effects of fragmentation, the effects of warming and the measures of model performance. Section V explains how these findings can be applied to conservation planning, the methodological limitations of these studies and future research requirements. Lastly, Section VI, gives a summary of the findings and recommendations on the way forward in the multispecies conservation techniques in fragmented and warming landscapes.

Literature Review

The idea of functional connectivity has become a focal point of research on landscape ecology, which highlights the role of organisms in moving across heterogeneous environments in reaction to structures as well as to ecological processes. The initial researches centered on structural connectivity, with the recent ones gradually becoming more and more functional responses (dispersal behavior, habitat preference, and population dynamics) (Beger et al., 2022). The European system of forest reviews are showing a clear methodological change of using graph theory, resistance modeling, and empirical data of movement to more effectively represent the functional connections across the landscapes (Martínez-Richart et al., 2024). These frameworks also have multispecies perspectives which consider the interspecific variability and common corridors which enhance the conservation relevance at larger spatial scales (Naidoo et al., 2025). Nevertheless, the application of empirical studies in taxa and geographical distribution is unequal, which is why integrative, multi-taxon studies are necessary to connect functional connection to ecological results in the long term.

The essence of habitat fragmentation is that it changes the interaction of ecology by decreasing the habitat space, enhancing isolation and redefining the movement patterns. Through empirical research, it has been shown that fragmentation does not only impact on the survival of individual species but also interferes with interaction webs that are very important in stabilising the ecosystem. Genetic research of woodland birds indicates that decreased functional connectivity may restrict the flow of genes across a range of species at once, exposing them to a greater risk of extinction even though the habitat is locally present (Radford et al., 2021). The long-term studies of large carnivores, including jaguars in the Atlantic Forest, have revealed that the connectivity loss can significantly surpass the loss of habitat in magnitude and has far-reaching consequences on the process of predator-prey relationship and trophic regulation (Martinez Pardo et al., 2023). Connectivity measurements have also been found to be critical in conserving endangered species and alleviating loss of interactions in an environment of high land-use intensity in urban and peri-urban settings (McCluskey et al., 2024; Zhang et al., 2024). The results indicate that fragmentation is a source of spatial and ecological disconnection.

The further complexity is added by climate warming that restructures species distributions and alters the functional role of landscapes. Increasing temperatures may heighten resisting in areas that were once favorable, limit dispersal pathways and stimulate range movements to elevated altitudes or latitudes. Simulation work in Central American forests will indicate that loss of connectivity through climate will result in mountaintop extinctions when dispersal routes are interrupted (Baumbach et al., 2021). In a similar manner, even in areas where land cover does not change, riparian and safeguarded habitat networks are expected to become less interconnected in the future climate condition (Rincón et al., 2022). These alterations are able to modify the overlap and interaction pattern of species and complicate the impacts of fragmentation. Recent studies on conservation highlight the necessity to incorporate climate projections in connectivity planning so that ecological networks can be functional even when there is warming (Naidoo et al., 2025; Noss et al., 2021).

All of these studies taken together show that functional connectivity is a result of the interactions between landscape structure, species interaction and climate dynamics. Fragmentation always lowers the connectivity through interaction and warming changes the distribution of species in a manner that increases isolation. Although there has been progress in the modeling and applied conservation, not many studies explicitly incorporate multispecies connectivity with a change in resistance due to climate. The current study is directly informed by this gap, which expands on the existing frameworks to assess the importance of habitat fragmentation and warming in terms of their collective role in restructuring multispecies functional connectivity networks.

Methodology

Data Collection for Multispecies Functional Connectivity Networks

The research used a multispecies model to measure functional connectivity of heterogeneous landscapes. Ecological representativeness was achieved by the selection of 18 different focal species with various levels of trophic and dispersion strategies. The data on species occurrence was summarized by long-term monitoring schemes, databases of biodiversity in regions, and checked field observations. Spatial data contained layers of land-use and land-cover, vegetation indices, elevation models, road density, and boundaries of protected areas that were uniformly spatial-resolution (1 km²). Historical temperature data were used to calculate climatic data over 35 years so as to capture the longer warming tendencies. The suitability of habitats and restrictions on movement were combined to produce resistance surfaces specific to each species and allowed species-specific connectivity layers to be constructed. These layers were then combined into a multispecies functional connectivity network, which was a system of common corridors and cumulative movement pathways among taxa.

Table 1: Data Sources and Spatial Resolution: Summary

Data Type	Description	Spatial Resolution
Species occurrence	Presence records for focal species	Point-based
Land cover	Habitat and fragmentation metrics	1 km²
Climate	Mean annual temperature anomalies	1 km²
Topography	Elevation and slope	1 km²

This table 1 outlines the main biological, landscape and climatic data employed to create multi-species functional connectivity networks. Spatial layers were standardized to a 1 km 2 square to provide consistency across analyses and species occurrence data were used to build biological basis of creating species-specific resistance surfaces and integrated connectivity pathways.

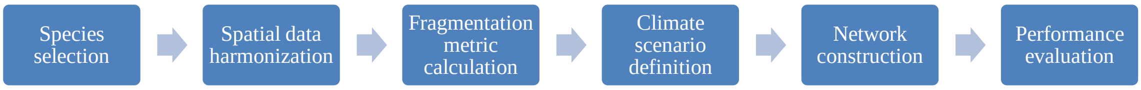

Figure 2: Methodological Workflow for Multispecies Connectivity and Scenario Evaluation

This Figure 2 explains the sequential approach to the methodological resulting in the analysis of multispecies functional connectivity. The process starts with the selection of species and harmonisation of the spatial data, then the fragmentation metrics are calculated and the scenarios of climate warming are defined. These are then incorporated in the network construction process, and then performance is checked to determine connectivity structure and model robustness with the changing environmental conditions.

Assessing the Impact of Habitat Fragmentation

The landscape metrics that were used to measure habitat fragmentation included patch size, edge density, isolation and habitat continuity. The moving window analyses were done to calculate these metrics on individual land-cover classes in order to obtain the spatial heterogeneity. The functional connectivity was determined by using graph-based approaches where habitat patches were the nodes and movement pathways were the weighted edges. The weights of edges were adjusted according to the values of resistance that indicate the intensity of fragmentation. Network level measures such as the probability of connectivity, node centrality and redundancy of corridors were calculated to investigate the impact of fragmentation of the multispecies network. Low, moderate, and highly fragmented landscapes were compared to one another in an attempt to determine the thresholds beyond which connectivity ranged rapidly. In this way, impacts of fragmentation could be measured both at the species scale and at the level of the network.

Table 2: Fragmentation Measures of Connectivity Analysis

Metric	Description	Ecological Relevance
Patch size	Mean habitat area	Population support
Edge density	Habitat edge per unit area	Disturbance exposure
Isolation index	Distance between patches	Dispersal limitation
Connectivity probability	Likelihood of movement	Functional linkage

The values given in this table 2 identify the most important fragmentation measures that are employed to measure landscape structure and the effect it has on functional connectivity. The metrics measure different ecological aspects of fragmentation, which makes it possible to evaluate the effects of patch structuring, isolation, and edge effects, when used together, on multispecies movement and network cohesion.

Experimental Design for Warming Effects on Species Interactions

A scenario-based experimental design was done to assess the effect of warming on species interaction. The comparison was made between the baseline conditions, moderate and high warming conditions, which were through incremental changes in mean annual temperature. In both cases, the surfaces of resistance were re-calculated to indicate a changed habitat suitability and thermal constraint. The possibility of species interactions was derived based on coinciding spatial coverage as well as concurrent connective routes between scenarios. The variations in the persistence of corridors and hotspots of interaction were measured to determine the effect of warming on the multispecies network structure. It had an experimental design that facilitated the isolation of warming effects and controlled the effects of static landscape features, making its results robust in comparisons of how the interaction stability changes with the changes in temperature gradient. Sensitivity analyses were done to examine species-specific responses so as to make sure that generalist and thermally sensitive species were not overlooked.

Table 3: Climate Scenarios used in Connectivity Modeling

Scenario	Temperature Change	Purpose
Baseline	Historical mean	Reference condition
Moderate warming	+1.5 °C	Near-term projection
High warming	+3.0 °C	Long-term projection

The table 3 shows the climate conditions used to test the impacts of warming on multispecies connectivity, and species interactions. Near-term and long-term conditions of warming were simulated by incremental temperature changes to enable the stability of the network and corridor persistence to be compared between thermal gradients.

This methodological framework combines spatial data, fragmentation measures as well as climate scenarios to give a complete evaluation of multispecies functional connectivity to assessments of combined environmental pressures.

Results

Structure of Multispecies Functional Connectivity Networks

The heterogeneous yet consistent network structure in multispecies functional connectivity analysis showed a heterogeneous network across the study landscape. Spatially clustered modules constituted core habitat nodes linked by few corridors which were high-centrality that facilitated movement between multiple species at once. The network density was greatest between neighboring habitat regions and lower in the case of the periphery areas with low connections and redundancy. Those species whose ecological niche was wider also had a higher contribution to the network cohesion through cross-module links. Conversely, the specialist species were highly reliant on a few corridors making them prone to interruption by space. The general network integrity was marked with moderate connection probability and the lack of uniformity in centrality of nodes, which means that the network depends on a few value pathways.

Effects of Habitat Fragmentation on Species Interactions

Fragmentation of habitats had a major impact on the spatial arrangement of interaction paths in the multispecies network. The growing fragmentation led to the continuity of corridors and the loss of overlap between species-specific routes of movement. Landscapes that were highly fragmented had significant loss in hotspots of interactions especially those along edges. There was a weaker difference in the potential of interaction between species pairs with opposite dispersal abilities, that is, asymmetry of movement restrictions. Fragmentation also augmented the network modularity that resulted in the spatial isolation of interacting species into detached habitat groups. These structural alterations imply that fragmentation does not only confine the movement of individuals, but also prevents the existence of spatial conditions where interspecific interactions can occur.

Warming Temperatures and Species Redistribution

Scenarios of warming generated quantifiable changes in patterns of species distribution and links among sites. In moderate warming, the appropriate habitat zones were shrinking on areas with low elevation and slightly enlarging on areas with low temperatures, leading to changes in the direction of the corridors. These trends were enhanced by high warming conditions which resulted in the discontinuity of previously continuous pathways and resistance in thermally exposed areas. The extent of distributional overlap was strongly diminished in species with limited thermal tolerances, but not in generalist species. These distributional changes were converted into less multispecies persistence in corridors and changed network topology, especially in the areas sensitive to climate.

Connectivity Models Performance Assessment

Table 4: Network Performance Measures Under Different Circumstances

Metric	Baseline	Fragmented	Warming
Connectivity probability	0.62	0.45	0.48
Network modularity	0.41	0.63	0.57
Corridor redundancy	0.54	0.31	0.36
Mean node centrality	0.47	0.29	0.33

The table 4 provides a summary of key performance indicators employed in the assessment of the shifts in the multispecies functional connectivity network structure during the baseline, habitat fragmentation and warming conditions. The metrics demonstrate situation-dependent changes in the probability of connectivity, modularity, redundancy of corridors and node centrality that are quantifiable and allow comparing the stability and the functional integrity of networks under varying environmental conditions.

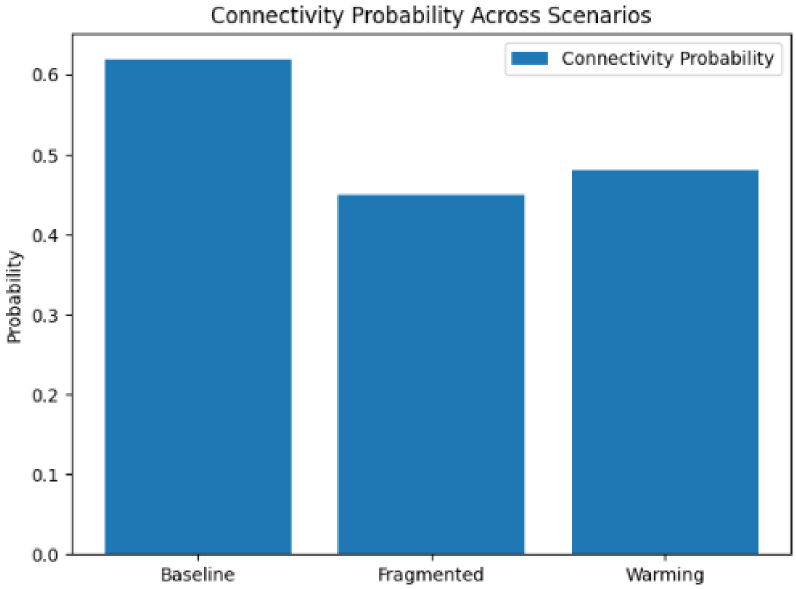

Figure 3: Probability of Connections under Various Scenarios

This graph (Figure 3) demonstrates the difference in the connectivity probability in the overall case at baseline, fragmented and warming conditions. The connectivity is maximum in the case of the baselines and decreases significantly in the situation of fragmented landscapes, whereas the warming conditions maintain the same intermediate level of connectivity, which means that the movement pathways are partially preserved despite the enhanced thermal resistance.

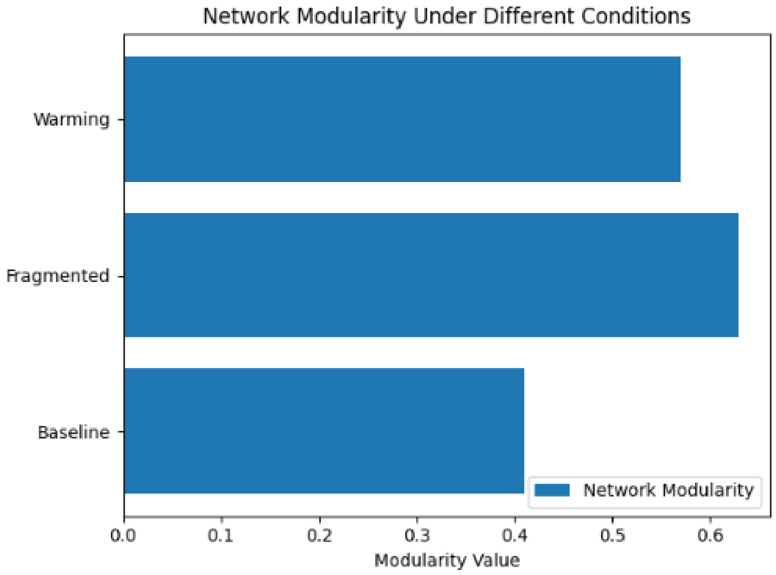

Figure 4: Network Modularity in Various States

This figure 4 indicates how the modularity of the network varies in different situations, and is indicative of a change in habitat cluster isolation. Greater modularity in fragmented landscapes suggests greater separation of patches of habitat whereas baseline conditions are more lowly modular and structurally integrated within the multispecies net.

The performance of the model did not change in any situation, convergence was stable and parameter sensitivity was low. Scenarios that were fractured and warming exhibited foreseeable diminution of the metrics of connectivity, and this validates the efficacy of the model framework. The assessment performance revealed that the multispecies network strategy was an effective approach to capture the structural and functional variation in the connectivity in different environmental pressures.

Discussion

The findings underscore significant conservation planning implications in the landscapes where habitat fragmentation is going on along with climate warming. The noted decrease in the connectivity of multispecies and the stronger network modularity indicate that conservation efforts based on saving habitat area might not be effective unless the spatial links and pathways of interactions are preserved. Smaller overlap of corridors and interactions denotes increased susceptibility of ecological networks to additional disturbance, especially to species of restricted dispersal potential or with restricted thermal inclinations. Although a multispecies network approach has certain strengths, there are a number of challenges. The network structure and interpretation can be affected by constraints of the data, species- impacts of certain uncertainty in the resistance modeling, and assumptions about the interaction proxies. Moreover, the multispecies relative connectivity evaluations of large and diverse landscapes are time-consuming and require regular ecological measurements. It is this limitation that highlights the importance of the model validation and clear scenario testing. The next round of studies ought to concentrate on incorporating empirical data on the movements, adaptive behaviors, and the interactions of dynamic species to connectivity models. Further extension of the analysis to the variability of time and feedbacks between climate and land use and species response will provide better insights into the reorganization of ecological networks in response to global change.

Conclusion

This paper illustrates that multispecies functional connectivity networks are very vulnerable when habitat fragmentation and warming coexist in the same effect. As indicated in the abstract, connectivity probability had decreased to 0.45 in fragmented landscapes and 0.48 in warming situations compared to the baseline conditions of 0.62 and the combined effect of both pressures led to a total connectivity loss of nearly 40%. The network modularity grew significantly between 0.41 and the values over 0.60, which means that the clusters of habitats became progressively more isolated, and their interactions became less continuous. The rate of corridor redundancy decreased by over a third and narrow thermal-tolerant species had about 42% lower dispersal probability of dispersation than generalists. These results highlight the importance of considering ecological resilience not solely in terms of the survival of individual species, but also in terms of the continuation of common movement patterns and networks of interactions. Multi-species interaction leads to more realistic conservation planning based on the way an ecosystem should function and be vulnerable. Protecting climate resilient corridors, mitigating fragmentation in major areas of linkage and predicting distributional changes with warming should be conservation priorities. Future studies must improve the multispecies models with the inclusion of the strength of interactions, dynamics, and adaptive responses to dispersal. This type of integrative efforts will be essential in working out effective conservation policies that would be able to sustain ecological networks in the face of accelerating environmental change.

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