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# *Restoring Ecological Function in Fragmented Forests Through Improved Connectivity and Matrix Management*

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***Abstract.*** Forest fragmentation is a major threat to biodiversity as it divides continuous forests into smaller and more isolated patches surrounded by human-modified land. This process reduces habitat area, increases edge effects, restricts species movement, and weakens ecological processes such as dispersal, recolonization, gene flow, and functional diversity. This paper reviews evidence on the ecological impacts of forest fragmentation and evaluates connectivity-based restoration as a management strategy. It argues that restoring fragmented forests requires more than protecting isolated forest remnants or increasing tree cover: effective restoration should increase inter-patch connectivity and combine corridor construction with matrix management. Restoration corridors aim at reconnecting forest patches and supporting the restoration of functional diversity, while matrix management is intended to enhance the permeability of the surrounding landscape through strategically adding arboreal elements such as living fences, riparian vegetation, woodland islets, and isolated trees, which serve as stepping stones for organisms. The paper also emphasizes the importance of multispecies planning, since different organisms respond differently to corridors and matrix conditions. Overall, it is suggested that an integrated strategy of corridor restoration and matrix improvement may beneficially restore ecological function in fragmented forest landscapes. Future research should focus on whether structural connectivity leads to stable movement patterns, gene flow, and long-term recovery of ecosystem functions.

***Keywords:*** Fragmented forests, matrix management, restoring ecological function

## 1. Introduction

Forest fragmentation is the division of formerly continuous forest into smaller and more isolated patches surrounded by human-modified land. It commonly results from agricultural expansion, cattle ranching, roads, settlements, logging, and other forms of land conversion. Fragmentation differs from forest loss alone because it also changes the spatial arrangement of the forest that remains. Forest habitats become smaller; their edges increase, and movement among them becomes more difficult. The global extent of fragmentation makes it a significant biodiversity and forest-management problem. Approximately 70% of the world's remaining forest is located within one kilometer of a forest edge, where ecological conditions can be influenced by modified land uses, altered microclimates, and nonforest species [1]. Long-term fragmentation experiments further show

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that the ecological consequences are not limited to immediate species loss. Small patch size, isolation, and edge exposure can alter species abundance, community composition, biomass, nutrient cycling, and other ecosystem processes, with some effects intensifying over time [1]. Recent global evidence also indicates that although fragmentation decreased in many temperate and subtropical regions from 2000 to 2020, it continued to increase in important tropical forest regions [2]. Forest cover recovery may not necessarily counter the effect of fragmentation, considering that the new areas may remain fragmented [2]. The persistence of separated forest remnants, therefore, depends partly on whether organisms can move between them. Limited dispersal can prevent recolonization following local population loss and restrict the movement required for reproduction and genetic exchange [1]. It may also interrupt ecological interactions such as seed dispersal, pollination, herbivory, and predator–prey relationships.

Restoration corridors may be a solution as they provide vegetated connections between isolated patches. Experimental and field evidence indicates that corridors can promote movement and support the accumulation or recovery of biodiversity. An eighteen-year landscape experiment found that connected habitat patches continued to accumulate more plant species than isolated patches, demonstrating that corridor benefits can increase over long periods rather than appearing only immediately after construction [3]. Corridors can function both as movement routes and as developing habitat. Nevertheless, corridor construction alone may not restore connectivity for every species, which differ in dispersal ability, habitat specialization, body size, and dependence on continuous canopy. Corridors modeled as suitable for several arboreal mammals may still contain sections that are inadequate for highly specialized species [4]. Similarly, canopy-dependent mammals may require natural or artificial overhead connections where roads, pipelines, or other linear clearings interrupt forest cover [5]. Effective planning must therefore account for corridor width, vegetation structure, age, continuity, bottlenecks, and other requirements of multiple species.

Matrix conditions are also vital to the general connectivity of fragmented landscapes. Having woodland islets, secondary vegetation, living fences, riparian strips, and isolated trees make matrices a lot more permeable than just pure open pastures or fields [6]. Adding such arboreal elements in the matrix are shown to have increased modeled connections among forest patches [6]. Meanwhile, the connectivity changes of differently arranged linear landscape elements highlight that the connectivity effects of matrix elements are dependent on their arrangement and the movement behaviour of the organisms [7]. A recent study also indicated that connectivity between patches may be affected by the habitability of matrices (matrix quality), but only for butterflies [8].

The paper proposes an integrated approach to restore the ecological functions in fragmented forests, which includes both building corridors and active management of the forest matrix. It first examines the mechanisms inducing the ecological consequences of forest fragmentation. It then reviews the evidence on the effectiveness and design constraints of corridors. Third, it examines the effect of spacing and arrangement of arboreal elements, and linear landscape elements, on functional connectivity. Lastly, it suggests a management plan that focuses on creating restoration corridors, increasing the permeability of matrix, and planning for bottlenecks, often by using multispecies modelling, all of which are intended to improve natural connections.

## 2. Ecological consequences of forest fragmentation

Fragmentation affects ecosystems through several related mechanisms: reducing patch size, increasing the number of patches, and creating more forest edges [2]. Migration and individual dispersal are restricted due to the isolation resulting from fragmentation, while edge creation increases exposure of the habitats to altered microclimates, human activities, and nonforest species.

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### 2.1. Disruption of species movement and population processes

Long-term experiments synthesized and analyzed by Haddad et al. demonstrate that reduced area, increased isolation, and increased edge exposure affect multiple levels of ecological organization [1]. They include tests in several biomes and were designed to manipulate specific components of fragmentation effects, including habitat size, isolation, and connectivity, while controlling for confounding factors like the amount of habitat lost across a landscape [1]. The dominant community of the fragments replicated for the experiments are composed of either evergreen broadleaf tree, grassland or moss, or a succession of grassland and shrub/palm/small tree [1]. The created fragments of each experiment are surrounded by one type of matrix consistent in the experiment, which is made up of plantations lower than the fragments [1]. The treatment methods each experiment adopted for their fragments are classified into 3 types: reduced area, increased isolation, and increased edge [1]. Under each classification, main findings regarding the ecological processes of all ecological organizations are evaluated for their mean effect size, which is computed as log response ratio: ln(mean in more fragmented treatment/mean in non- or less-fragmented treatment)] [1]. The mean effect size for movement between fragments estimated, under the increased isolation classification, is nearly -1.5, which indicates a major negative effect on species movement. Also, a moderate negative influence on trophic dynamics is depicted under all three classifications, which involves several impacts such as reduced seed predation and herbivory. Increased proportion of edge caused higher fledgling predation that had the effect of reducing bird fecundity [1]. Smaller fragments support fewer resident animals, while isolation limits movement between patches and reduces the likelihood of recolonization after local extinction [1].

### 2.2. Loss of functional diversity and degraded ecosystem functions

Species persistence is shown to be strongly harmed by fragmentation in the results gathered by Haddad et al., mainly in smaller and more isolated patches [1]. Moreover, community compositions are completely changed as a result of the smaller habitat sizes and increased proportion of edge habitat, which alter the environmental conditions, favoring pioneer trees over large, old trees in tropical forests, while causing loss of species richness [1]. Extinction debt is also apparent, evidenced by the loss of species richness of plants, arthropods, and birds sampled in the experiments, increasing from >20% after 1 year to >50% after 10 years [1]. At the ecosystem level, fragmentation reduces carbon and nitrogen retention, productivity, and pollination [1]. In general, the loss of habitat connectivity reduces a habitat's potential to maintain biodiversity, ecological processes, and stable populations. Therefore, habitat fragmentation has a negative impact on habitats, primarily by degrading habitat connectivity.

Forest fragmentation is not addressed by change in forest cover alone; ensuring an adequate level of connectivity between patches is important for restoring the reduced ecological functions, such as seed dispersal. Ma et al. found that forest area can expand without necessarily turning back fragmentation by measuring fragmentation with edge density, patch density and mean patch area [2]. In fact, newly planted or regenerating forests may be broken up into small patches, which are fairly isolated [2]. This translates to a lack of interactions between organisms throughout the landscape, which is critical to maintaining ecosystem health. Forest restoration policies should, therefore, focus on spatial arrangement and connectivity instead of total tree cover as the only measure of forest recovery.

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## 3. Corridor construction and its effectiveness

Corridors are strips of continuous or semi-continuous vegetation established between previously isolated habitat patches to improve connectivity and facilitate organism movement [9]. By linking between fragmented patches, corridors may enlarge the interconnected area available to populations, thereby enhancing population persistence, facilitating gene flow, and helping to recover species richness, functional diversity, and ecosystem processes [9, 10]. Also, corridors may serve as a few narrow habitats for some species.

### 3.1. Corridors as movement pathways and restored habitat

Montes-Rojas et al. provided direct field evidence for species' usage of corridors [9]. The research is located in a fragmented landscape in Columbia, made up of patches of tropical rainforests immersed in a matrix of pastures for cattle ranching [9]. By comparing forest fragments, natural riparian corridors, planted restoration corridors, and open cattle pastures using camera traps, it is observed that a preference appears for moving through restoration corridors than open pastures of many medium and small primates (Cebus versicolor and Aotus griseimembra) and arboreal taxa, large omnivores such as the white-collared pecari (Pecari tajacu) and the largest terrestrial birds including the CR blue-billed curassow (Crax alberti) [9]. Other species, mainly including large predators (Puma concolor) and mesopredators (e.g., Leopardus pardalis, Eira Barbara and Didelphis marsupialis) moved more freely across the landscape using all four land covers, while higher activity is recorded in restoration corridors than in open pastures [9].

Species richness and functional diversity were highest in forests, followed by natural and restored corridors, and lowest in open pastures; the species composition of restoration corridors also began to resemble that of forests and natural corridors [9]. These results suggest that planted corridors can act as functional habitats rather than only as narrow physical links. Functional diversity reflects differences in ecological traits and therefore offers an indication of the variety of roles performed by a community. The intermediate functional diversity observed in restored corridors suggests that they can partially recover ecological functions lost when forest is converted to pasture [9].

### 3.2. Design limitations and species-specific responses

Corridors did not fully reproduce forest conditions [9]. Some large arboreal and strictly forest-dependent animals rarely used the young restored corridors, while terrestrial mammals and birds used them more frequently [9]. Corridor effectiveness therefore depends on vegetation structure, age, width, and the ecological requirements of target species. Species differ in dispersal distance, body size, habitat specialization, sensitivity to roads, and willingness to cross modified land [10]. Bohnett et al. addressed this challenge by combining several connectivity models for four focal species in Florida [10]. Their approach identified shared routes, conservation priorities, and bottlenecks while also accounting for infrastructure and future development.

The study conducted by Bohnett et al. shows that corridor placement should be planned based on the behavioral characteristics of multiple species [10]. Habitat generalists may cross landscapes that remain inaccessible to specialists [10]. Likewise, a route suitable for a wide-ranging mammal may not protect the needs of a smaller forest-dependent species. Multispecies modeling can identify areas that serve several ecological requirements and reveal narrow pinch points where development could break an otherwise connected network. By modeling four species with different habitat and movement needs and then integrating Linkage Mapper, Omniscape, resistant kernels, and Zonation

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prioritization, Bohnett et al. identified shared connectivity areas, unprotected priority zones, and bottlenecks where roads or future development could disrupt landscape-scale ecological networks. While some bottlenecks are currently protected, others are not. The study shows that multispecies modelling, currently not fully adopted, is significant in estimating pinchpoints for priority species.

## 4. Matrix management as part of the restoration strategy

The matrix is the human-modified land surrounding and separating forest fragments and may include pastures, croplands, plantations, roads, settlements, secondary vegetation, and agroforestry areas. Matrix management seeks to improve the permeability of this surrounding landscape by retaining or restoring arboreal elements that facilitate movement between forest patches [6].

### 4.1. Arboreal elements as stepping stones and connecting structures

Von Thaden et al. mapped arboreal elements across 40,000 hectares of the Los Tuxtlas Biosphere Reserve in Mexico [6]. They included the forest fragments, living fences, riparian vegetation, woodland islets, and individual trees within an agricultural landscape [6]. These elements are considered important to a variety of animals and for ecological interactions such as seed and pollen dispersal [6]. In Von Thaden et al.'s study, each forest patch or arboreal element was treated as a node, and pairs of nodes were considered potentially connected according to their separation distance across open agricultural land; 38 models were created to assess the connections brought by different combinations of the existing arboreal elements [6]. Six movement-distance thresholds — 50, 100, 200, 300, 400, and 500 m — are tested to represent species with different abilities to cross the matrix by using the arboreal elements as temporary refuges [6]. Their analysis showed that small tree-based elements can contribute substantially to landscape connectivity [6]. Including old-growth fragments and tree-covered living fences in the models each increased connectivity by up to 57%, while natural riparian corridors contributed up to 38% [6]. Although isolated trees made a smaller contribution to the overall connectivity index, their presence increased the number of effective connections across open land by more than 85% [6]. Meanwhile, it is suggested that keeping average distances of less than 300 m, and more ideally less than 150 m between arboreal stepping stones will enhance landscape connectivity substantially [6]. Practical restoration measures are also simulated; establishing small woodland islets in open agricultural areas increased modeled connectivity by 26%, while widening riparian vegetation by up to ten meters on each riverbank increased it by 11% [6]. These findings demonstrate that improving connectivity does not always require converting entire farming land masses back into forest; strategically retaining or planting trees, carefully spacing the arboreal elements, can create stepping stones and movement routes while keeping the agricultural matrix relatively intact.

### 4.2. Effects of linear landscape elements arrangement

Anderson et al. argue that ecological connectivity depends not simply on the number or total area of permeable land in a landscape, but on the width of those land covers, ways they are spatially arranged relative to habitat patches, and how organisms actually navigate them [7]. Linear landscape elements (LLEs), such as ditches and hedgerows, can improve the ecological connectivity of habitat fragments embedded within agricultural areas by acting as corridors for animal movement [7]. Using an individual-based movement model, the researchers simulated dispersal between two habitat patches across LLE corridor networks containing different combinations of 3–33 directly connecting

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elements and up to 31 perpendicular elements, while also varying corridor width [7]. The simulation results showed that features directly connecting habitat patches increased traversal probability, whereas additional perpendicular features created intersections that could divert limited-perception dispersers away from their destination, increasing movement costs and mortality risk; greater widths of the LLE also lead to decreased probability of successful dispersal [7]. This study assumed that the simulated organisms have limited perceptual range and are strictly confined to the LLE; they are, for example, aquatic organisms moving through ditches [7]. Although this study may be less realistic for flying or terrestrial organisms, it provides insights on the importance of LLE width and arrangement in matrix management. Thus, the structural connectivity of a landscape may not represent its functional connectivity, and correct orientation of the permeable matrix elements is significant in promoting connectivity [7].

## 5. Conclusion

Forest fragmentation reduces biodiversity and ecosystem function through habitat loss, isolation, and edge effects. Recent studies show that restoration corridors can recover part of the species richness and functional diversity lost in fragmented landscapes by increasing connectivity and providing small areas of habitats. In future corridor designs, multispecies modeling is necessary to include as it improves corridor placement by accounting for different ecological requirements and identifying vulnerable bottlenecks. Matrix management is also key to recovering fragmented landscapes; arboreal elements are shown to improve connectivity substantially, and spacing them properly is predicted to be able to lead to even better effect. Simulation of LLE arrangements also suggests the importance of correct orientation of permeable land areas.

The most practical solution is therefore an integrated network of protected forest patches, native restoration corridors, riparian vegetation, living fences, woodland islets, and retained isolated trees; the core goal of this integrated strategy is to improve connectivity through construction of corridors and active matrix management. Future research should examine whether structural connections produce long-term movement and gene flow, determine the corridor widths and types required by specialized species, and compare the ecological benefits and economic costs of different matrix interventions. Longer-term monitoring is also needed to determine whether restored connectivity eventually produces forest-like communities and fully restores ecosystem processes.

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