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ENGINEERING-BASED ASSESSMENT OF FOREST FRAGMENTATION AND LANDSCAPE CONNECTIVITY FOR SUSTAINABLE ENVIRONMENTAL MANAGEMENT

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ABSTRACT

Forest fragmentation is a threat to continuity in the ecosystem, causes greater edge effect and decreases forest landscape structure. Engineering analysis of fragmentation indices will help in sustainable environmental planning by recognizing landscape connectivity influences. This study aimed to assess how forest fragmentation indicators influence landscape connectivity and to evaluate regional variation in forest structural continuity. A quantitative secondary-data design was applied using landscape-level forest fragmentation metrics. Descriptive statistics were used to summarize major variables, Pearson correlation analysis examined relationships among fragmentation indicators, and multiple linear regression evaluated the influence of patch density, edge density, aggregation index, and forest cover on landscape connectivity. Country-level comparison was also performed to identify regional differences. Landscape connectivity showed moderate structural continuity across the analyzed forest systems. Aggregation index had the strongest positive association with connectivity, while patch density and edge density negatively influenced connectivity. The regression model explained 57.3% of the variation in landscape connectivity, confirming that spatial configuration is a major determinant of forest structural cohesion. Country-level results showed clear regional variation, with some countries maintaining stronger connectivity and others showing greater fragmentation pressure. Forest connectivity depends more strongly on patch arrangement than forest cover alone. Sustainable environmental management should prioritize aggregated forest structures, ecological corridors, and the reduction of excessive edge formation to improve landscape continuity.

1. Introduction

Forests are integral to ecological balance, climate control, biodiversity and ecosystem services, which are vital for environmental stability and human health. As a result, sustainable forest management has gained significance as a part of environmental engineering and resource conservation efforts due to the major role forest ecosystems play in carbon sequestration, soil protection, hydrological regulation and habitat preservation (Putz et al., 2022). Forests not only have ecological value, but also have socio-economic value in terms of producing timber, supporting livelihoods, and resilience to climate change. But, further anthropogenic pressures, such as agricultural encroachments, urbanisation, infrastructure development and land use change, still cause forest degradation and spatial fragmentation at the global landscape level. The ecological disturbances, the loss of biodiversity and the instability of carbon are the main reasons for why fragmented forests are more vulnerable to climate change, which has increased concerns about the sustainability of forest ecosystems. Forest degradation compromises ecological continuity and some ecosystems' capacity to cope with new climatic conditions (Brack, 2019). Forest biomes also act as important carbon sinks, which help bind carbon in biomass and absorb carbon from the atmosphere and thus contribute to climate change mitigation. Hence, these systems can be disrupted by fragmentation and affect the ecological stability and global environmental sustainability (Dar et al., 2020). Thus, the importance of comprehending the structural organization of forests in a fragmented landscape has grown in importance for environmental planning and conservation management using engineering approaches. Forest fragmentation has been found to have increased significantly in the past 20 years, especially in the tropics and subtropics, in recent global evaluations. The large-scale fragmentation processes have led to significant habitat fragmentation and ecological effects on habitat persistence and ecosystem functioning (Ma et al., 2023). Fragmentation also leads to a greater exposure of forest edges, habitat isolation, and a decrease in connectivity of ecological corridors. These processes have direct impacts on species movement, regeneration processes and landscape resilience. Research studies on tropical forest fragments have revealed that even small forest fragments can suffer from long-term ecological degradation and loss of forest integrity as a result of edge effects and decreased connectivity (Hansen et al., 2020). Geospatial and landscape based analytical techniques are playing an increasing role in environmental engineering for monitoring forest fragmentation and assessing ecosystem sustainability. The structural aspects of fragmented landscapes can be quantified using spatial metrics like patch density, edge density, aggregation index and connectivity indicators (Kumar et al., 2022). These metrics are commonly used to detect spatial patterns in ecological disturbance and are used to inform conservation oriented land management decisions. The development of remote sensing and landscape modelling also has further enhanced the capacity to analyse forest configuration and to assess fragmentation processes at large spatial scales. Landscape fragmentation analysis has been a topic of much interest in ecological and environmental studies, as it allows quantitative assessment of the spatial heterogeneity and habitat structure. Various imaging and spatial analytical techniques have been used to determine fragmentation patterns and ecological discontinuity within forest systems (Fynn & Campbell, 2019). Fragmentation metrics have also been incorporated into SFM frameworks to help conserve biodiversity and ecological continuity in landscapes subject to SFM. Structural connectivity is seen as a critical element in ecological integrity in temperate forest ecosystems and a necessary element in integrative management strategies (Mölder et al., 2019). Past research has also shown that fragmentation of forests has a profound impact on the distribution of biodiversity, the persistence of species and habitat function. A study in China found that the ecological instability and biodiversity loss in fragmented forest areas are related to the intensity of forest fragmentation (Liu et al., 2019). Land-scape ecology highlights that ecological processes are highly dependent on landscape scale spatial configuration, patch arrangement and landscape scale connectivity of habitats (Sanderson, 2020). As a result, fragmentation metrics are now widely applied in environmental engineering applications related to conservation planning, land-use optimization and sustainable resource management as well as in ecological studies. Within fragmentation studies, the spatial connectivity has become a crucial aspect as it indicates the extent to which habitat patches are structurally connected in the landscape. Connectivity is essential for species movement, ecological interactions and ecosystem resilience in the face of environmental stresses. Linking species distribution and spatial gap analysis has proven to be an essential part of efficient conservation planning and management (Ahmadi et al., 2020). Likewise, the need for open structural connectivity in forests to maintain and support biodiversity and ecological succession processes is well acknowledged (Kozel et al., 2021). While a lot of research has been done on forest fragmentation and conservation of biodiversity, there are some gaps in the literature reviewed. Prior research has tended to emphasize local ecological observations or fragmentation assessments in individual regions, with a more restricted ability to make comparisons across geographic settings in general. Further, some studies place a greater focus on biodiversity outcomes and do not quantify the combined impacts of fragmentation metrics on structural landscape connectivity. However, little focus has been placed on engineering-based statistical frameworks that can incorporate a number of fragmentation indicators into one analytical framework for sustainable environmental management. Thus, quantitative studies that investigate the relationships between forest fragmentation metrics and landscape connectivity with common spatial indicators throughout a variety of regions are still needed. In the present study, we aim to fill this gap and aim for an engineering-based evaluation of forest fragmentation and landscape connectivity by applying quantitative landscape metrics from several forest regions. The study assesses the descriptive attributes of the main fragmentation indicators, investigates the correlation between the fragmentation variables and identifies the effect of the landscape variables, namely patch density, edge density, aggregation index and forest cover on landscape connectivity. The study will provide a contribution towards sustainable environmental management through the comparative statistical analyses; increase the knowledge on the influence of landscape structure on ecological continuity in fragmented forest.

2. Methodology

2.1 Research Design

A quantitative secondary data research design was used in this study to analyse the relationship between forest fragmentation metrics and landscape connectivity. This was chosen due to the applicability to statistically assess spatial landscape characteristics at multiple geographic regions, utilizing common ecological indicators. The study was conducted to identify the effects of variables related to fragmentation on the structural connectivity in forest ecosystems. The analysis was cross-sectional, and the data included observations from across the spatial landscape of forests, but not temporal data from monitoring. Descriptive statistics, correlation analysis and multiple linear regression were used to assess the relationships between the fragmentation metrics and connectivity indicators.

2.2 Data Source

The study was carried out using the LandFrag data set created by Gonçalves-Souza and Vancine (2025). The dataset comprises global landscape metrics related to forest loss and fragmentation, and spatial patterns related to biodiversity, across a number of forest regions. It contains standardized indicators like patch density, edge density, aggregation index, largest patch index and connectivity indicators based on fragmented forest landscapes. This original data set is landscape-scale ecological observation data from various countries and environments, and is thus appropriate for comparative fragmentation analysis.

2.3 Data Preparation

The data was first processed to verify the structure of the data set, the type of variables and the missing values in all the variables. The problem arises when information, such as variables, is stored in a non-numeric format, which requires them to be converted to a numeric format for analytical consistency. Observations with missing data for the main analysis variables were omitted from the final data. Landscape structure and fragmentation variables (forest cover, patch density, edge density, aggregation index, largest patch index, and landscape connectivity) were among the retained variables. Data were standardized for analytical presentation and interpretation using variable names.

2.4 Study Variables

Connectivity in the landscape was chosen as the dependent variable since it denotes the continuity in structure in the forested landscapes that are fragmented. The independent variables that were chosen included forest cover, patch density, edge density, and aggregation index. These variables were chosen due to the fact that they are commonly used as indicators of fragmented landscapes. Patch density and edge density served as proxies for landscape fragmentation and habitat exposure, respectively, while the aggregation index was used to determine the clustering pattern of forest patches. Forest cover was used to find out whether forest cover was responsible for connectivity within fragmented landscapes.

2.5 Data Analysis Techniques

Descriptive statistical analysis was used to describe the distribution and variability of the fragmentation metrics. Descriptive statistics such as mean, median, standard deviation, minimum and maximum values were computed to describe the properties of the data. The relationships among the fragmentation variables were then examined with Pearson correlation analysis to determine the strength and direction of the relationships. Both positive and negative relationships between landscape metrics and connectivity indicators were identified using correlation coefficients. Multiple linear regression was then used to identify the effects of chosen fragmentation variables on landscape connectivity. Landscape connectivity was used as the dependent variable and forest cover, patch density, edge density and aggregation index as predictor variables. The regression model was tested using the coefficients of the model, their levels of significance and the coefficient of determination. Comparative country-level analysis was also conducted to explore differences in connectivity in geographic regions.

3. Results

3.1 Descriptive Characteristics of Forest Fragmentation Metrics

Descriptive analysis showed considerable differences in forest fragmentation and landscape configuration between the study areas. The mean value for forest cover was 61.73%, suggesting that many of the study landscapes had moderate to high amounts of forest cover. But indicators of fragmentation, which included patch density and edge density, were highly variable, indicating a high degree of heterogeneity of landscape structure between sampled areas. The mean value for landscape connectivity was 0.285, and the structural connectivity among the forest systems analyzed was moderate. Descriptive statistics of the main fragmentation and connectivity variables included in this study are shown in Table 1.

Table 1. Descriptive Statistics of Forest Fragmentation and Connectivity Metrics

Variable	Mean	Median	Minimum	Maximum
Fragment Area	4082.087	53.000	-19.967	300000.000
Buffer Distance	1084.519	1000.000	3.336	2000.000
Mean Patch Area	76.224	11.615	0.000	5580.000
Forest Cover	61.734	61.240	0.048	464.527
Number of Patches	31.911	12.000	0.000	1091.000
Patch Density	7.730	5.082	0.000	136.845
Mean Nearest Neighbor Distance	72.418	69.960	0.000	1132.825
Aggregation Index	69.606	86.788	0.000	99.948
Edge Density	61.085	55.449	0.000	484.508
Largest Patch Index	50.499	50.000	0.000	100.000
Mean Perimeter Area Ratio	0.089	0.089	0.000	0.372
Landscape Connectivity	0.285	0.271	0.000	0.973

The distributions observed suggest that several fragmentation variables, including fragment area, number of patches and edge density, were positively skewed because of the presence of landscapes with extreme values and high levels of fragmentation. By contrast, the distribution of the aggregation index and landscape connectivity were comparatively more stable. In this section, the degree of correlation between the various fragmentation metrics is investigated.

3.2 Correlation Analysis of Fragmentation Metrics

Pearson correlation showed that there were several significant relationships between the forest fragmentation variables. The aggregation index had the highest positive correlation with landscape connectivity (r = 0.733), suggesting that this measure of forest structure is a significant factor in structural continuity. Forest cover was also highly positively associated with the largest patch index (r = 0.967), indicating that landscapes with more forest cover are likely to have a larger maximum forest patch. In contrast, the largest patch index was negatively correlated with aggregation index (r = -0.384) and landscape connectivity (r = -0.330), suggesting that there are complex spatial relationships between the formation of dominant patches and the overall cohesion of the landscape. There was also a strong positive relationship between patch density and edge density (r = 0.727), thus suggesting that fragmented landscapes tend to have greater edge effects. Pearson correlation coefficients between the principal fragmentation variables are summarized in Table 2. These relationships between the variables have been graphically represented in the correlation structure in Figure 1, showing how the fragmentation metrics negatively correlate with connectivity indicators, whereas connectivity indicators showed positive associations: the connectivity indicators positively correlate with the fragmentation metrics.

Table 2. Pearson Correlation Matrix of Forest Fragmentation Metrics

Variable	**Forest Cover**	**Patch Density**	**Edge Density**	**Aggregation Index**	**Largest Patch Index**	**Landscape Connectivity**
Forest Cover	1.000	-0.282	-0.238	-0.335	0.967	-0.275
Patch Density	-0.282	1.000	0.727	0.133	-0.293	-0.052
Edge Density	-0.238	0.727	1.000	0.366	-0.286	0.105
Aggregation Index	-0.335	0.133	0.366	1.000	-0.384	0.733
Largest Patch Index	0.967	-0.293	-0.286	-0.384	1.000	-0.330
Landscape Connectivity	-0.275	-0.052	0.105	0.733	-0.330	1.000

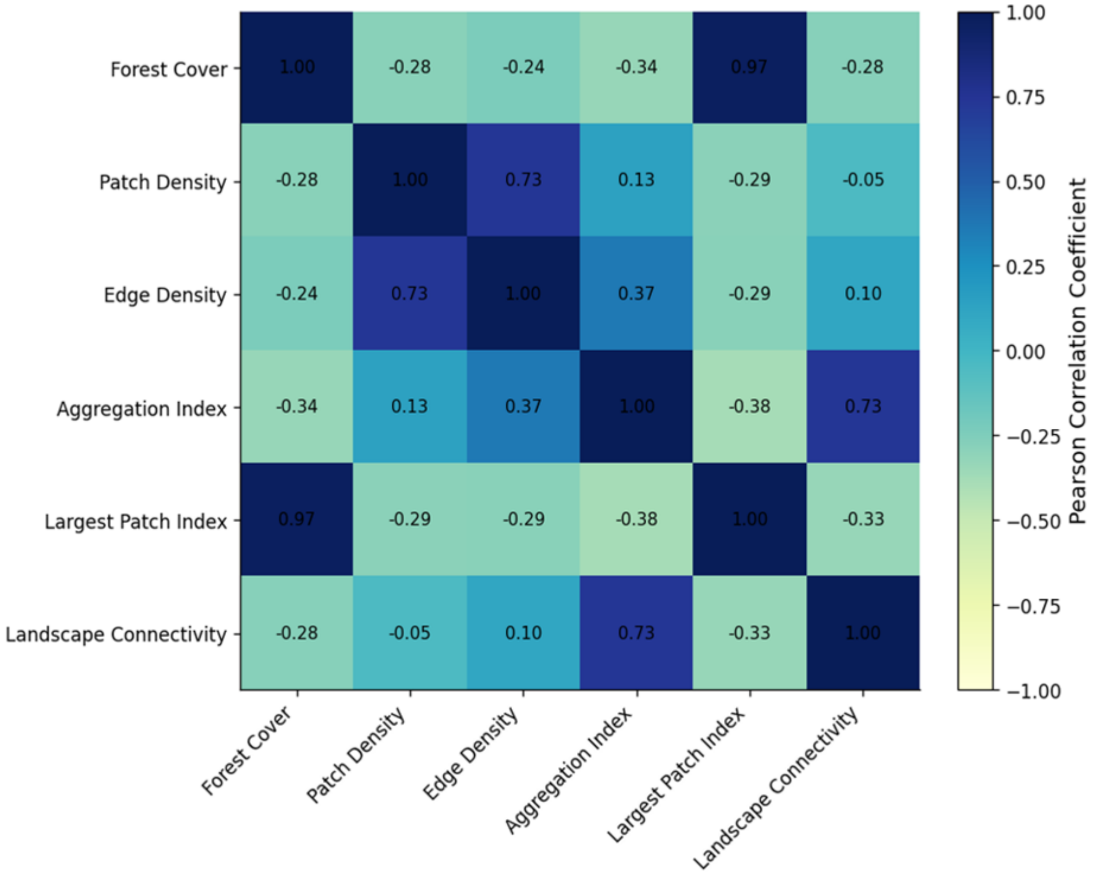

Figure 1. Correlation Matrix of Forest Fragmentation Metrics

The heatmap illustrates that the aggregation index was generally most positively related to landscape connectivity, while fragmentation-related indices like patch density and edge density were not as closely related or were negatively associated with structural connectivity.

3.3 Regression Analysis of Landscape Connectivity

To test the effect of selected fragmentation metrics on landscape connectivity, multiple linear regression was performed. The selected predictors explained a relatively large portion of the variance in landscape connectivity, with the model accounting for about 57.3% of the variance ($R^2 = 0.573$). The best positive predictor of connectivity was aggregation index ($\beta = 0.0043$, $p < 0.001$), indicating that a clustered forest structure significantly enhances structural connectivity. In contrast, the patch density ($\beta = -0.0015$, $p < 0.001$) and the edge density ($\beta = -0.0006$, $p < 0.001$) negatively shaped connectivity, indicating that fragmentation by itself hurts ecological connectivity. Forest cover also had a statistically significant negative coefficient ($\beta = -0.0005$, $p < 0.001$), suggesting that the spatial structure of forests is more important than the amount of forest cover. The regression coefficients and statistics of the models are given in Table 3.

Table 3. Multiple Linear Regression Results for Predicting Landscape Connectivity

Predictor Variable	**Coefficient**	**Standard Error**	**t Statistic**	**p Value**
Constant	0.0565	0.0029	19.2013	< 0.001
Patch Density	-0.0015	0.0001	-11.8130	< 0.001
Edge Density	-0.0006	0.0000	-23.1572	< 0.001
Aggregation Index	0.0043	0.0000	171.2894	< 0.001
Forest Cover	-0.0005	0.0000	-16.4498	< 0.001

The overall model significance was high ($F = 9502.23$, $p < 0.001$), implying that the regression analysis was valid in explaining the patterns of landscape connectivity. Figure 2A depicts the inverse correlation between patch density and landscape connectivity. Figure 2B portrays the correlation between edge density and landscape connectivity. Figure 2C highlights the positive correlation between the aggregation index and landscape connectivity. Figure 2D indicates the correlation between forest cover and landscape connectivity.

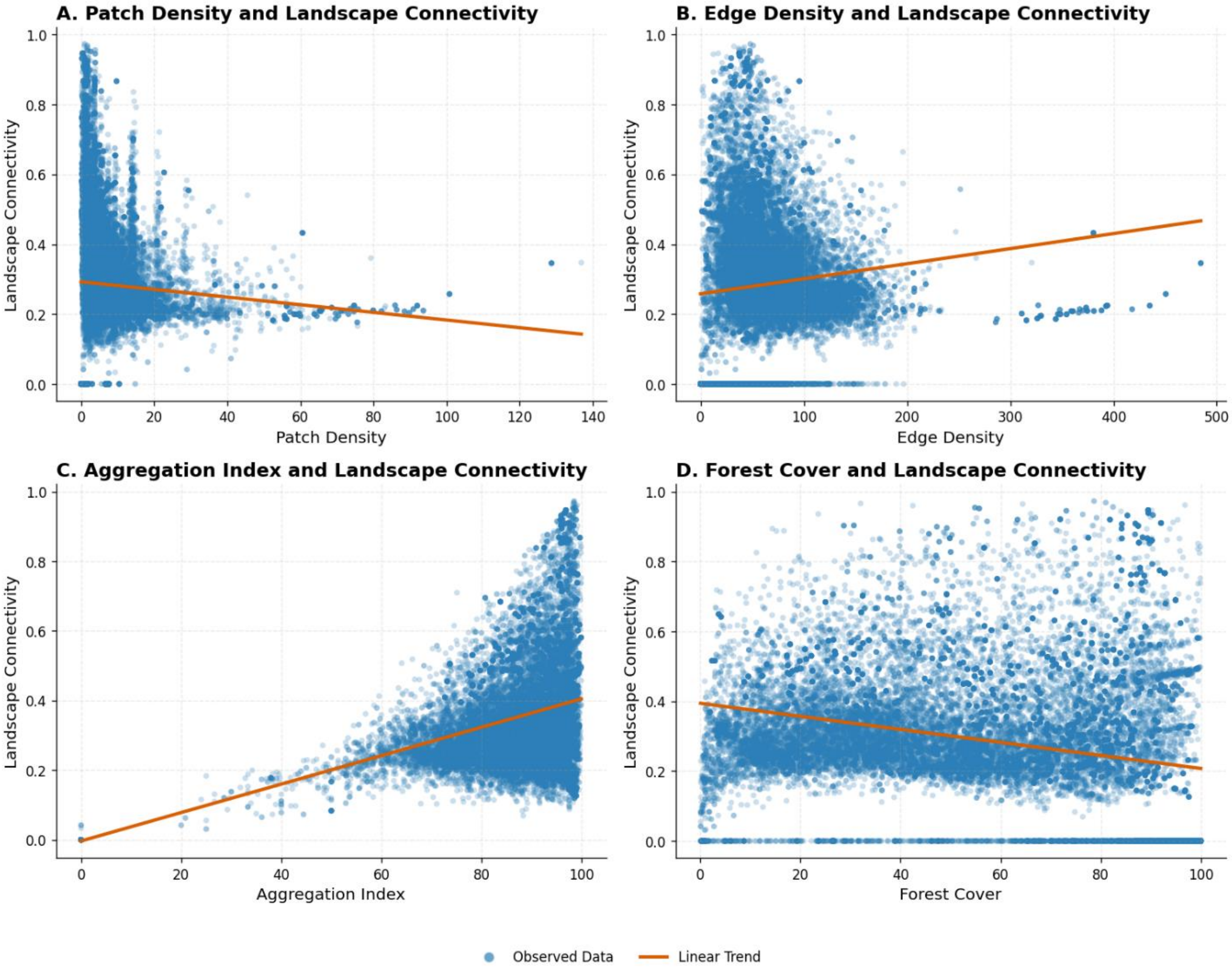

Figure 2. Relationships Between Forest Fragmentation Metrics and Landscape Connectivity: (A) Patch Density and Landscape Connectivity, (B) Edge Density and Landscape Connectivity, (C) Aggregation Index and Landscape Connectivity, and (D) Forest Cover and Landscape Connectivity

All the scatterplots show a distinct negative correlation between connectivity and either patch density or edge density. In contrast, the aggregation index showed a strong and positive linear relationship with landscape connectivity, which further highlighted its role in the ecology of maintaining forest continuity.

3.4 Country-Level Comparison of Forest Connectivity

Significant regional differences in forest connectivity were found in the countries analysed. Thailand and French Guiana had the highest mean connectivity, reflecting more aggregated patterns and relatively continuous forest structures. On the other hand, Sri Lanka, Malaysia and Ghana had comparatively low connectivity values, indicating more fragmented landscape configurations. The comparative distribution of mean landscape connectivity is shown by country in Figure 3.

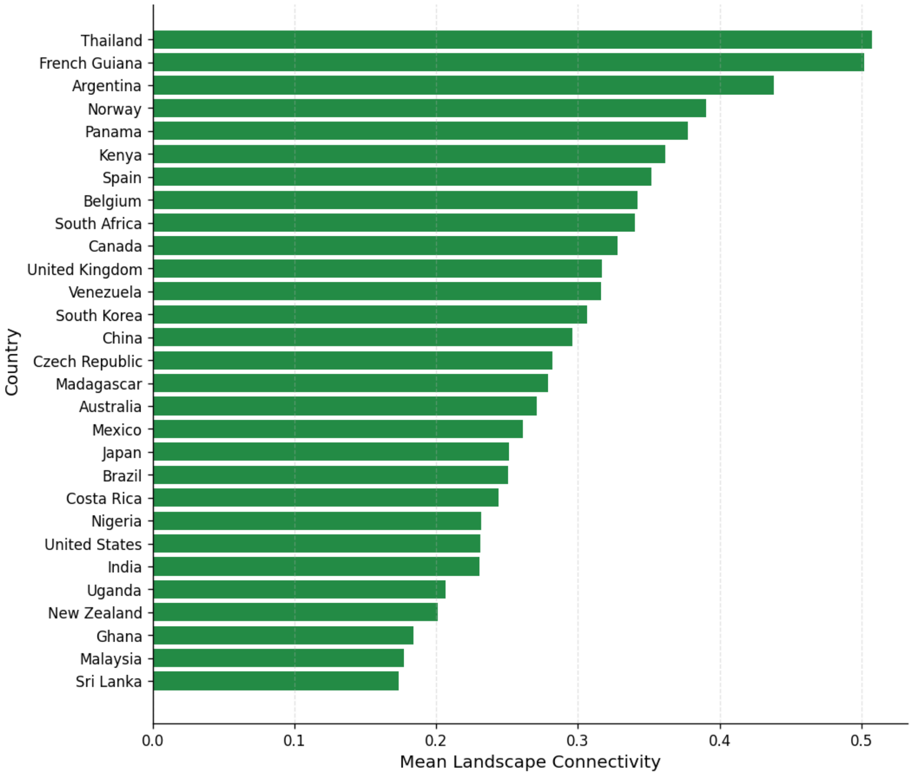

Figure 3. Country-Level Forest Connectivity Comparison

Fostered fragmentation processes are, in general, associated with a lower connectivity in countries holding higher edge density and patch density values. The countries with the highest edge density values were Madagascar, the United Kingdom and Costa Rica, expressing a higher level of edge effects and habitat exposure.

4. Discussion

Forest landscape connectivity was primarily influenced by the spatial configuration of patches and not forest cover alone. The most robust finding was that the aggregation index had a positive influence on landscape connectivity, which means that spatially continuous and clustered forest patches are structurally more cohesive than forest patches that are dispersed. This discovery indicates that ecological continuity is not just a function of forest presence, but also of the spatial configuration of forest patches in a landscape. More aggregated landscapes are more likely to facilitate movement, decrease isolation, and sustain ecological processes in fragmented landscapes. Within the regression model, a negative relationship was found between patch density, edge density and landscape connectivity. Higher patch density suggests a greater fragmentation of forests, and higher edge density suggests a greater exposure of edges between forest and non-forest land uses. When combined, these indicators indicate increased fragmentation, the spatiotemporal separation of forests and the growing intrusiveness of external influences. The negative effects of these variables support the hypothesis that fragmentation decreases structural continuity and the ability of forest systems to act as a connected ecological network.

It is also important that the coefficient for forest cover is negative. Forest cover has been used to represent ecological quality, but the results indicate that this does not necessarily equate to increased connectivity with a higher forest proportion. Even where a landscape has a high percentage of forest cover, it may be structurally fragmented because of poor connectivity between patches, dispersion of patches, and/or patch isolation. This is consistent with the notion that environmental management needs to not just take account of the quantity of forests, but also the spatial configuration, patch clustering and continuity of corridors. At the country level, results also showed that the connectivity patterns are different across countries. Thailand and French Guiana had the highest mean connectivity values, indicating more continuous landscape structures. Sri Lanka, Malaysia and Ghana, in comparison, had lower connectivity values with more fragmented landscape conditions. These differences further emphasize the need to consider landscape planning at the local level, as similar proportions of forest cover can lead to different ecological effects when the patches are arranged differently, and the fragmentation is more or less intense.

The results agree with earlier research, indicating the susceptibility to fragmentation is well captured by spatial indicators and landscape metrics. The present results agree with those of Batar et al. (2021), who underscored that spatial landscape structure is a major factor contributing to the fragmentation risk. In the same way, ecological vulnerability assessments using GIS have demonstrated that the incorporation of spatial measurements within the planning framework at the landscape level is beneficial for environmental risk assessment (Rehman et al., 2021). De Matos et al. (2021) also suggested the need to prioritise connectedness of forest fragments, as these are the ones that can improve the landscape structure. The present analysis shows a strong positive correlation between aggregation index and connectivity, which supports this view, given that larger patches of aggregated forest are more likely to be effective restoration anchors. Liu et al. (2020) also showed the use of connectivity tools to define forested landscapes conservation and restoration priorities, which highlighted the importance of quantitative connectivity assessment. Results also align with mitigation strategies based on connectivity. The present finding that habitat structural connectivity can be statistically explained by fragmentation measures is relevant to the findings of Bergès et al. (2020) that the use of habitat connectivity modeling can help in mitigation and biodiversity offset decisions. In the urban or peri-urban area, the connectivity of green infrastructure corridors improves landscape connectivity, which proves that the arrangement of space and the design of the green infrastructure corridors are important for sustainable forest planning, as Zhang et al. (2019) showed.

The variation across country levels seen in this study is consistent with previous findings that fragments of forest could be used to facilitate connectivity if they are strategically located within a wider landscape. Ribeiro et al. (2022) identified that although fragments may be spatially isolated, they can still provide ecological value in an urban landscape, indicating that fragments can play a role in the connectivity of protected areas. Tiang et al. (2021) also emphasized the role of scattered trees and small patches within fragmented agricultural landscapes, suggesting that connectivity planning should focus on large forest patches, as well as smaller dispersed patches. The observed relationship between fragmentation and connectivity also agrees with studies using advanced spatial structure analysis. Forest fragmentation dynamics can be interpreted as structural and fractal, as demonstrated by Andronache et al. (2019), and this is a reason why measuring the amount of forest is not enough, but also its spatial form and continuity.

The results are relevant to sustainable environmental engineering and forest landscape management. First, restoration should focus on enhancing spatial connectivity, not just on increasing the area of forest. If the new patches created in reforestation or afforestation are isolated, then there may be limited ecological benefits. Second, by maintaining landscape connections, buffer zones and forest corridors, land-use planning should limit the unnecessary subdivision of patches and the expansion of edges. Third, aggregation index, patch density and edge density can be used as practical monitoring indicators to identify landscapes in greatest need of intervention. In terms of policy and planning, the findings imply that forest management should incorporate landscape metrics within environmental impact assessment and restoration prioritization and at the regional level, within conservation planning. Spatial assessment based on engineering principles can assist decision makers to determine where corridors, stepping-stone habitats and areas for restoration may best enhance landscape connectivity.

There are some caveats to be noted. Secondary cross-sectional data were used; no temporal changes in forest connectivity were assessed. The study also concentrated on landscape metrics and the species movement, biodiversity abundance, climate variables and field-based ecological measurements were not directly considered. Further, caution should be used in making country-level comparisons, as sampling intensity varied between countries. Future research should incorporate time-series satellite data to understand changes in connectivity over time. Future research could be developed to incorporate biodiversity data and other landscape metrics with climate data and land-use change data to create more complete sustainability models. Priority restoration zones identified by machine learning and spatial optimization methods could also be used to predict future fragmentation risks under various land-use scenarios.

5. Conclusion

Spatial configuration, including patch aggregation, is a strong determinant of forest landscape connectivity. The results highlight the beneficial effects of aggregated forest structure on the ecological continuum, and the negative effects of high patch density and edge density on landscape cohesion. While the quantity of forest cover was not enough to explain connectivity, it was shown that sustainable forest management should take into account the quantity and configuration of forest patches. A high proportion of the variation in landscape connectivity was accounted for by the regression model, which indicated that landscape connectivity measures are good engineering counterparts for evaluating forest structural integrity. Comparing country-level data also highlighted big regional differences, with some landscapes being more connected while others faced a higher level of fragmentation pressure. The study emphasizes the importance of quantitative landscape measures for sustainable environmental management. The connectivity of forest networks, forest corridors and minimization of excess edge formation should be given special attention in restoration and planning processes. Incorporation of temporal satellite data, biodiversity indicators and field observations should be explored in future research to reinforce the understanding of the dynamics of forest connectivity in the context of land use and climate change.

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