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VISUAL INTERPRETATION OF HABITAT DYNAMICS: AN INTERDISCIPLINARY APPROACH TO LIFE SCIENCE AND GEOSCIENCE RESEARCH

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ABSTRACT:
The change in biodiversity is often associated with habitat loss and fragmentation, but it is not clear whether the relationship between habitat patch area and species richness was similar among land-use systems and biogeographic settings. A global site-level dataset comprising 1,843 sampling sites drawn from 88 independent studies was used to evaluate how species richness varies with habitat configuration while accounting for land use, biome, latitude, and net primary productivity. Species richness was analyzed as log(1 + richness), habitat patch area as log10(m²), and linear mixed-effects models were fitted with study identity as a random intercept. In addition to an additive model, an interaction model tested whether patch size effects differed among land-use categories. Species richness showed a latitudinal gradient, with absolute latitude remaining a significant predictor in the mixed-effects framework ($\beta = 0.053$, $SE = 0.013$, $p < 0.001$). Patch size exhibited a positive bivariate association with richness, and productivity was positively associated in multivariate models. However, in the interaction model, the main patch-size term was marginal ($\beta = -0.119$, $p = 0.062$), and multiple patch-size × land-use interaction terms were significant, indicating that patch-size slopes differed among land-use systems rather than remaining uniform. Habitat configuration was associated with species richness, but its interpretation depended on land-use identity and broader environmental gradients, supporting integrative ecological–geospatial assessment of habitat dynamics.

KEYWORDS: biodiversity, habitat, land use, landscape structure, spatial design, global change

1. INTRODUCTION

The biodiversity of the world is experiencing a rapid deterioration due to increasing pressure on it, which is anthropogenic in origin. Habitat conversion, climate change, land-use intensification, and ecosystem degradation all pose a threat to the ecological stability and species persistence on the global level (National Academies of Sciences et al., 2019). These issues are on the scale and complexity level that demands integrated environmental systems that can tackle the spatial, ecological, and socio-environmental aspects of these issues. The loss of biodiversity is commonly accepted as one of the characteristic environmental concerns of the twenty-first century (Palombo, 2021), with consequences to the sustainability and resilience of ecosystems. Still, global syntheses also underscored the ubiquity of the human effect on biodiversity across both regions and taxa (Keck et al., 2025). A significant factor leading to reduced biodiversity is habitat change, and its impact is frequently manifested by direct habitat loss and disturbed land-cover structure. In South and Southeast Asia, land transformation has been linked to a loss in biodiversity indicators that can be measured (Tan et al., 2022). On a broader scale, the reduction of biodiversity is influenced by several interacting drivers, such as land conversion, exploitation, and environmental degradation (Singh et al., 2021). These pressures may interface with climate-based changes that affect the pattern of species and the persistence (Scheffers and Pecl, 2019). Simultaneously, the fact that biodiversity loss is going hand in hand with other worldwide risks, such as climate change and infectious disease dynamics, underlines the necessity of a combined ecological evaluation on different scales (Pfenning-Butterworth et al., 2024). Habitat fragmentation is one of the mechanisms that has been subjected to long-term scientific interest in the context of habitat modification and the related reduction of biodiversity. Fragmentation changes the structure of the habitat in terms of patch size and spatial distribution and may alter ecological conditions to which species are exposed. Nonetheless, it is still unclear whether fragmentation itself is the source of biodiversity loss or the amount of total habitat is the key factor (Fahrig et al., 2019). Recent efforts have suggested more conceptual reconciliation in this discussion as they focus on reliance on ecological context, scale, and landscape structure (Valente

et al., 2023). These views imply that the effects of fragmentation might not be uniform but might be different in each system or follow one straight line.
Another complication of biodiversity responses is land-use change since land-use categories vary in terms of habitat structure, disturbances, and resource availability. Extensive studies show that the global land-use has contrasts on biodiversity across functional groups, suggesting that the richness response can be taxonomic and ecological community responses based on taxonomic and ecological structure (Newbold et al., 2020). The observations in drylands and the Mediterranean also indicate that the reaction of biodiversity to land use may vary among regions with different climatic and structural limitations (García-Vega and Newbold, 2020). Simultaneously, it is difficult to assemble similar evidence on land-use effects since studies are different in terms of study design, spatial resolution and ecological variation (Davison et al., 2021). In addition to land use and fragmentation, biodiversity patterns are arranged by macroecological gradients (latitude and productivity). Environmental change mediated by climate affects community structure and conservation patterns, in particular, species follow changing climate wraps (Scheffers and Pecl, 2019). Biodiversity loss may also have ecological impacts that have more far-reaching effects, such as host-pathogen interactions and community-scale control (Halliday et al., 2020). Such connections support the importance of studying biodiversity patterns in frameworks that integrate the local structure of the habitat with the general geographic gradient. The recent developments in spatial analysis have enhanced the collaboration of ecological and geoscientific views and make it possible to interpret the habitat configuration and the landscape structure in a more explicit way. Surveys of geovisual analytics emphasize the use of interactive spatial visualization to enrich conservation science, meaning the ability to interpret intricate ecological data (Lacey and Nelson, 2023). Beyond that, interdisciplinary research is being acknowledged as a key to overcoming the intricate problems of the environment and applying both strategies in the fields of science (Raimbault, 2019).
Although the habitat fragmentation and land-use change have been researched extensively, there are gaps. Most of the studies consider patch size effects or land-use variations independently and fail to give an inference about the interaction of habitat configuration with land-use context once the productivity and large geographic gradients have been taken into account. The given limitation applies since, in reality, land-use change and fragmentation tend to co-exist, and their interplay cannot be observed in the context of isolated analyses.
The current paper will focus on species richness with regard to habitat structure in various land-use and biogeographic settings in terms of a hierarchical analytical approach. It analyses the relationship between the patch area of habitats and their richness, differences among land-use systems, and macroecological gradients including latitude and productivity. The research attempts to unravel the relationship between the configuration of habitats and patterns of biodiversity in the heterogeneous landscapes by incorporating spatial structure and ecological variables.

2. MATERIALS AND METHODS

2.1 Study Design and Analytical Framework

A cross-system quantitative study design based on examining the species richness response of the habitat patch size in various land-use and biogeographic conditions was applied in this study. A global site-level dataset, which was compiled by Deng et al. (2023), was used in analyses. Since it was observed that some of the independent studies provided the observations, linear mixed-effects models were used, where the identity of the studies would serve as a random intercept to address the hierarchical data structure.

2.2 Data Source

The publicly available data of Deng et al. (2023) were used as data. The analytical subset contained 1,843 sampling sites contained within 88 independent studies across different biomes. All the sites had data on the richness of species, area of a habitat patch, land-use type, location, and net primary productivity. Sites that had all the information on these variables were only retained as an input to an analysis, and the habitat patch area was log-transformed after removing non-positive values.

2.3 Response Variable

Species richness per site was the main variable of response, which was defined as the number of recorded species in the sampling unit. Since the richness values were skewed positively and had a heteroscedastic variance among the environmental gradients, a log(1 + richness) transformation was used to transform the species richness before the model was used. This conversion minimized skew and enhanced symmetry of residual values but retained zero values.

2.4 Environmental Predictors

The area of habitat patches was measured in square meters and logarithmically back-transformed, which is a base-10 logarithmic transformation, to correct a right-skewed distribution and a multi-order magnitude distribution. The log10 transformation helps in the interpretation of responses given in different orders of magnitude of patch size. The category of land-use was considered a categorical predictor and comprised primary vegetation, mature secondary vegetation, intermediate secondary vegetation, young secondary vegetation, secondary vegetation of indeterminate age, plantation forest, cropland, pasture, and urban systems. To include the ecosystem productivity, net primary productivity was added as a continuous predictor in grams of carbon per square meter per year (gC m^{-2} yr). The site coordinates were calculated into absolute latitude, which was used as a continuous variable to capture the large-scale geographic gradients with no reference to hemisphere. The identity of the biome was added in the form of a categorical predictor to include the macro ecological and climatic background.

2.5 Exploratory Analysis

The descriptive statistics were calculated to describe the distribution of the biodiversity and the environmental variables. A summary of land-use and biome was conducted in the form of frequencies and percentages of sampling representation of categories. Pearson correlation was done on pairs of continuous predictor variables and variables of richness to understand the possibility of multicollinearity before the model was constructed.

2.6 Statistical Modeling

The connections between the environmental predictors and the log-transformed species richness were assessed using the linear mixed-effects models. The identity of the studies was defined to be a random intercept, as a measure of clustering sites by study. The estimation of models was done based on restricted maximum likelihood. A preliminary additive model was used to test the independent variables of the log10 patch area of habitat, land-use group, net primary productivity, absolute latitude, and identity of biome on the richness of species. In order to test the hypothesis that all land-use systems had different associations between habitat patch size and species richness, an interaction term of log10 habitat patch area and land-use category became part of the final model. This specification enabled the slope of the patch size-richness relationship to vary between land-use categories. Model coefficients were evaluated using Wald statistics, and statistical significance was assessed at $\alpha = 0.05$. Fixed-effect estimates are reported with corresponding standard errors and p-values.

2.7 Model Diagnostics

The model assumptions were tested by looking at the distributions of residuals and patterns of variances. The logarithmic transformation of the species richness enhanced the residual symmetry as well as minimized heteroscedasticity compared to the non-transformed response. Analysis of the correlation table between predictors revealed that there was no exceeding correlation between any pair of predictors above 0.30, indicating the presence of minimal multicollinearity. The study was included as a random intercept, which considered the variation between source studies in the hierarchical structure.

3. RESULTS

3.1 Dataset Structure and Environmental Heterogeneity

The final analytical dataset comprised 1,843 sampling sites nested within 88 independent studies, spanning broad geographic and ecological gradients. Species richness ranged from 1 to 229 species per site (mean = 17.63; SD = 25.54). After log-transformation to stabilize variance, the mean log-transformed richness was 2.24 (SD = 1.16). Habitat patch area exhibited substantial structural heterogeneity, spanning several orders of magnitude; the mean log10 patch area was 5.96 (SD = 1.52). Net primary productivity (NPP) averaged 923.76 gC m^{-2} yr^{-1} (SD = 492.51), while absolute latitude ranged from 0.24° to 60.29° (mean = 23.88°), confirming representation from tropical to temperate regions (Table 1).

Table 1. Descriptive statistics of environmental and biodiversity variables (n = 1,843)

Variable	Mean	SD	Minimum	25th percentile	Median	75th percentile	Maximum
Species richness	17.63	25.54	1.00	2.00	8.00	21.00	229.00
Log-transformed species richness	2.24	1.16	0.69	1.10	2.20	3.09	5.44
Net primary productivity (gC m^{-2} yr^{-1})	923.76	492.51	43.95	485.66	794.67	1290.63	2303.05
Log10 habitat patch area (m^2)	5.96	1.52	-0.80	4.59	5.77	7.00	10.03
Absolute latitude (°)	23.88	15.48	0.24	13.58	18.58	41.47	60.29

Land-use categories were unevenly represented (Table 2), with Primary vegetation accounting for 44.9% of sites and Pasture 19.8%. Secondary vegetation classes collectively represented approximately 25% of observations, whereas Urban systems were rare (<1%). Biome distribution was strongly tropical (Table 3), with Tropical & Subtropical Moist Broadleaf Forests and Tropical & Subtropical Grasslands/Savannas together comprising nearly 60% of sampling locations.

Table 2. Distribution of sampling sites across land-use systems

Land-use category	Count	Percent
Primary vegetation	827	44.9%
Pasture	365	19.8%
Young secondary vegetation	178	9.7%

Secondary vegetation (indeterminate age)	160	8.7%
Plantation forest	124	6.7%
Intermediate secondary vegetation	99	5.4%
Cropland	54	2.9%
Mature secondary vegetation	29	1.6%
Urban	7	0.4%

Table 3. Distribution of sampling sites across biomes

Biome	Count	Percent
Tropical & Subtropical Moist Broadleaf Forests	638	34.6%
Tropical & Subtropical Grasslands, Savannas & Shrublands	462	25.1%
Montane Grasslands & Shrublands	339	18.4%
Temperate Broadleaf & Mixed Forests	210	11.4%
Mediterranean Forests, Woodlands & Scrub	87	4.7%
Temperate Conifer Forests	58	3.1%
Boreal Forests/Taiga	27	1.5%
Deserts & Xeric Shrublands	11	0.6%
Tropical & Subtropical Dry Broadleaf Forests	11	0.6%

3.2 Correlation Structure Among Environmental Drivers

It was found that the pairwise correlations between biodiversity and environmental predictors were mostly weak to moderate (Table 4). Habitat patch size (r = 0.17) and NPP (r = 0.13) had a positive relationship with log-transformed richness. Patch size also had a closer relationship with productivity (r = 0.29), indicating a partial structural-energetic relationship. No significant correlation was found between absolute latitude and richness (r = 0.09), and a weakly negative with patch size (r = -0.18). The magnitude of all the correlations was not more than 0.30, which is not very high and does not suggest that multicollinearity should be avoided; instead, the prediction should be allowed in the multivariate model.

Table 4. Correlation matrix among key variables

Variable	Log richness	Species richness	NPP	Log patch area	Absolute latitude
Log richness	1.00	0.82	0.13	0.17	0.09
Species richness	0.82	1.00	0.06	0.19	0.05
Net primary productivity	0.13	0.06	1.00	0.29	−0.04
Log patch area	0.17	0.19	0.29	1.00	−0.18
Absolute latitude	0.09	0.05	−0.04	−0.18	1.00

3.3 Latitudinal Gradient in Species Richness

The richness of the species was systematically distributed among the latitude strips. Having the sites clustered in 5° absolute latitude intervals, the mean log-transformed richness (log[1 + richness]) and standard errors assumed was greater at lower latitudes and gradually decreasing with increasing latitude (Figure 1). Such a trend shows definite macroecological organization of biodiversity geographic space.

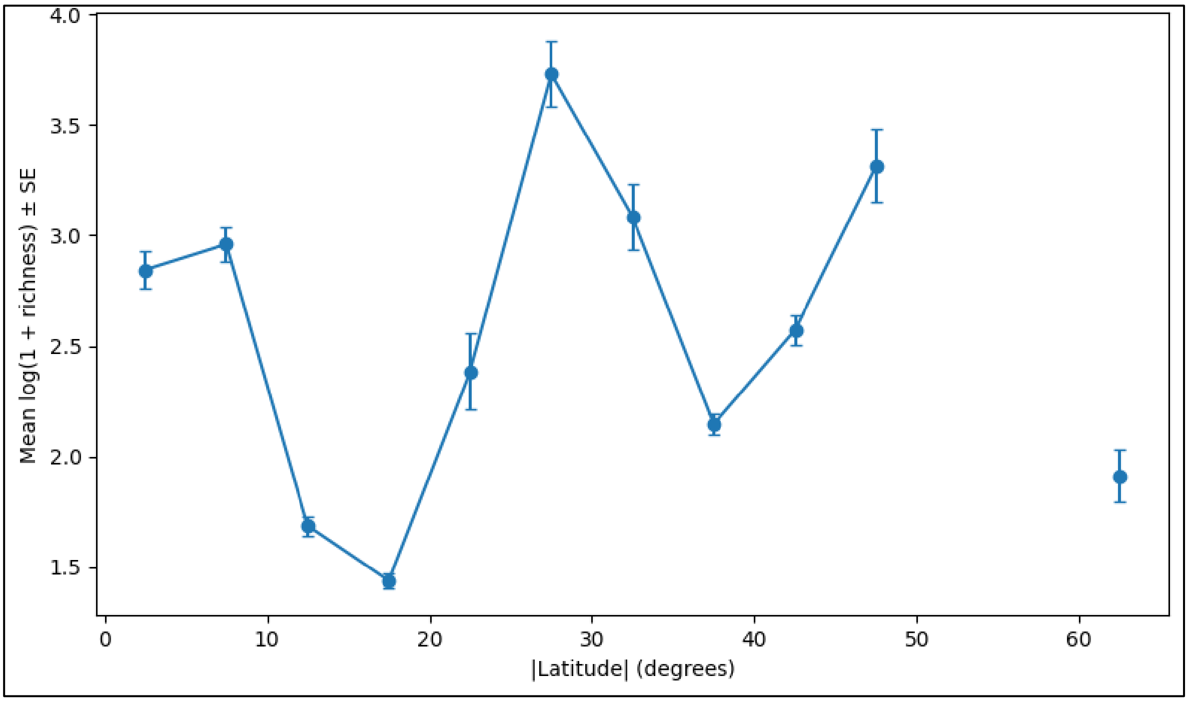

Figure 1. Latitudinal gradient of log-transformed species richness across absolute latitude bands.

3.4 Relationship Between Habitat Patch Size and Biodiversity

The species richness in the habitat patch area showed a positive bivariate correlation with the habitat patch area in the global dataset. The log 10 habitat patch area versus log transform richness scatter plot shows the overall increasing trend of the variable orders of magnitude with respect to the patch size (Figure 2).

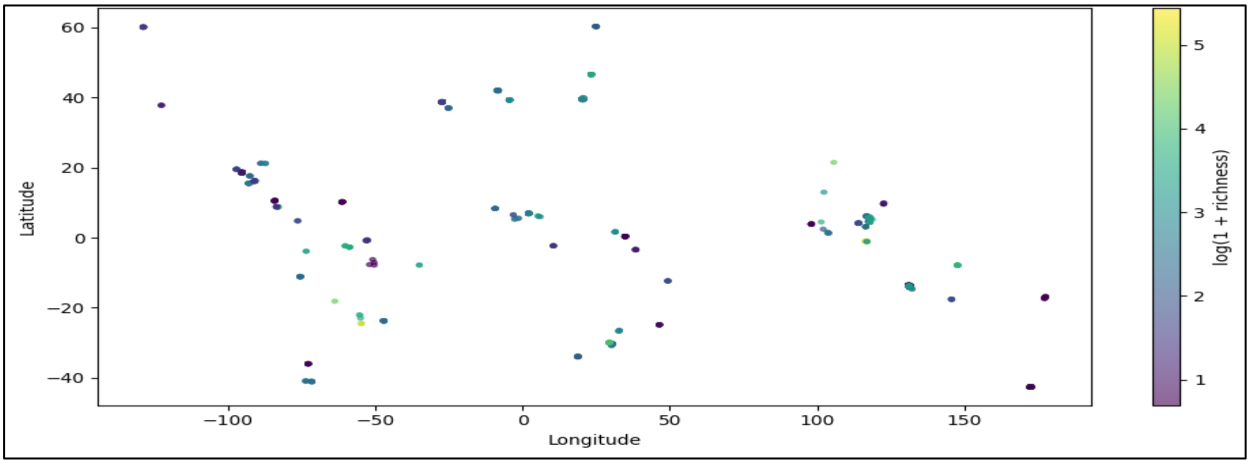

Figure 2. Relationship between log10 habitat patch area and log-transformed species richness across sampling sites.

The regression line pooling indicates that the combined data indicate the richness was prone to increase with the patch size. However, the variability of the site was also very high, and the strength of such association depended on the context of land-use in multivariate models. This pattern of relative consistency is repeated in the moderate positive patch-size by richness correlation (Table 4), and the interaction model (Table 5) indicates that there was no uniformity in patch-size by land-use interaction slopes across systems. Taken together, these results suggest that habitat structure has an association with biodiversity change at greater spatial levels, but that contextuality defines its impact.

Table 5. Selected fixed-effect terms from the mixed-effects interaction model examining patch size × land-use effects

Predictor	Coefficient	Standard Error	p-value
Absolute latitude	0.053	0.013	<0.001
Net primary productivity	0.00008	0.00004	0.040
Log10 habitat patch area	-0.119	0.064	0.062
Log10 habitat patch area × Secondary (indeterminate age)	0.261	0.087	0.003
Log10 habitat patch area × Intermediate secondary	0.177	0.070	0.013
Log10 habitat patch area × Primary vegetation	0.160	0.065	0.032

Log10 habitat patch area × Plantation forest	0.172	0.074	0.020
Log10 habitat patch area × Pasture	0.130	0.065	0.046
Log10 habitat patch area × Urban	0.942	0.446	0.035

3.5 Land-Use Differences in Mean Richness

There was a difference in mean biodiversity between land-use systems. Mean log-transformed species richness in categories indicates that there is a significant difference between the means across land-use types, with plantation forest and intermediate secondary vegetation having higher means as compared to urban systems and secondary vegetation of undetermined age (Figure 3).

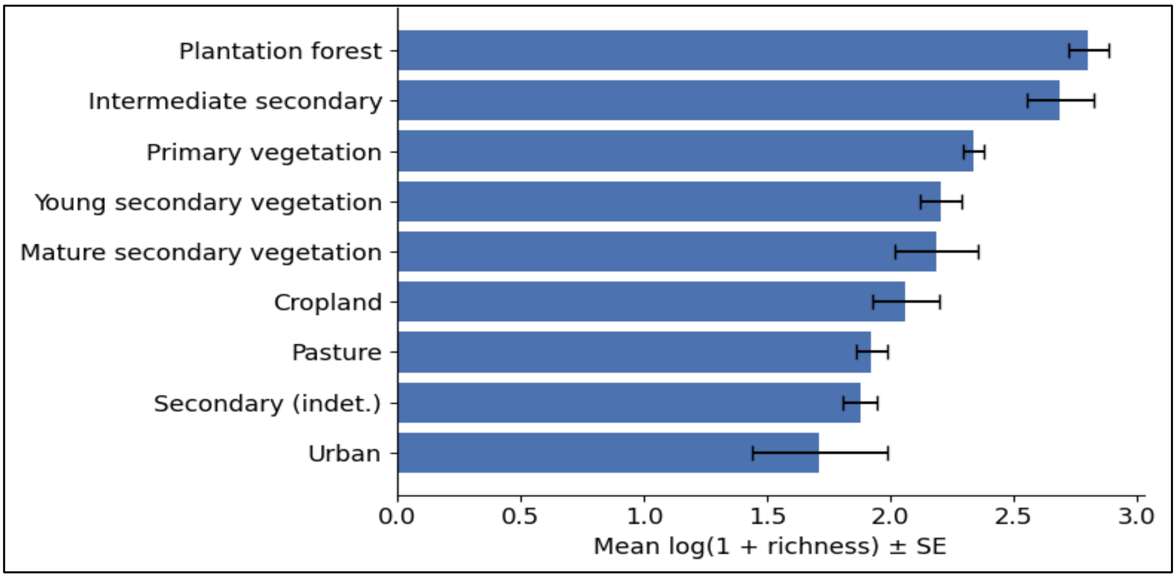

Figure 3. Mean log-transformed species richness across land-use systems.

These differences indicate that biodiversity patterns are influenced not only by habitat configuration but also by the structural and ecological characteristics associated with specific land-use regimes. Although variability within categories was evident, the distribution of means suggests systematic contrasts among land-use systems in their capacity to support species richness.

3.6 Context-Dependent Effects of Habitat Fragmentation

The influence of habitat patch size on species richness was not uniform across land-use systems. The mixed-effects interaction model revealed significant land-use–specific modulation of patch-size effects (Table 5). Although the overall main effect of patch size was marginal, multiple interaction terms were statistically significant, indicating that the slope of the patch size–richness relationship differed among land-use categories. This divergence is a model-derived prediction and slope differences in the landscape-use system among land-use systems and among classes displaying enhanced biodiversity responses to augmented patch size as compared to the reference condition (Figure 4). Specifically, there were steeper responses to modified landscapes, including plantation forest and secondary vegetation systems, than the more intact systems.

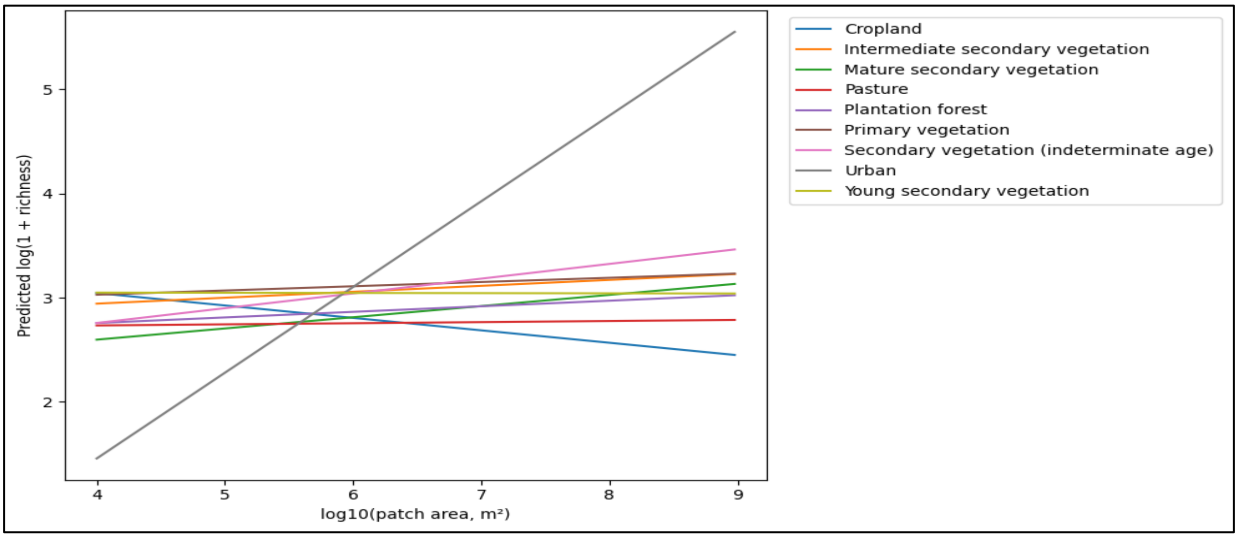

Figure 4. Predicted richness responses to habitat patch size across land-use systems.

The fact that the predicted trajectories separate is an indication that the effects of fragmentation are not consistent regardless of the environmental context. These results suggest that the ecology of habitat structure is significantly sensitive in terms of the context of land-use that surrounds it, and support the significance of considering structural and land-use variables when analyzing biodiversity.

3.7 Structural Differences in Habitat Configuration

The distributional analysis of the area of the habitat patch showed that there were evident structural differences among the key land-use systems. Interpretation of log-transformed patch area data demonstrates that primary vegetation systems are more apt to cover larger and usually bigger patch areas, whereas pasture and secondary vegetation systems are of relatively smaller patch areas with a relatively narrow range (Figure 5).

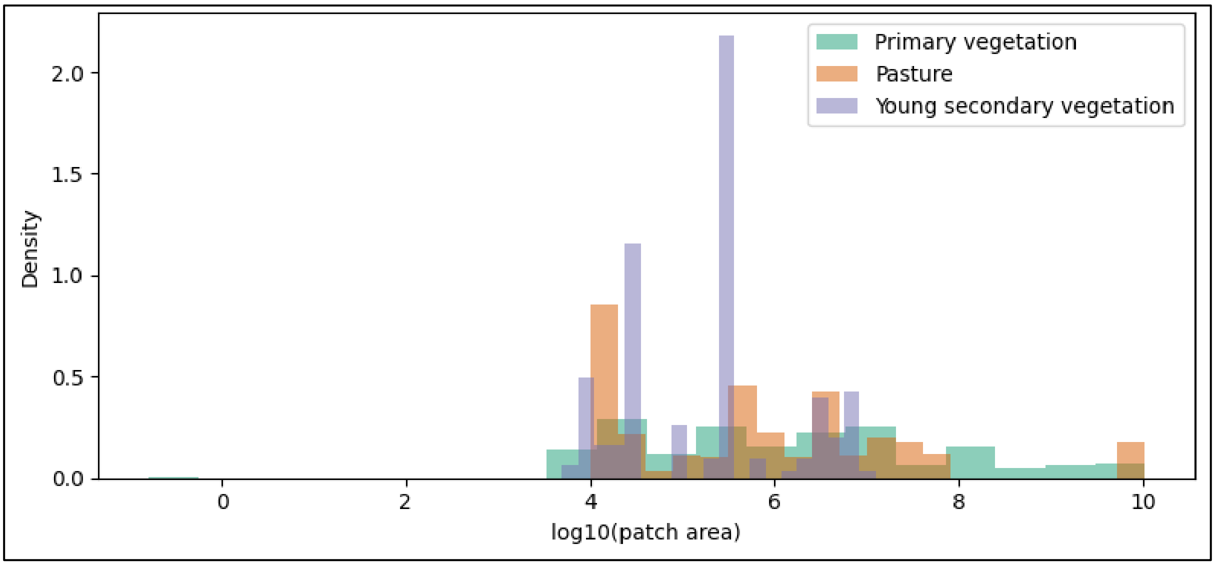

Figure 5. Distribution of habitat patch sizes across major land-use types.

The different distributions give different habitat configuration regimes between land-use categories and give structural context to the interaction effects in the mixed-effects model. Such trends indicate that the degree of fragmentation and geographic distribution vary within land-use regimes in a systematic fashion, which adds to the diversity in the responses to biodiversity.

4. DISCUSSION

The study investigated the relationship between the richness of species and habitat configuration in various land-use and biogeographic settings. Three major patterns were formed. First, there was a patterned latitudinal gradient in the species richness, which suggests that the macroecological position is a source of baseline biodiversity variance. Second, there was a positive correlation between the size of the habitat patch and the richness in the pooled data, indicating that larger habitat patches were likely to lead to high levels of richness. Third, and most importantly, the patch size effect was different across land-use systems, which was reflected by the importance of the interaction terms in the mixed-effects model. Interaction outcomes show that the configuration of habitats does not cause a consistent impact within environmental situations. Although to a large extent, bigger patches meant increased richness, the magnitude and direction of the relationship changed with land-use category. This implies that patch size in itself is not an adequate measure of ecological quality or complexity. Rather, the patch area seems to be correlated with such land-use variables as disturbance intensity, vegetation structure, and management regime. The relationship was loose or less predictable in other land-use systems than in systems where a stronger richness gain was correlated with an increase in patch size. The fact that the latitudinal signal still has a strong effect on biodiversity control after land use and biome identity means that geographic scale gradients still organize biodiversity even with the local habitat setup. In the same way, the fact that productivity has been included in the model implies that the role of energetic context may mediate the response of biodiversity. A combination of these results helps to support the view that biodiversity patterns are generated at the confluence of structural habitat features, land-use environment, and macroecological gradients and not because of an individual driver.

The context-specific effect of habitat configuration in this work is consistent with the prior studies that have established that the dynamics of spatial habitats are to be considered most effectively in cases where configuration measures are combined with ecological models (Wang et al., 2020). The results of studies that evaluate habitat suitability with remotely sensed indicators, including water indices in wetland systems, demonstrate that the quality of habitat can vary across space and time and has an effect on biodiversity responses that are not directly proportional to the area of static patches (Teng et al., 2021). The reduced richness of urban systems is in line with the results that found that urban expansion tends to decrease the quality of natural habitats and the structural integrity (Song et al., 2020). Similarly, analyses of the habitat quality change in land-use change based on spatiotemporal patterns indicate that biodiversity changes may shift with the changes in structures between land-use trajectories, supporting the need to examine configuration across land-use trajectories (Li et al., 2022).

Biodiversity modeling activities have been enhanced by the high-resolution land-cover data, which has enhanced the ability to characterize landscape structure and identify the variations in configuration (Yang and Huang, 2021). Satellite-based measurements of habitats in multi-temporal have also shown that dynamic structural indices can be useful in mapping the habitat of large mammals and other species (Oeser et al., 2020). Likewise, remotely sensed Dynamic Habitat Indices have also been found to be correlated with the richness of bird species, and the example demonstrates that indices based on productivity can account for the changes in the patterns of biodiversity (Hobi et al., 2021). These results justify the fact that productivity and spatial structure have been incorporated in a single analysis framework in the present study. Species-specific conservation research also provides evidence that the effects of habitat configuration are ecological. As an illustration, dynamic open-canopy woodlands have been demonstrated to be important to the conservation of specialist butterflies, indicating that structural quality and structure configuration interact in determining biodiversity results (Habel et al., 2022). Reptiles in arid and semi-arid areas react to habitat degradation depending on the landscape condition and the strength of disturbance, which further highlights the non-uniformity of the habitat-biodiversity interactions (Elbahi et al., 2023). Together, these works indicate the meaning that patch effects are not universally applicable; the effects are dependent on land-use aspects and the environment.

These results indicate that the habitat structure needs a more extensive ecological and land-use framework in the context of determining the biodiversity patterns. The conservation measures based on the size of the patches, with no regard to the type of land use or environmental gradient, can fail to capture the same significant variation in biodiversity response. The combination of structural habitat measures with local ecological data can thus become a more refined system of assessing patterns of biodiversity in heterogeneous landscapes. Another important aspect, which the study identifies, is the importance of interdisciplinary methods integrating ecological information with spatial analysis. Through the study of the habitat structure, macroecological gradients and productivity, variation in biodiversity at different levels can be explained at different levels simultaneously. These integrative models can enhance the comprehension of the landscape structure in the interaction with the larger environmental drivers.

There are certain constraints that one should take into account when reading these findings. The data analyzed is derived through observation, and thus, the associations that are identified should not be understood as direct causal influences. The patch size of habitats can also be correlated with other landscape features, including vegetation status or immediate management activities that were not directly modeled. More so, the representation across the categories of land use was inconsistent throughout the dataset, which can affect the relative accuracy of some estimates. Lastly, species richness is a general measure of biodiversity, and it fails to indicate variation in terms of species structure or functional characteristics. Future studies that would include more biodiversity indices and more descriptions of the habitats should perhaps aid in narrowing down these trends. The temporally explicit land-cover products and dynamic habitat indicators can be included in the studies to capture the changes in configuration over time. It can also be clear if habitat structure interacts with ecological specialization and disturbance sensitivity through further extensions of analyses to other measures of biodiversity and taxonomic categories. Combined with them, these ways would further improve the comprehension of the relationship between habitat dynamics and biodiversity patterns in a wide array of landscapes.

5. CONCLUSION

The broad-scale difference in species richness is constructed by habitat configuration and land-use situation in unison. Richness was found to follow a strong latitudinal gradient and generally positive correlation with habitat patch area across a multi-study dataset on a global scale, although the strength of this correlation varied across land-use systems. It was shown that patch size impacts had context-dependent effects, with some of the altered land uses responding more strongly to increasing patch area than others, and productivity and latitude also added further explanatory structure through mixed-effects modeling. Combined with these patterns substantiate the opinion that habitat patch size is informative about the biodiversity assessment, and its implications should be considered in terms of land-use identity and macroecological gradients. These results emphasize the importance of combining an ecological inference approach with geospatially available measures of habitat in order to gain a better understanding of how habitat dynamics vary across a heterogeneous landscape.

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