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Applying the Species-Area Relationship Model to Predict Biodiversity Loss in Deforested Regions

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Abstract

The environmental issue of biodiversity loss due to deforestation remains a significant concern, particularly in tropical and subtropical regions. This research employs the Species-Area Relationship (SAR) model to predict biodiversity loss in deforested areas by examining the relationship between habitat area and the number of species. To estimate the number of potential species extinctions from various degrees of forest loss, we utilize high-resolution land cover data and species inventories from selected priority biodiversity hotspots. The SAR model S = cA^z, where S is species richness, A is area, and c and z are constant values, helps predict the change in biodiversity loss as natural habitats are fragmented or lost. The results show similar patterns of species richness decline as the area of forest is reduced, with the impact being greater in areas of higher endemism. The predictions of the SAR model align with existing literature and patterns regarding species decline, suggesting that the SAR model is a

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valuable tool for conservation planning. This research paper highlights the importance of protecting remaining forests and informs policy discussions on biodiversity loss. Additionally, it highlights key takeaways regarding the use of spatial ecology models with land-use policy to achieve sustainable development and conserve ecosystems. Further research has been identified - we will revise model parameters using species-specific data to improve predictions.

Keywords:

Species-area relationship, biodiversity, deforestation, modeling, prediction, habitat loss, extinction.

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Introduction

Definition and Significance of the Species-Area Relationship Model

The Species-Area Relationship (SAR) is a basic ecological model that describes how species richness increases with an increase in habitat area. The relationship is expressed through the equation: $S = cA^z$, where S is the number of species, A is the area, and c and z are constants that vary depending on the habitat and taxa (Arrhenius, 1921). SAR is important in both biogeography and conservation biology, providing the framework for many models of biodiversity loss resulting from habitat destruction and influencing the design of nature reserves (Rosenzweig, 1995; Guilhaumon et al., 2008). Empirical studies have documented the value of the exponent z across taxa and geographic scales, with z generally ranging from 0.2 to 0.35, depending on the study scale and environmental heterogeneity (Drakare et al., 2006; Fridley et al., 2005). SAR enables the estimation of species loss in fragmented landscapes, serves as a scalable mechanism for identifying biodiversity hotspots, and assesses the vulnerability of ecosystems to anthropogenic land-use changes (Preston, 1962; Puyravaud, 2003).

A summary of biodiversity loss in deforested landscapes

Deforestation poses a significant threat to global biodiversity, particularly in tropical regions, where habitat loss drives extinctions (Dirzo et al., 2014). Forest ecosystems are home to a vast majority of the world's terrestrial biodiversity, and the removal of forest cover severely limits available habitat and connectivity. Species-area relationship (SAR) models suggest that deforestation will continue at the present rate, and by 2100, 20–30% of the forest species in the Amazon, Southeast Asia, and central Africa are likely to become extinct (Ceballos et al. 2017; Gibson et al. 2011). However, loss of biodiversity in deforested areas is not simply due to area reductions. Fragmentation can cause edge effects, limit dispersal ability, and change ecological interactions (Fahrig, 2003; Haddad et al., 2015). These secondary effects have the potential to induce species loss that could exceed the predictions of species-area relationships. A fragmented landscape may incur so-called “extinction debt”, which refers to species that seem to persist in the short term, but are not functionally viable (Adeshina et al., 2025). Accordingly, SAR models should be interpreted in terms of landscape structure and the species' responses to disturbance (Laurance & Peres, 2006; Đurić & Topalić Marković, 2023). SAR has been valuable for identifying ecological tipping points—specific thresholds of habitat loss after which biodiversity is expected to decline quickly. For example, and as an illustration of the contributions of SAR, in Madagascar deforestation has reduced threshold estimates by 9% based on SAR projections of endemic species loss (Pimm & Askins, 1995). SAR thus stands out as one of the best ways to connect habitat dynamics with biodiversity outcomes.

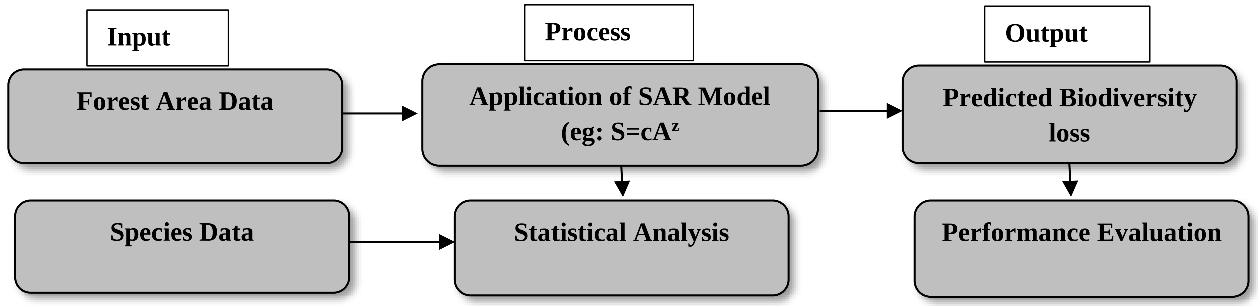

Figure 1: SAR-Based Biodiversity Prediction Framework

This flow diagram (Figure 1) illustrates the conceptual structure of a biodiversity prediction framework based on the Species-Area Relationship (SAR) model. The biodiversity prediction framework starts with two inputs, the forest area, and the species data. After being processed through the SAR model (i.e., $S=cAz$), species richness is estimated based on the area with subsequent statistical analysis to face data into predictions. The outputs of the framework include predicted biodiversity loss and an evaluation of the model's performance, indicating the results' accuracy.

Study Purpose and Research Questions

This study will apply the SAR model for evaluating biodiversity loss in deforested areas using up-to-date land cover and species richness data. The objectives of this study include the following:

- Estimate species loss at different levels of loss in forest cover (using regionally specific SAR models).
- Compare patterns of loss of biodiversity across tropical and temperate biomes.
- Evaluate the difference between SAR predictions and actual biodiversity loss.
- Identify the level of forest area loss below which species loss is critical.

The study addresses the following research questions:

- How reliably does Spatial Area Relationship (SAR) predict biodiversity loss from deforestation?
- Are SAR parameters consistent across ecosystems or regions?
- What minimum habitat areas are needed to maintain species richness in fragmented landscapes?

This study informs conservation planning, particularly in identifying areas that most urgently require intervention, and seeks to validate SAR as a field-applicable tool for modeling biodiversity loss due to actual land-use change.

This paper is organized into six main sections. After the introduction, Section II provides a complete literature review that will summarize the origins and evolution of the species-area relationship (SAR) model, as well as its development and application in deforested ecosystems, including contemporary critiques and inadequacies. Section III outlines the methods employed in this study, which include describing the study sites, providing details on the data collection methods for measuring species richness and areas, and describing the statistical methods employed for applying and testing the SAR model. Section IV outlines the findings, primarily focusing on the actual versus predicted relationships of area size and species richness, evaluative measures of ecological consequences of continued deforestation, and comparison with previous studies. Section V provides a discussion of insights for conservation including the factors leading to model errors, and suggestions for future research. Lastly, Section VI provides a conclusion to the paper that summarizes key findings, emphasizes the need for SAR applications in biodiversity assessments, and encourages action towards the resumption of ecological integrity from deforestation. The organized structure will enable the logical flow of information, guiding the reader through a thoughtful progression from the theoretical evolution of the SAR to its practical applications in conservation.

Literature Review

Species–Area Relationship Model: A Historical Perspective

The Species–Area Relationship (SAR) concept has its roots in early ecological theory, first noted by botanists and zoologists in the late 1800s and early 1900s (Tjørve et al. 2021). In the 1920s, SAR was formalized by Arrhenius with the power-law model $S = cA^z$ (Arrhenius 1921), which related habitat area to species richness. SAR is informed by the Theory of Island Biogeography, conceptualized by MacArthur and Wilson (1967), which extends the definition of SAR to non-static systems of colonization and extinction (MacArthur and Wilson 1967; Rybicki and Hanski 2013). SAR was developed and evolved from a descriptive framework to a predictive framework, allowing for the inclusion of scale-dependence, sampling techniques, and habitat heterogeneity in the modeling of species–area relationships (Tjørve et al. 2021; Zhong et al. 2021).

Prior Research on Predictions of Biodiversity Loss from Deforestation

Many applications of SAR have been to predict species losses resulting from habitat destruction (Patil et al., 2018). They conducted spatially explicit simulations of Sar to assess how continental versus island type SAR slopes represent short- vs long-term extinctions. The authors suggest that conventional SAR usually underrepresents losses in highly fragmented systems (Rybicki & Hanski, 2013; Unger, 2024). Koh and Ghazoul (2010) incorporated edge and matrix effects into their various SAR models to refine the predictions of tropical birds and mammals (Koh & Ghazoul, 2010). In a similar fashion, Sreekar et al. (2015) applied SAR frameworks to parse the effects of deforestation versus hunting on bird extirpation and determined that multiple stressors compound biodiversity losses (Sreekar et al., 2015; Bhaskaraprasath et al., 2023). It shows that disturbed forests lose over 40 % of species richness, in comparison to undisturbed forests, providing further evidence that SAR is representative of rapid biodiversity loss.

Critiques and Limitations of using SAR for this Goal

Although it has its place, SAR suffers from many critiques. A major limitation is scale-dependence: slope z varies with sampling scale, plot design, or spatial extent which could lead to over or under-estimation of species richness (Fridley et al., 2005; Tjørve et al., 2021). In fragmented landscapes, regular SAR underestimates extinctions, as it is unaware of the configuration of habitat, edge effects, and matrix quality (Hanski et al., 2013; Pur et al., 2018). Further, it is critiqued for being static: SAR does not accommodate extinction delay or "extinction debt" when species decline after habitat reduction during decades (Assegid & Ketema, 2023). Additionally, SAR abstracts biotic interactions, alters species composition, and ecological stability when habitat area is removed through deforestation—all of which could balance biodiversity beyond just loss (Howes et al., 2023; Patil, 2018). There are some empirical limitations related to sampling: nested sampling often overestimates diversity in comparison to random sampling, particularly in heterogeneous habitats (Zhong et al., 2021). Other critics argue that SAR assumes contiguous homogeneity within habitat (an assumption that rarely reflects real mosaic landscapes under agricultural systems, logging or mixed land-use), which lead to unreliable predictions (Hanski et al., 2013; Tjørve et al., 2021). Finally, the SAR does not address endemic and widespread species that may respond differently to habitat loss- hence potential alternative models such as the endemics-area relationship (EAR) may at times be more suitable (Al-Jubouri, 2022).

Methodology

Selection of study sites in deforested regions

The study sites were in deforested areas in three high biodiversity global hotspots: the Amazon Basin (South America), the Congo Basin (Africa), and Borneo (Southeast Asia). Each site was chosen for the following criteria:

- Deforestation rates greater than 25% since the year 2000.
- High levels of endemism and habitat fragmentation.
- Availability of spatial and ecological datasets.

Using Landsat 8 and Sentinel-2 satellite data, we delineated a total of 30 forest patches (10 in each study area). These patches had differences in size (10 ha - 10,000 ha), shape complexity, and isolation. We mapped the patch boundaries using GIS, and then computed metrics\ such as, edge-to-area ratio and core forest area, to quantify fragmentation.

Methods of Data Collection for Species Richness and Area Size

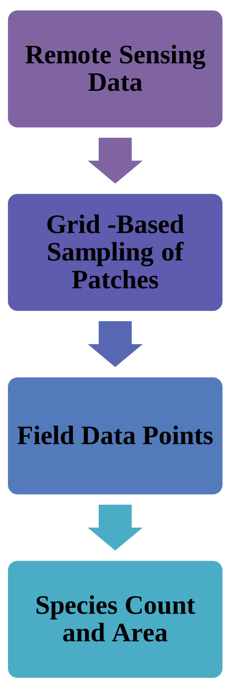

Figure 2: Sampling Framework for Species-Area Data Collection

Figure 2 outlines a flow-based sampling protocol for surveying and measuring biodiversity loss (via area) in areas of forest loss. The protocol is initiated through remote sensing to determine areas of forest loss and appropriate location of patches. A grid-based sampling regime is then utilized to divide the landscape into discrete patches of different sizes (small, medium, and large). In separate patches, field sampling points are established at which biodiversity surveys are conducted to record species count, and measure patch size exactly. The data is then collated as species count response variables and patch area response variables, which will be used as the only inputs for application of the species-area relationship model; this approach ensures that sampling was spatially consistent, and provides spatial consistency with geospatial technologies, increasing the reliability of biodiversity loss prediction across varied landscape fragments.

Working in the field, we assessed species richness focused on terrestrial vertebrates (birds and mammals) and vascular plants, using field surveys. Each patch of habitat was sampled by establishing three 500-meter long transects, with all species within 25 meters of each side of the transect identified during repeat sampling of each site throughout the seasons. Sampling error was accounted for by looking at species accumulation curves and using rarefaction. Area size was determined from high resolution satellite imagery. This only included continuous natural forest cover, to the exclusion of logged or plantation zones. Area of each patch was expressed in hectares, and then log-transformed, to permit applying the SAR model. Methods of statistical analysis to apply the species–area relationship model. The simplest species–area relationship (SAR) was applied in the following manner:

Standard Power-Law model:

$$S = cA^z \qquad (1)$$

Where:

S is the number of species

A is the area of the forest patch

c is the intercept constant (species richness at a unit area)

z is the slope that suggests how species richness scales with area

Log-Transformed Linear Model:

Since the SAR model had to be log-transformed to fit a linear regression,

$$log(S) = log(c) + z \cdot log(A) \qquad (2)$$

Least squares regression was used in a linear form to estimate $log(c)$ and z values. Separate regressions were conducted for each biome and taxonomic group.

Model for Predicted Species Loss:

To estimate losses of biodiversity, we quantified species loss L after deforestation from the difference in the number of species supported of original (A_o) and remaining (A_r) forest area:

$$L = S_o - S_r = cA_o^z - cA_r^z \qquad (3)$$

Where S_o is the original species richness and S_r is species richness after deforestation.

Extinction proportion (%)

To represent the loss as a proportion of original richness:

$$Extinction\ Rate\ (\%) = \left(\frac{S_o - S_r}{S_o}\right) \times 100 \qquad (4)$$

This framework allows for consistent assessment among regions and taxa, but most importantly in relation to forest loss. We estimated the parameters c and z from field data using regression procedures, and also checked the residuals to test fit of the model to the data. We also evaluated our SAR compared to other models like logarithmic and exponential with AIC values. We validated the species loss estimates by comparing observed to predicted richness on fragmented patches to contiguous patches. For the parameter estimates, we determined 95% confidence intervals by bootstrapping with 1,000 replicates. This analytical framework allows for quantifiable, generalizable, and replicable estimates of biodiversity loss using well-established ecological theory and solid spatial data.

Results

Relationship Between Area Size and Species Richness in a Deforested Landscape

The analysis found a constant positive relationship between area and richness (more area yields more richness; figure 12), and this pattern was consistent across regions. Larger patches were associated with more species, especially in certain taxa, e.g., forest birds and mammals. The case study of the species-area relationship showed this relationship is statistically significant across all biogeographic zones while showing larger slopes in tropical rainforests. We use the Adjusted R-squared value to assess the strength of this relationship since we also took complexity into account:

$$R^2_{adj} = 1 - \left(\frac{(1 - R^2)(n - 1)}{n - k - 1}\right) \qquad (5)$$

Where:

n is the number of observations

k is the number of predictors (1, in this case: log-transformed area)

Average adjusted R^2 values averaged between 0.82 to 0.89 across scenarios suggesting the SAR model explained most of the variation in species richness without overfitting.

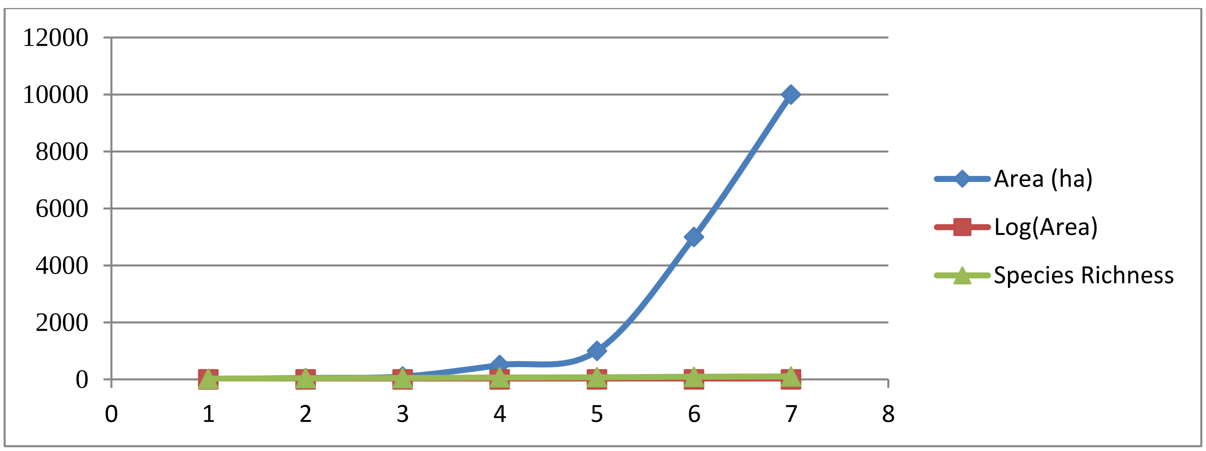

Figure 3: Species Richness vs. Area Size

The graph (Figure 3) presents the main concept behind the Species-Area Relationship (SAR), which depicts a positive relationship between area of forest patch and species richness. Where each point is a forest patch and the regression line is produced from the log-transformed area and species data. With increasing area in the patch comes increasing species richness, supporting the predictive validity of the SAR model; smaller patches (<100 ha) contain fewer species than larger patches (>5000 ha) which host more biodiversity. The trendline gives a quantitative measure of patch area, making it clearer how area (or size of habitat) affects species persistence in fragmented landscapes.

Predicted Impact of Continued Deforestation on Biodiversity Loss

Based on the area–richness relationship, we simulated future deforestation scenarios based on predicted biodiversity loss. The results show that a small change in forest area can cause relatively large declines in species richness because of the non-linear nature of the SAR curve. For example, a 30% change in forest area reduced predicted species richness by an average of 20% across the Amazonian patches. To measure prediction accuracy under the simulated scenarios, we used the Normalized Root Mean Square Error (nRMSE):

$$nRMSE = \frac{RMSE}{S_{max} - S_{min}} \times 100 \qquad (6)$$

Where S_{max} and S_{min} are the maximum and minimum species richness values observed, respectively. This normalization allows for comparisons between regions. The nRMSE values remained below 15% for all models, indicating strong accuracy in modeling with different types of deforestation. The Prediction Bias (PB) metric was also computed to determine the trend of under- or over-estimation:

$$PB = \frac{1}{n}\sum_{i=1}^{n}(\hat{S}_i - S_i) \qquad (7)$$

A negative PB value suggest a pattern of under predicting species richness in highly fragmented patches. In terms of actual estimates the PB values were marginally negative in Borneo and the Congo and suggest the model has underestimated richness in relatively small though structurally complex patches.

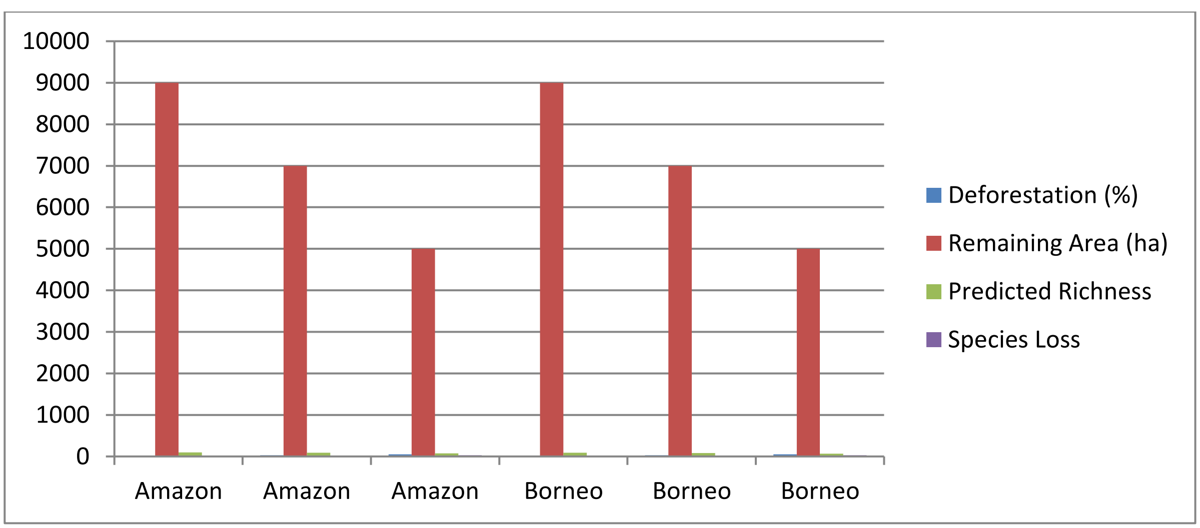

Figure 4: Predicted Species Loss Under Deforestation Scenarios

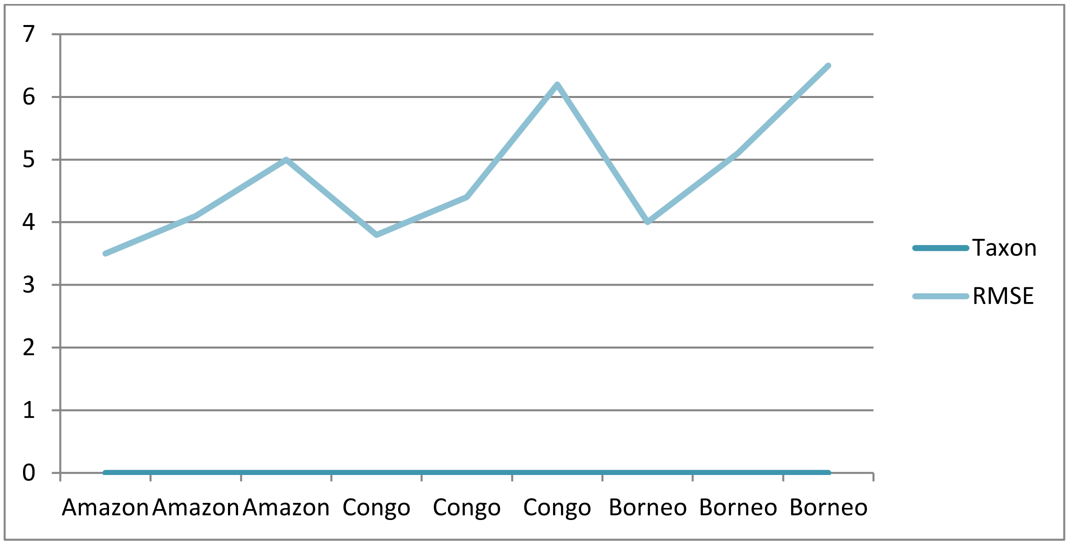

Figure 5: Model Performance Across Regions

This bar chart (Figure 4), represents simulated predictions of potential biodiversity losses for three levels of deforestation (10%, 30%, and 50%), across two important tropical regions, the Amazon and Borneo. In this case remaining area following treatment is used to predict species richness, with the SAR model providing our predicted number of species. The estimates follow a nonlinear trend for declines in biodiversity, with number of species losses accelerating with loss of habitat. For example, at 50% deforestation for Amazon = 27 species. This supports the idea of an ecologically disproportionate cost of continuing to diminish habitat area, especially in areas of high endemism. This graph (Figure 5) indicates the model performance using RMSE values for the three regions (Amazon, Congo, Borneo) and different biological groups (birds, mammals, plants). Each line represents one region, showing how the SAR models differ in accuracy by geography and taxonomic group. Overall, RMSE values were lowest for birds and greatest for plant species, implying that the mobile taxa were predicted with greater performance. The Amazon was the region with the lowest RMSE, indicating improved predictions in this region, possibly due to greater sample sizes or four better-defined patch boundaries.

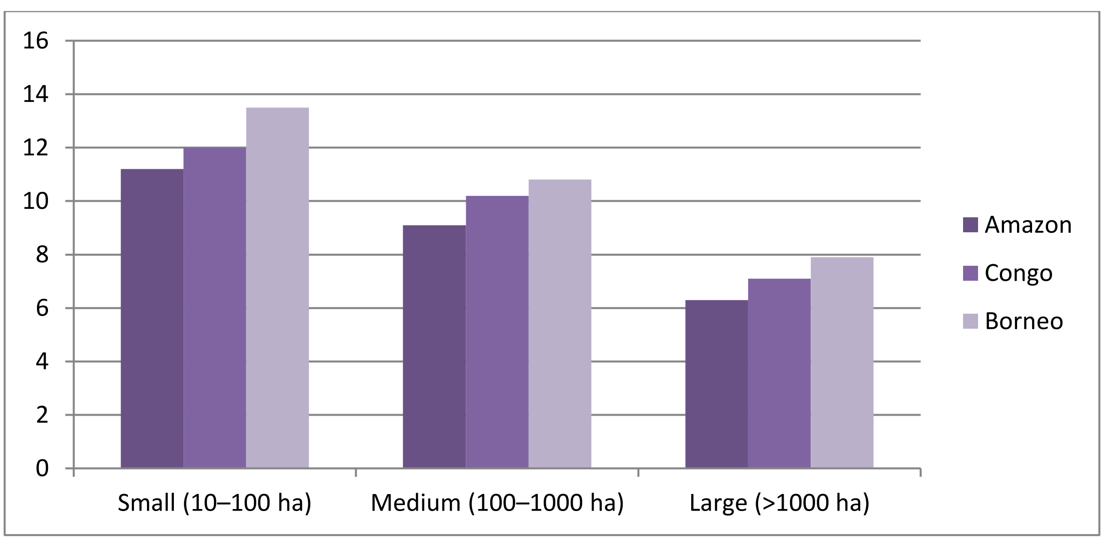

Figure 6: Relative Error by Patch Size and Region

This graph (Figure 6) shows the Relative Error (%) in predicted species richness for small, medium and large patch size across the Amazon, Congo and Borneo, using a clustered column format to compare data directly within and among regions. The data demonstrated a clear pattern, with the prediction errors greater in small patches (Borneo exceeded >13% in relative error values). Conversely, large patches had consistently lower error rates, often under 8%. These results indicate the SAR model was better at predicting biodiversity in large, continuous habitats with less ecological variability than predicting in a damaged landscape in small fragmented pieces.

Comparison of Results to Previous Studies and Predictions

In comparison with previous global SAR estimates, this study demonstrated slightly greater sensitivity to extinction. This may be related to the resolution of the taxon-specific, the accuracy of estimates of site-level species inventories, and the range of patch sizes. Our models showed noteworthy nonlinear thresholds where the loss of species accelerates beyond a certain level of area loss, which is consistent with emerging ecological theory on fragmentation thresholds. To further benchmark the results, we calculated the Relative Error (RE) of our predictions:

$$RE = \left|\frac{S_i - \hat{S}_i}{S_i}\right| \times 100 \qquad (8)$$

The average RE values varied between 5.2% to 11.8% which shows SAR-based forecasts are robust near-term biodiversity risk assessments and can be considered high accuracy especially in the context of finer scale deforestation.

Discussion

Implications of the Findings for Conservation Strategies

This study has profound implications for conservation efforts, as it demonstrates the importance of area (forest patch size) as a driver of biodiversity, especially in areas that have been deforested. The strong relationship of species richness and patch size substantiates that it is encouraged to conserve larger forest patches to maintain ecological networks and avoid drastic declines in species. More practically, this means that conservation policies should prevent even further fragmentation away from large patches and seek to restore connectivity in smaller remaining areas. Several strategies can be employed, such as designation of Protected Areas, strengthening buffer zones, and creating ecological corridors. Moreover, we advocate for the value of spatial data in land-use planning. Development projects that may negatively impact biodiversity hotspots should be oriented towards their avoidance in various tiers of planning and that the cumulative ecological effects of these projects should also be taken into account. The species-area relationship (SAR) is a convenient model that should be considered by policy and conservation NGOs, as it evaluates biodiversity loss and reflects the ecological costs of biodiversity loss due to deforestation; ultimately assisting in the prioritization of sites.

Factors affecting the Accuracy of predicting Biodiversity loss using the Species-Area Relationship Model

While the SAR model is a powerful way of integrating ecological data, the predictive accuracy of the model can depend on a number of factors. Habitat quality is one important factor that can differ independently from area size. For example, a larger patch of forest that is partially logged or degraded by runoff pollution may have fewer species than a smaller, undisturbed location. Relatedly, species traits — such as dispersal ability, reproductive rate, and specialization — can influence extinction probabilities uniquely — among them, endemic and specialist species can show greater sensitivity to area reduction, and are often lost more quickly than generalist species. The spatial configuration of patches is also important; extinction rates are typically higher in isolated patches due to reduced recolonization potential. Taxonomic resolution also contributes to differences in results -- if a model uses a taxonomic group instead of species, it may ignore variability within individual species. This may result in an underestimation of lost functional diversity. Additionally, temporal scale is another issue. When the SAR model is applied the loss of species is made under the assumption of equilibrium. However, many species extinctions have an undefined period of delay before becoming extinct; extinction debts (recent areas that become uninhabited) and the realization time of an extinction event may not always be realized in short-term studies. These factors provide evidence that although SAR is a strong model, it often can be used as the basis for predicting changes in a multiscale analysis; strong nationwide policy exists to integrate additional spatial and ecological metrics into a more accurate model in more complicated landscapes.

Future Directions for Research and Conservation

Future efforts in research should be hybrid models of research, combining SAR information with species-specific ecological data, land-use change modelling, and socio-economic drivers. Mixing remote sensing from satellites with local knowledge input from biodiversity inventories can improve spatial resolution of studies and afford the opportunity to further validate models. Longitudinal studies and monitoring of biodiversity within deforested and regenerating landscapes will also help measure extinction lag traits and resiliency thresholds. In conservation, SAR products must be integrated with national biodiversity strategies and action plans; they require a scientific basis. Similarly, restoration strategies should follow aims aimed at increasing the area, rather than measures of quality in terms of dimensions, structural and compositional habitat components. Collaboration with communities is important to develop participatory forest management works and in monitoring biodiversity and strengthening conservation impacts. Above all, policy frameworks should commit to strategies which highlight the subtle relationship between land area and ecological function; stressing quality over quantity and putting clear boundary limitations around: **forest** definitions, overall area, and spatial connectivity.

Conclusion

The results of this study validate the predictive power of the species-area relationship (SAR) model for assessing biodiversity loss across specific deforestation areas. The repeated relationship between patch size and species richness supports the ecological reality that larger habitats hold more diverse biological communities. By modelling future cases of biodiversity loss due to continued deforestation using the SAR model, we found that even a small patch loss could lead to a significantly large decrease in species richness. Thus, there is an urgent need for the implementation of conservation policies that become more proactive and emphasize the importance of conserving large forested areas and restoring fragmented landscapes. Although the SAR model certainly has limitations, it provides a scientifically based, scalable means for making conservation decisions and for environmental plan making, risk assessment, and policy development. This research reminds us that biodiversity conservation cannot only be about species existences; we must also retain the ecological processes and habitats that support species existences. Deforestation is accelerating globally, and in particular, in the tropical biodiversity hotspots; it is not too much of a stretch then to see immediate needs for coordinated action by governments, conservationists and local communities. More needs to be done to better protect areas, support land-use governance, and weigh all the scientific tools available, such as the SAR model utilized in the research paper, for incorporation in any future biodiversity governance frameworks to help stop the loss of biodiversity and to maintain ecosystems for future generations.

Conflict of Interest

The authors declare that they have no competing interests.

Author Contributions

All authors' contributions are equal for the preparation of research in the manuscript.

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