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A case of non-metric multidimensional scaling of alpha (α), beta (β) and gamma (γ) biological diversity across the diverse forest habitats

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Abstract: The ecological intricacies that govern biodiversity is an essential understanding for the effective conservation of natural ecosystems. The study examines the impact of different forest habitats i.e. forests, rivers, and tourist areas on biodiversity across trees, birds, mammals, reptiles, and invertebrates. Field data were collected from 90 plots using various methods, such as quadrat sampling for trees, circular strip transects for aves, and live trapping for mammals and reptiles. Biodiversity indices (alpha, beta, gamma) were analyzed using the R programming environment, employing the vegan and iNEXT packages. Results revealed significant differences in species richness and composition among habitats. Forests exhibited high alpha diversity indices, with values of 86 for trees, 104 for aves, and 46 for mammals. River-associated forests showed increased species richness and evenness, with notable beta diversity, especially for invertebrates. Conversely, tourist areas displayed reduced species richness and slightly lower alpha diversity indices for trees and invertebrates. The Shannon diversity index was highest for trees (3.60) and lowest for invertebrates (1.00), highlighting the negative impact of human activities in tourist areas. Games-Howell tests and NMDS confirmed significant variation in species distributions between habitats, with rarefaction curves indicating the highest richness in forests. The study also linked conservation efforts, such as reforestation and anti-poaching activities, to improvements in biodiversity. Recommendations include prioritizing the protection of high-biodiversity areas, habitat restoration, ongoing monitoring, public education, and strict enforcement of environmental policies. These strategies are essential for enhancing biodiversity conservation and maintaining ecological integrity. The findings provide critical insights into the relationship between habitat types and biodiversity, supporting effective conservation and management practices.
Keywords: Biodiversity, iNEXT, Kaptai National Park, Forest ecology, NMDS, Rarefaction

Farklı orman habitatlarında alfa (α), beta (β) ve gama (γ) biyoçeşitliliği üzerine metrik olmayan çok boyutlu ölçeklendirme analizi örneği

Öz: Doğal ekosistemlerin etkin korunabilmesi için biyoçeşitliliği yöneten ekolojik inceliklerin anlaşılması önem arz etmektedir. Bu çalışma, ormanlar, nehirler ve turistik alanlar gibi farklı orman habitatlarının ağaçlar, kuşlar, memeliler, sürüngenler ve omurgasızlar arasındaki biyolojik çeşitlilik üzerindeki etkisini incelemektedir. Saha verileri, ağaçlar için kuadrat örnekleme, kuşlar için dairesel şerit transektler ve memeliler ve sürüngenler için canlı yakalama gibi çeşitli yöntemler kullanılarak 90 parselden toplanmıştır. Biyoçeşitlilik endeksleri (alfa, beta, gama) R programlama ortamı kullanılarak vegan ve iNEXT paketleri ile analiz edilmiştir. Sonuçlar, habitatlar arasında tür zenginliği ve kompozisyonunda önemli farklılıklar olduğunu ortaya koymuştur. Ormanlar, ağaçlar için 86, kuşlar için 104 ve memeliler için 46 değerleriyle yüksek alfa çeşitlilik endeksleri sergilemiştir. Nehirle ilişkili ormanlar, özellikle omurgasızlar için kayda değer beta çeşitliliği ile birlikte artan tür zenginliği göstermiştir. Buna karşılık, turistik alanlar, ağaçlar ve omurgasızlar için tür zenginliğinde azalma ve biraz daha düşük alfa çeşitliliği indeksleri göstermiştir. Shannon çeşitlilik endeksi ağaçlar için en yüksek (3.60) ve omurgasızlar için en düşük (1.00) değerde olup, turistik bölgelerdeki insan faaliyetlerinin olumsuz etkisini vurgulamaktadır. Habitatlar arasındaki tür dağılımlarında önemli bir varyasyon olduğunu doğrulamış, seyrekleşme eğrileri ise en yüksek zenginliğin ormanlarda olduğunu göstermiştir. . Çalışma ayrıca ağaçlandırma ve kaçak avcılıkla mücadele faaliyetleri gibi koruma çabalarını biyoçeşitlilikteki iyileşmelerle ilişkilendirmiştir. Öneriler arasında yüksek biyoçeşitliliğe sahip alanların korunmasına öncelik verilmesi, habitat restorasyonu, sürekli izleme, halk eğitimi ve çevre politikalarının sıkı bir şekilde uygulanması yer almaktadır. Bu stratejiler biyolojik çeşitliliğin korunması ve ekolojik bütünlüğün sürdürülmesi için elzemdir. Bulgular, habitat türleri ve biyoçeşitlilik arasındaki ilişkiye dair kritik bilgiler sunarak etkili koruma ve yönetim uygulamalarını desteklemektedir.
Anahtar kelimeler: Biyoçeşitlilik, iNEXT, Kaptai Milli Parkı, Orman ekolojisi, NMDS, Seyreltme

1. Introduction

Kaptai National Park (KNP) is a vital protected area in Bangladesh's Kaptai Upazila of the Rangamati Hill District, spanning 5,464.78 hectares. Established in 1999, the park aims to protect its rich biodiversity (Rahman et al., 2020), which has been threatened by human activities and environmental changes. The transition of the Kaptai forest into a national park brought stricter regulations, causing tension between the local communities, who depend on the forest for their livelihoods, and park managers (Ahsan and Haidar, 2017; Hasan et al., 2023). This situation illustrates

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the delicate balance between conservation efforts and the needs of local people, emphasizing the importance of collaborative management strategies. Historically, Kaptai National Park was known as the Sitapahar Reserve, covering 14,448 acres (Abdullah et al., 2022; Chowdhury et al., 2018). Local communities used this land for subsistence until the 1960s when the Kaptai hydroelectric dam was built, displacing thousands of people to the forest's outskirts and interior. These communities relied on the forest for agriculture, fishing, bamboo and handloom crafts, and jhum cultivation (a traditional form of shifting agriculture), increasing pressure on forest resources. The situation worsened in 1975 due to armed conflicts between local tribes and the Bangladesh government. In response, the government designated the area as Kaptai National Park in 1999 to protect the forest by limiting human activities. While crucial for conservation, this move restricted local communities' access to forest resources, leading to tensions (Abdullah et al., 2018; Chowdhury et al., 2019). To address these conflicts, Bangladesh adopted a forest co-management system that involves local communities in decision-making, recognizing their essential role in conservation. As of 2016, 17 of Bangladesh's 49 protected areas operate under co-management frameworks, with Kaptai National Park being a key example (Rahman et al., 2017a). This approach aims to balance ecological preservation with the socio-economic needs of forest-dependent populations, fostering cooperation and shared stewardship.

Kaptai National Park features mixed evergreen forests, diverse wildlife, and significant water bodies, including Kaptai Lake and the Karnaphuli River. These natural resources support the park's biodiversity and provide essential services to residents (Reza, 2010; Reza and Perry, 2015). The park's moist tropical climate, characterized by high annual rainfall and a pronounced monsoon season, influences its ecological dynamics and management Challenges. The Park’s biodiversity is remarkable, with a variety of plant and animal species. The plant life includes teak (*Tectona grandis*), garjan (*Dipterocarpus turbinatus*), and several bamboo (*Bambusa sp.*) and cane (*Saccharum sp.*) species. The fauna includes numerous bird species like sparrows (*Passer domesticus*), egrets (*Ardea alba*), and kingfishers (*Alcedo atthis*), and mammals such as elephants (*Elephas maximus*), barking deer (*Muntiacus muntjak*), and gibbons (*Hylobatidae sp.*) (Hasan, et al., 2023; Miah et al., 2023; Reza, 2010; Reza and Perry, 2015). The park's aquatic ecosystems, especially Kaptai Lake, support a significant fish population, vital for many local residents' livelihoods. The management of Kaptai National Park has evolved to address both conservation and community needs. The Integrated Protected Area Co-management (IPAC) project, launched in 2009, integrates local communities into the park's stewardship (Chakraborty et al., 2021; Nolan and Callan, 2006; Rahman et al., 2017b; Smith et al., 2020). This project promotes the sustainable use of resources while protecting the park's ecological integrity, aiming to resolve conflicts and enhance conservation efforts. Kaptai National Park exemplifies the broader challenges and opportunities in conservation management. Its journey from a reserved forest to a contested protected area, and finally to a co-managed park, reflects ongoing efforts to balance human needs with ecological preservation. By involving local communities in management, the park aims to achieve a sustainable balance, ensuring the protection of its invaluable biodiversity while supporting the livelihoods of those who depend on its resources (Alam et al., 2019; Chowdhury et al., 2018; Rahman et al., 2020; Uddin et al., 2020).

This study aims to assess biodiversity across different forest habitats within Kaptai National Park, Bangladesh, employing tailored ecological methods. It focuses on quantifying species richness, abundance, and diversity indices for trees, birds, mammals, reptiles, and invertebrates in the general forest, river-associated, and tourist-associated areas. Utilizing rigorous sampling techniques like quadrat sampling, transect surveys, live trapping, and pitfall traps, the research aims to elucidate biodiversity patterns influenced by habitat types and human activities. Statistical analyses using R programming will evaluate these patterns, correlating biodiversity metrics with conservation efforts. Ultimately, this study seeks to inform habitat-specific conservation strategies crucial for preserving Kaptai National Park's rich biodiversity amidst environmental and anthropogenic pressures.

2. Material and Methods

2.1. Study region

Kaptai National Park, established in 1999, is a major national park in Bangladesh, located in the Rangamati district and covering a vast 5,464.78 hectares (Rahman et al., 2020). It is part of the Rangamati Hill Tracts (South) Forest Division, which was formed by splitting the Chittagong Hill Tracts Forest Division. The Park includes six forest reserves and is also part of the Rampahar Reserve Forest of the Chittagong South Forest Division. Geographically, it is situated in the Kaptai Upazila of the Rangamati Hill Tract district, northeast of Chittagong city. The Park is divided into two forest ranges: the Kaptai Range and the Karnaphuli Range. It lies between the geographical coordinates of 20°30'1.3" N and 22°10'18.2" N latitude, and 92°10'11.9" E and 92°17'0" E longitude (Chowdhury et al., 2018; Dutta et al., 2015; Sharashy, 2022).

KNP stands out for its diverse flora and fauna and plays a crucial role in the conservation of the region's rich biodiversity (Das et al., 2016). Its establishment was aimed at protecting this biodiversity from threats posed by human activities and environmental changes, ensuring the park remains a haven for numerous plant and animal species (Sharashy, 2022).

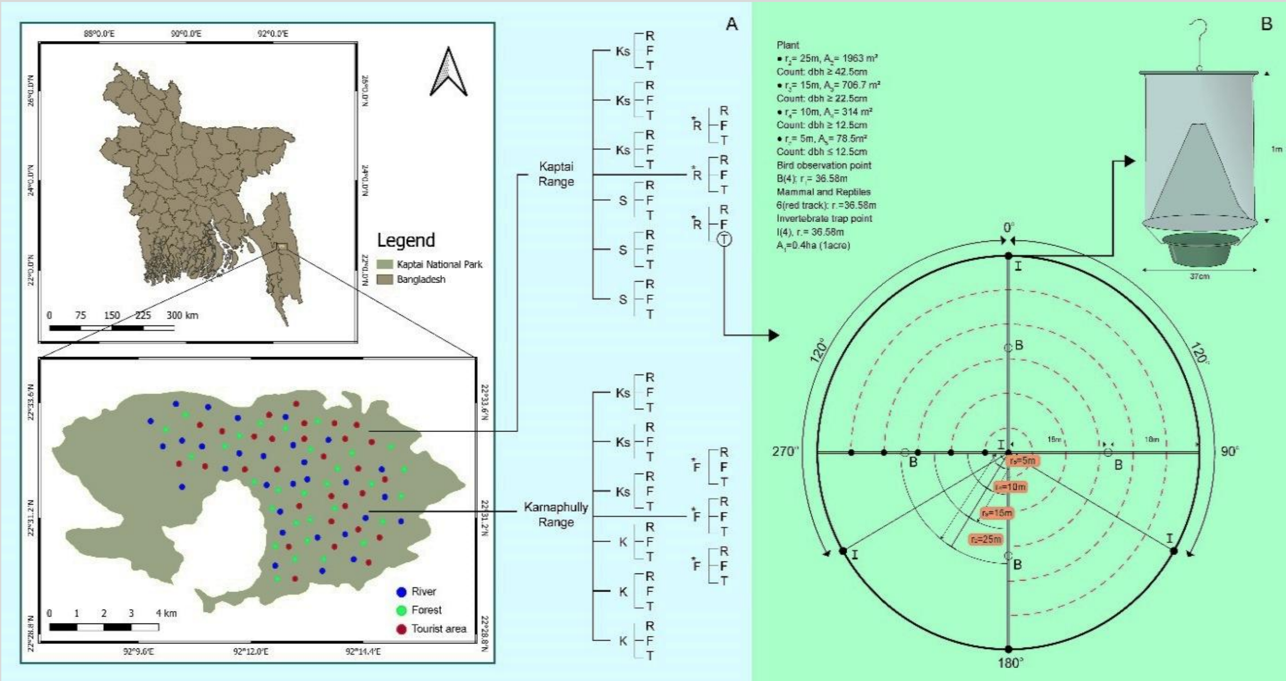

Figure 1. Biodiversity study in Kaptai National Park, Bangladesh: survey locations and methodological overview

2.2. Sampling design and biodiversity sampling

In ecological research, various methods are employed to effectively study different species groups. The top-left section of the map (Figure 1) illustrates the geographic location of the park within the country, with an inset showing key ecological features such as forests (green areas), tourist zones (red dots), and rivers (blue dots). Sampling took place in two main ranges: the Kaptai Range and the Karnaphuli Range. These areas were further divided into three ecological zones—river-associated (R), forest-associated (F), and tourist-associated (T)—to capture biodiversity variations across different environments (Scherer et al., 2023). The study ensured a comprehensive representation of biodiversity by sampling a variety of ecological niches (Karl et al., 2024).

The research uses a multi-scale sampling strategy to assess biodiversity in Kaptai National Park. Plant sampling is organized into quadrats of varying sizes depending on species and size classes. For trees with a diameter at breast height (DBH) of ≥ 42.5 cm, a 25 m radius (A = 1963 m²) is used (Scherer et al., 2021). This larger plot size is designed to capture mature, large trees and ensure the sampling area is large enough to account for the spatial distribution of such individuals (Yousefiard et al.,2024). For smaller trees with DBH ≥ 22.5 cm, a 15 m radius (A = 706.7 m²) is applied (Mahata et al.,2024), providing a more appropriate scale for mid-sized trees while still encompassing a sufficient number of individuals (Bredemeier et al., 2007). For those with DBH ≥ 12.5 cm, a 10 m radius (A = 314 m²) is used, which is suitable for smaller trees and saplings that require less area for accurate representation. Saplings and smaller plants are sampled within a 5 m radius (A = 78.5 m²), appropriate for capturing young plants with smaller spatial distributions (Scherer et al., 2021). These nested plot sizes ensure accurate sampling of all plant categories, from mature trees to saplings, and are designed to be flexible enough for different species.

Bird observation points are placed at a radius of 36.58 m, enabling effective surveying of avian species within a standardized area. The larger radius helps to encompass a broader view of the habitat, improving the likelihood of detecting bird species across the varied ecological zones. Mammal and reptile sampling involves tracking (with a radius of 36.58 m) to record signs of their presence, such as footprints or droppings. This radius is sufficient to capture a wide range of mammal and reptile species, which may have larger home ranges. Invertebrates, including insects, are monitored using pitfall traps within the same radius. Each trap point follows a 36.58 m radius as well, ensuring consistent data collection across all species groups.

To maintain consistency, the total sampling area is standardized to 0.4 ha (1 acre) across all ecological zones, ensuring comparability and uniformity of data across plant, bird, mammal, reptile, and invertebrate sampling. This standardization facilitates precise biodiversity and ecological assessments in the study area.

Sampling methods for different species groups were tailored accordingly. Plant sampling, including trees, shrubs, and herbs, used 25 m² circular plots to ensure standardized data collection. In each plot, species composition, tree height, DBH, and canopy coverage were recorded. Herbaceous plants were assessed within 1 m² subplots within the larger quadrats. This method allows for detailed assessments of herbaceous diversity while minimizing disturbance to larger trees. Bird surveys were conducted using circular strip transects, with observation points at the center of circles with radii of 12.5 m and 25 m, enabling systematic monitoring of bird species across different habitats. The combination of these varied plot sizes ensures a comprehensive approach to biodiversity assessment, covering different plant and animal groups across a range of spatial scales (Figures 1).

2.3. Data analysis

The study focused on assessing biodiversity across three different forest habitats.Forest areas were defined as regions within a meter of the buffer zone, river-associated forest areas as 30 meters from the river's edge, and tourist-associated forest areas included all relevant sections. Data were systematically collected from 90 plots (Brockerhoff et al., 2017; Rahman et al., 2016; Reza, 2010; Reza and Perry, 2015; Scherer et al., 2021), with each habitat containing 6 plots for each group of species (trees, birds, mammals, reptiles, and invertebrates), resulting in a total of 18 plots per group (Figure 1). The data were analyzed using the R programming environment. Biodiversity indices such as abundance, evenness, and the Shannon and Simpson indices (Table 1) were calculated using the vegan package (Miah et al., 2023; Nolan and Callan, 2006). Visualizations were created using the ggplot2 package, and the Games-Howell and Welch tests were applied to generate violin plots that illustrate biodiversity variations across habitats while accounting for variation in plot size. Further statistical analysis was conducted using the iNEXT package, including one-way ANOVA to explore biodiversity differences. The study also examined the impact of conservation efforts by correlating diversity metrics with factors like reforestation projects and anti-poaching patrols (Smith et al., 2020) following methodological framework in Figure 2.

Preliminary results showed significant differences in biodiversity among the habitats, with river-associated forests exhibiting higher species richness and evenness, likely due to their proximity to water bodies. These findings highlight the importance of tailored conservation strategies and emphasize the need for habitat-specific management practices to enhance biodiversity conservation effectively.

3. Results

3.1. Comparison of site alpha, beta, and gamma diversity

In examining the tree communities across forest, river, and tourist areas, the study found that the distribution of tree species was quite uniform. The evenness analysis revealed no significant differences between these habitats, with p-values of 0.319 across the habitats. This means that tree species are spread out similarly in all three habitats. When looking at diversity indices, both forest and river habitats had an alpha diversity index of 86 (Majumdar et al., 2014), while the tourist area was slightly lower at 84. This indicates a consistent number of unique tree species in each habitat, with the tourist area having just a bit less diversity. The beta diversity index, which measures differences in species composition between habitats using Bray-Curtis dissimilarity, showed moderate to significant differences. This means that while the number of species might be similar, the actual types of species vary between the habitats. Overall, the gamma diversity index, which considers unique species across all habitats, was 46. This suggests a moderate level of species uniqueness across the different environments, indicating a fair amount of diversity within the tree populations studied (Figure 3).

Table 1. Equation used in the analysis

No.	Equation
1.	$\alpha_{r\,f\,t} = \Sigma$ Abundance $\alpha_{r\,f\,t}$
2a.	$\beta_{r\sim f} = \Sigma\, A_r \sim A_f \mid \beta_{r\sim f} = \Sigma \mid A_r \sim A_f \mid$
2b.	$\beta_{r\sim t} = \Sigma\, A_r \sim A_t \mid \beta_{r\sim t} = \Sigma \mid A_r \sim A_f \mid$
2c.	$\beta_{f\sim t} = \Sigma\, A_f \sim A_t \mid \beta_{f\sim t} = \Sigma \mid A_f \sim A_t \mid$
3.	$\gamma = (S_r \cup S_t \cup S_f)$
4.	$H' = -\sum_{i=1}^{s} p_i . \ln P_i\ ;\ J' = \frac{H}{\ln S}$

Note: Equations used in this analysis of biodiversity. Where, S = species, A = abundance, f = forest area, r = river associated forest area, t = tourist associated with forest, S is the number of species, Shannon-Wiene index H' (Colwell, 2009; Magurran, 1988; Simpson, 1949), J' is Pielou's evenness index (Pielou, 1966), and p_i is the proportion of individuals in the i^{th} species. 1 to 3 equations are used for data analysis for this study

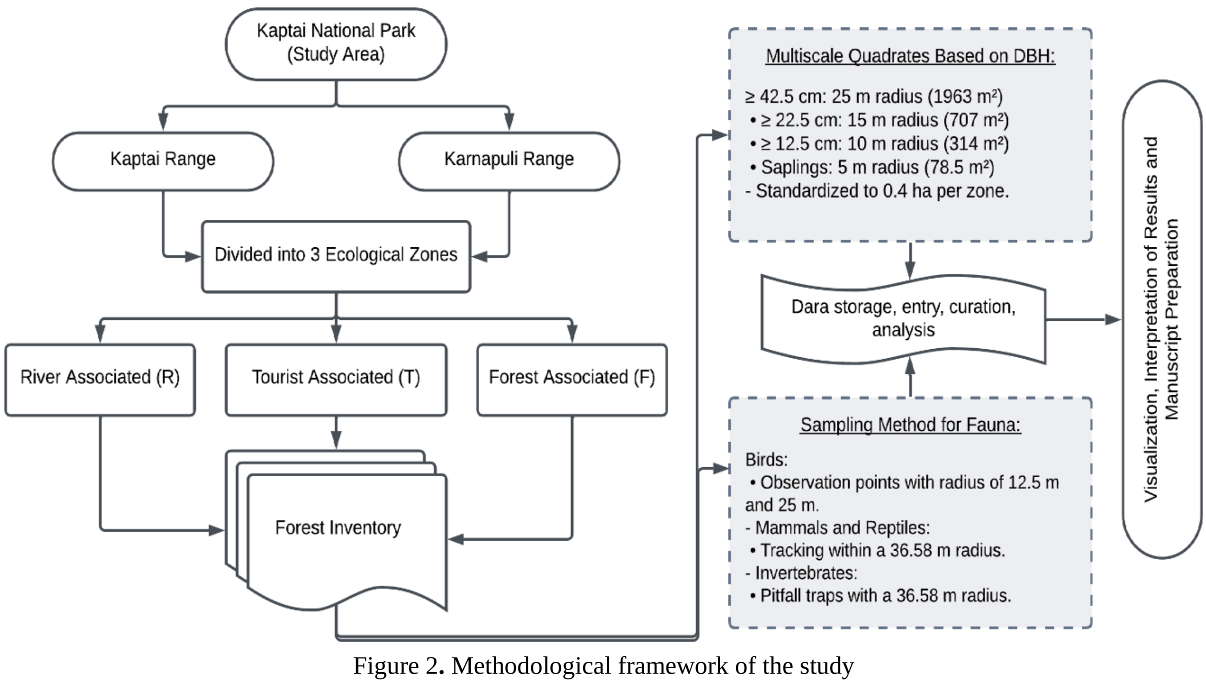

Figure 2. Methodological framework of the study

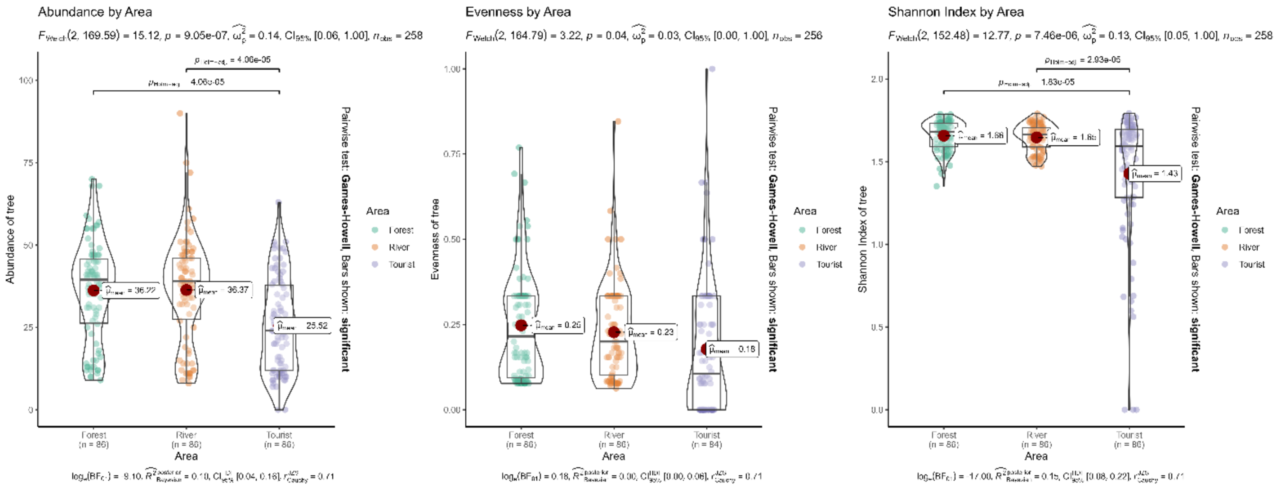

Figure 3. Revealing ecological disparities in tree abundance, evenness, and Shannon Index across Forest, River, and Tourist areas. An F-test (F $_{Welch}$ (2, 2)) indicates significant differences among the areas. Pairwise comparisons using the Games-Howell test reveal significant distinctions. Additionally, Bayesian analysis is incorporated, with log Bayes Factors (log (BF)) providing strong evidence for differences between the areas

In the bird section, the evenness of species across river, forest, and tourist areas showed no significant differences, with a p-value of 0.318. This means the variation in evenness within each habitat is much greater than any differences between them. When looking at diversity indices, the forest had an alpha diversity index of 104 for unique species, while both the river and tourist habitats were at 105, indicating a similar number of unique bird species in each habitat. The beta diversity index (Brockerhoff et al., 2017; de Souza Valente et al., 2020; Głowacka and Flis-Olszewska, 2022), using Bray-Curtis dissimilarity, showed moderate to high differences in species composition between the habitats, indicating noticeable differences in the types of species present. Overall, the gamma diversity index for unique species across all habitats was 51, suggesting a rich variety of bird species (Figure 4).

In the mammal section, the evenness of species across different habitats—river, forest, and tourist areas—showed no significant differences (P = 0.32). The alpha diversity index for unique species was consistent at 46 for all habitats, indicating a similar number of unique mammal species in each area. The beta diversity index, calculated using Bray-Curtis dissimilarity, showed moderate to high differences in species composition between the habitats, meaning there are noticeable differences in the types of species present in each habitat (Dutta and Hossain, 2016; Kessler et al., 2009). Overall, the gamma diversity index for unique species across all habitats was 9, suggesting a limited number of unique species. These results indicate a relatively uniform distribution of mammal species across the surveyed habitats, with minimal variation in species evenness (Figure 5).

In the reptile section of the study shows that the evenness of species across different habitats—river, forest, and tourist areas—was quite similar, with no significant differences (p-values around 0.32). Both the river and forest habitats hosted 45 species each, reflecting a consistent level of alpha diversity. The tourist habitat was slightly less diverse, with 41 species (Mandl et al., 2010; Roy and Bhattacharya, 2023; Uddin et al., 2020). When we looked at beta diversity, which measures differences in species composition between habitats using the Bray-Curtis dissimilarity index, we noticed distinct patterns in species abundance. This means that while the number of species might be similar, the specific species present varied between habitats. The overall diversity, or gamma diversity index, was 12 (Rahman et al., 2017a; Liu et al., 2019; Reza and Perry, 2015; Uddin et al., 2020), indicating a slightly higher total diversity compared to the bird and mammal sections of the study. These results suggest that while the number of species (evenness) is fairly uniform across the different reptile habitats, there are some differences in which species are found where (Figure 6).

In terms of invertebrates, the assessment examines that the evenness of species across rivers, forests, and tourist habitats was quite similar, with no significant differences (p-values around 0.321). This means that species were distributed evenly across these habitats. Both the river and forest habitats had 35 species each, reflecting their alpha diversity, while the tourist habitat had slightly fewer species, with 33 (Reza, 2010). When we looked at beta diversity using the Bray-Curtis dissimilarity matrix, we observed differences in species composition between the habitats. This analysis highlighted unique patterns in species abundance and showed that the community structures varied among the habitats. The gamma diversity index, which represents the total number of unique species across all habitats was 3 (Majumdar et al., 2014; Rahman et al., 2011). This indicates a relatively low overall diversity compared to other sections of the study. These findings suggest that while species distribution is quite uniform across different invertebrate habitats, the specific species present and their community structures differ (Figure 7). Overall, these findings suggest that while there are no significant differences in evenness among habitats, there are notable differences in species composition, indicating varied community structures across the studied invertebrate habitats.

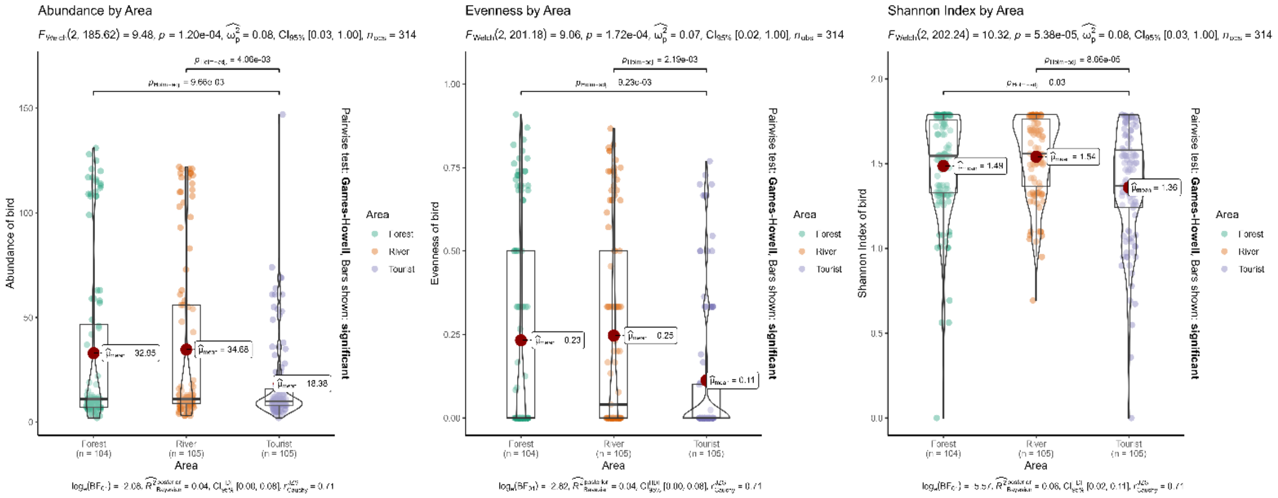

Figure 4. Revealing ecological disparities in bird abundance, evenness, and Shannon index across Forest, River, and Tourist areas. An F-test ($F_{Welch}(2,2)$) indicates significant differences among the areas. Pairwise comparisons using the Games-Howell test reveal significant distinctions. Additionally, Bayesian analysis is incorporated, with log Bayes Factors (log(BF)) providing strong evidence for differences between the areas.

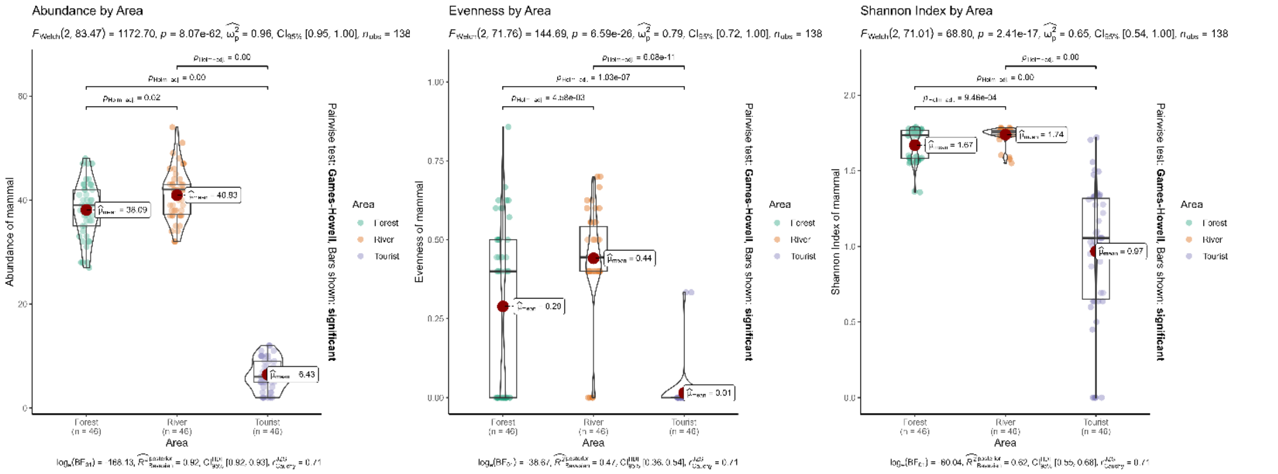

Figure 5. Uncovering ecological variations in mammal abundance, evenness, and Shannon index across Forest, River, and Tourist areas. An F-test demonstrates significant disparities among these areas. The Games-Howell test further identifies significant differences through pairwise comparisons. Moreover, Bayesian analysis is used, with log Bayes factors (log(bf)) offering robust evidence of these differences.

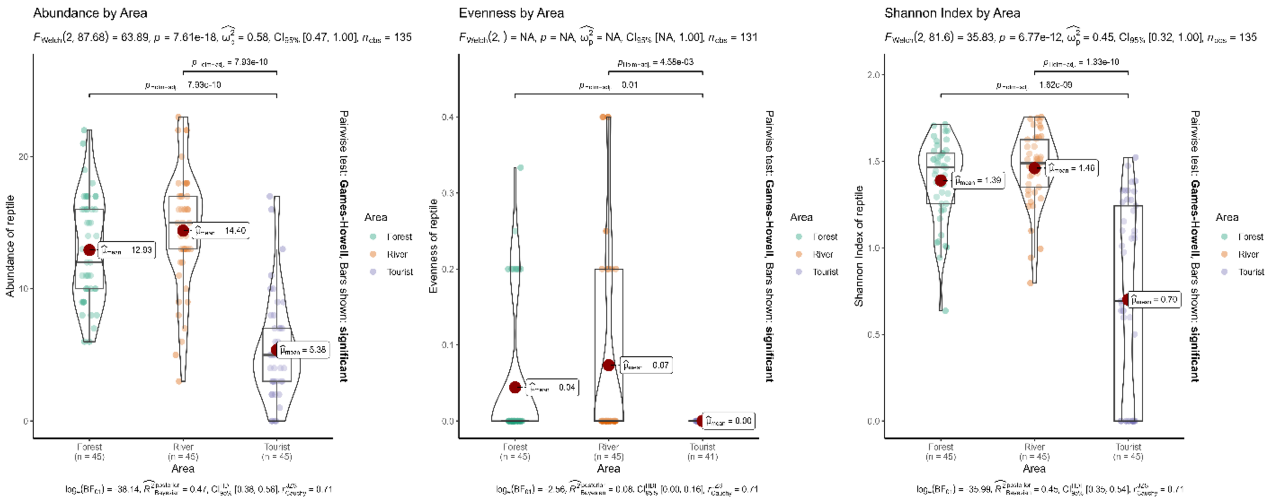

Figure 6. Highlighting ecological differences in reptile abundance, evenness, and Shannon index across Forest, River, and Tourist Areas. An F-test shows significant variations among the areas. The Games-Howell test conducts pairwise comparisons that identify clear differences. Additionally, Bayesian analysis is employed, with log Bayes Factors (log(BF)) indicating substantial evidence of these differences.

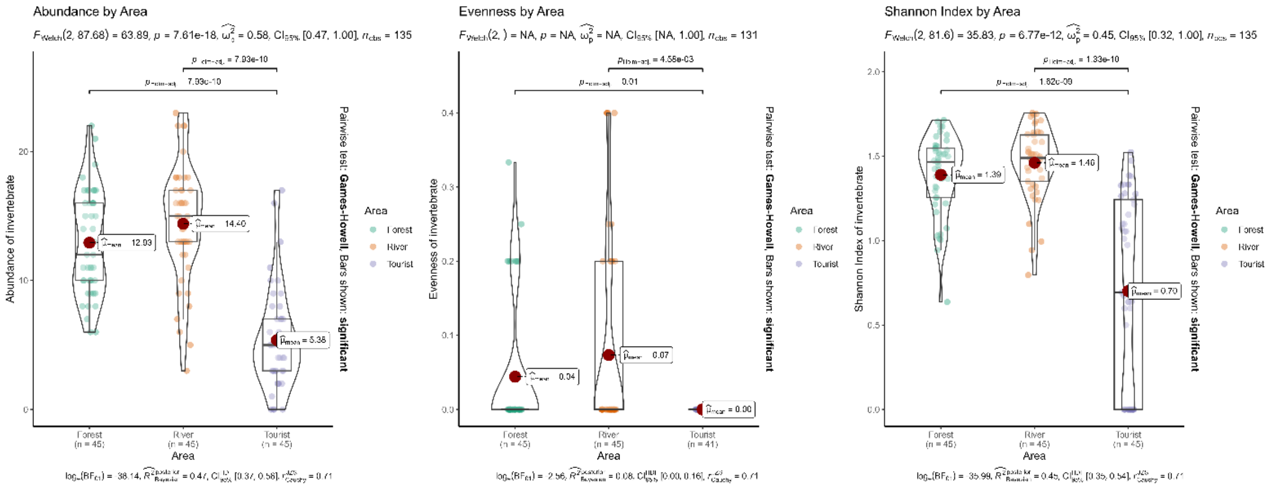

Figure 7. Exploring differences in invertebrate abundance, evenness, and diversity in forest, river, and tourist areas. An F-test shows significant differences between these areas. The Games-Howell test identifies important distinctions through pairwise comparisons. Also, Bayesian analysis with log Bayes factors strongly supports these differences.

3.2. Comparative analysis across habitats

The tree forests in our study show the highest levels of species abundance, evenness, and Shannon index, indicating a well-balanced distribution of species. On the other hand, the tourist area has the lowest scores in these metrics, which might be due to environmental stress or human impact. The forests near rivers have lower evenness compared to the main forest area, suggesting a less uniform distribution of trees in these regions (Mohd-Taib et al., 2020; Pozo and Säumel, 2018). For birds, mammals, and reptiles, the Games-Howell test revealed significant differences between the areas. Specifically, pairwise comparisons showed that the tourist-associated forest area is markedly different from both the river-associated forest area and the tourist area itself. These differences are marked on the plot with brackets and p-values (Rahman et al., 2017a). Furthermore, Bayesian analysis provided log Bayes Factors, offering strong evidence for these differences. The Games-Howell test for invertebrates also indicated significant differences between the habitats. Pairwise comparisons showed that the tourist-associated forest areas are significantly different from the main forest area ($p = 0.01$) and the tourist area ($p < 0.05$). Bayesian analysis reinforced these findings, with log Bayes Factors showing strong evidence for differences: -2.56 for the comparison between forest within river habitats and -35.96 for forest within tourist areas.

Table 2**.** Shannon and evenness indices of several forest taxonomy groups under biodiversity study.

Biological classes	Diversity indices	
	Shannon Diversity	Evenness
Tree	3.60	0.94
Birds	2.44	0.62
Mammals	1.92	0.87
Reptiles	2.39	0.96
Invertebrates	1.00	0.91

*This table displays Shannon and evenness indices for different taxonomic groups within forest ecosystems, providing insights into species diversity and the evenness of species distribution—key indicators in ongoing biodiversity assessments. Species abundance and evenness are crucial biodiversity metrics. Abundance counts individuals per species, while evenness assesses their distribution. To calculate evenness, use Pielou's index: first, determine each species' proportion P_i of the total population. Compute the Shannon-Wiener index $H'$by summing the products of each $P_i$and its natural logarithm. Then, divide H' by the natural logarithm of the total species count S. This index reveals how evenly individuals are spread across species.

3.3. Rarefaction of taxonomic groups within habitats

The experiment assessed species richness across trees, birds, mammals, reptiles, and invertebrates in forest, river, and tourist areas using rarefaction curves. The forest habitat boasted the highest species richness, especially among trees, which showed a steep initial increase in the curve, indicating a high diversity even with small sample sizes. Mammals and reptiles also exhibited significant richness, with invertebrates slightly lower (Das et al., 2016). In contrast, the river habitat had notably low invertebrate diversity, evidenced by a steep rarefaction curve. The tourist area showed the highest tree diversity but plateaued quickly (Dutta et al., 2015), suggesting fewer overall species. Birds and invertebrates in tourist areas had comparable but significantly lower richness than in forests, reflecting the negative impact of human disturbance on these habitats.

The rarefaction curves reveal significant differences in species richness among various taxonomic groups and habitats. Forest habitats are highly diverse, especially for trees, and have moderate diversity for mammals and reptiles. River habitats, on the other hand, are particularly rich in mammals, reptiles, and invertebrates (Chowdhury et al., 2019; Das et al., 2016; Rahman et al., 2013). Tourist areas, likely impacted by human activity, generally show reduced species richness across most groups, though trees still maintain considerable diversity. These findings highlight the crucial role of habitat type in determining species diversity and offer valuable insights for conservation efforts aimed at preserving biodiversity (Brockerhoff et al., 2017; de Souza Valente et al., 2020; Rahman et al., 2017b), particularly in forest areas affected by tourism (Figure 8).

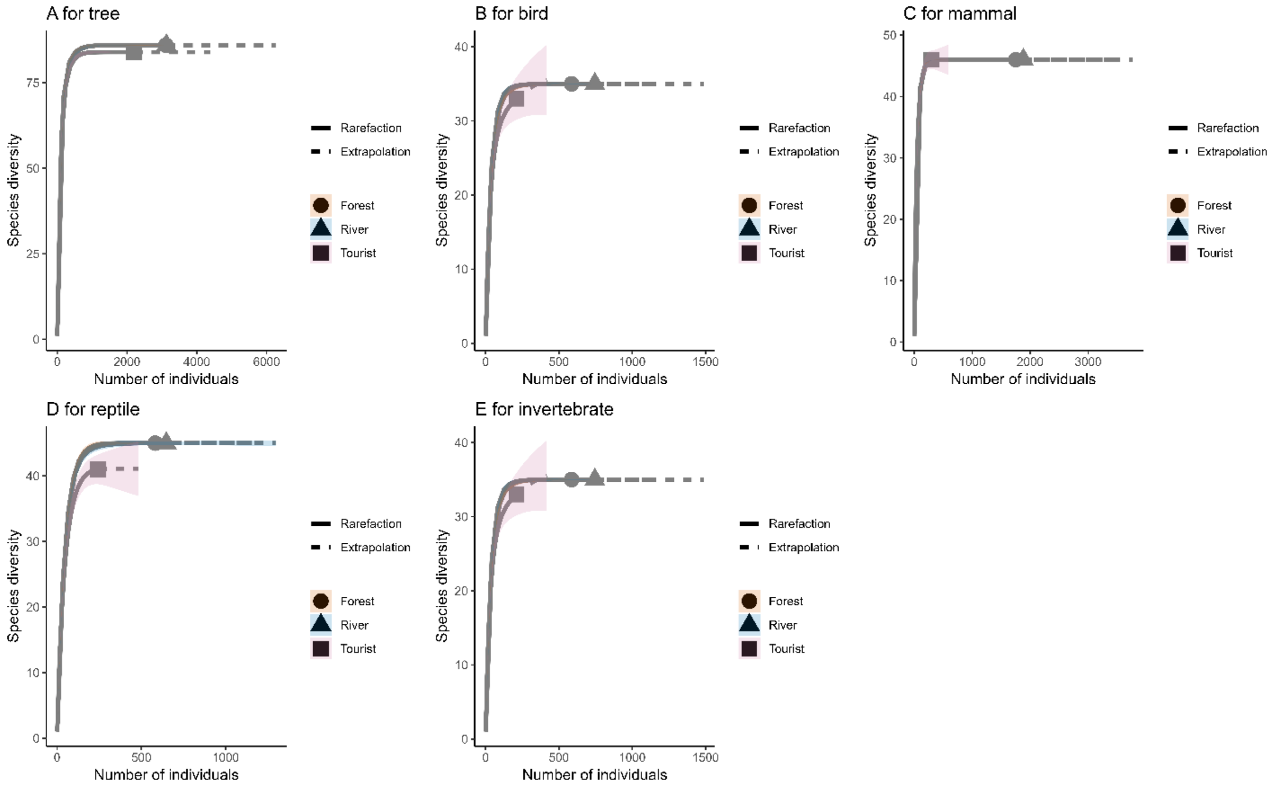

Figure 8. Rarefaction curves for five taxonomic groups (a) trees, b) birds, c) mammals, d) reptiles, and e) invertebrates) across forest, river, and tourist area habitats. The shaded areas represent the 95% confidence intervals. The X-axis shows the number of sequencing strips randomly extracted from a sample, while the Y-axis indicates the number of Shannon indexes constructed, reflecting sequencing depth. Different habitats are represented by different colored curves.

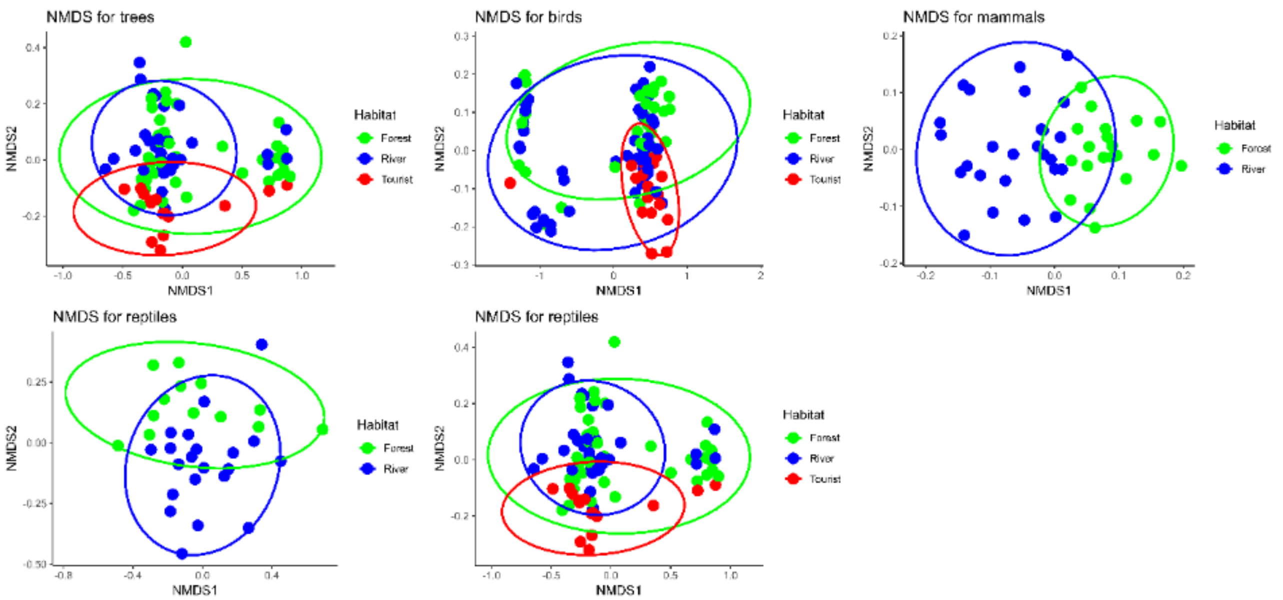

Figure 9. Multidimensional Scaling (NMDS) analysis: comparing three habitats with loss of maximum dimension habitat.

3.4. Non-metric Multidimensional Scaling (NMDS) Analysis

To visualize the differences in species composition among five taxonomic groups (trees, birds, mammals, reptiles, and invertebrates) across three distinct habitats (forest, river, and tourist area), we performed an NMDS analysis. In the forest habitat, the NMDS plot (Figure 9) showed a distinct clustering of tree species, indicating a unique composition separate from other habitats, highlighting the specialized nature of forest tree communities (Głowacka and Flis-Olszewska, 2022; Rahman et al., 2017b; Scherer et al., 2023). Mammals and reptiles also formed noticeable clusters, reflecting their adaptation to the forest environment. Birds and invertebrates were more dispersed, suggesting they are more broadly distributed across different habitats. In the river habitat, invertebrates exhibited a unique clustering pattern, indicating their specialization in aquatic environments (Reza, 2010; Reza and Perry, 2015; Roy and Bhattacharya, 2023; Xu et al., 2014), while birds showed moderate clustering, reflecting the diversity of avian species in riverine areas. Trees and mammals were more scattered, showing less distinct species composition than in forests, and reptiles were the least distinct, with a widespread distribution. In the tourist area, species composition differed from forest and river habitats, likely due to human disturbance. Birds and invertebrates showed moderate clustering but were less distinct, and mammals and reptiles had the most dispersed distribution (Uddin et al., 2020), indicating less specialized communities. These findings highlight significant differences in species composition among taxonomic groups and habitats, emphasizing the importance of forest habitats for unique tree and mammal communities, river habitats for invertebrate diversity, and the impact of human activity on species composition in tourist areas. This information is valuable for developing conservation strategies to preserve the unique species compositions across different habitats.

4. Discussion

The study sets out to explore how different habitats—forests, rivers, and tourist areas—affect the diversity and species composition of trees, birds, mammals, reptiles, and invertebrates. Using alpha (α), beta (β), and gamma (γ) diversity indices, along with rarefaction curves and NMDS analysis, we gained insights into how habitat types influence species diversity and composition. Comparing our findings with existing research, we found both similarities and contrasts. Our α-diversity indices revealed rich species diversity across habitats, with forests and rivers supporting diverse tree populations (86 species each), consistent with stable environments. In contrast, bird diversity was unexpectedly high across all habitats (104–105 species), differing from Hayat et al., (2010), who observed declines in human-affected areas. β- Diversity assessments highlighted distinct species compositions influenced by habitat types, resonating with Hayat et al., (2010) for mammals and extended to reptiles and invertebrates in our study. Evenness metrics indicated relatively balanced species distributions within taxonomic groups across habitats (p-value around 0.32), contrasting with findings by (Roy and Bhattacharya, 2023) in impacted areas.

The rarefaction curves echoed patterns seen in disturbed habitats reported by Tripathi et al., (2004), particularly evident in tourist areas where species richness plateaued quicker due to likely habitat degradation. NMDS analysis confirmed significant differences in species composition among habitats, and illustrating habitat-specific clustering for reptiles and birds, while also revealing similar patterns for invertebrates and trees. Lower Shannon-Wiener index values (1.10–1.35) in our study (Table 2) indicated reduced species diversity compared to global tropical forests, highlighting regional biodiversity disparities noted in studies across the India and Malaysia. Factors like habitat fragmentation and human activities likely contribute to this lower diversity, underscoring the need for targeted conservation efforts and further research to address underlying causes.

The findings highlight the critical role of habitat type in shaping species diversity and composition, consistent with broader ecological studies. Protecting forest and river habitats is crucial for biodiversity conservation, especially given the vulnerability of invertebrate populations in the river ecosystems. Similarly, mitigating human impacts in tourist areas is essential to preserve species richness and composition, aligning with conservation priorities emphasized for sustaining diverse reptile communities through effective habitat preservation strategies.

5. Conclusion

The ecological study across forest, river, and tourist area habitats reveals intriguing differences in biodiversity among trees, birds, mammals, reptiles, and invertebrates. While evenness levels and alpha diversity indices indicate consistent species distributions within each group across habitats, beta diversity indices unveil significant variations in species composition and community structures unique to each habitat type. Forests emerge as biodiversity hotspots with well-balanced ecosystems, likely due to minimal human disturbance. In contrast, tourist areas show less distinct species compositions, likely influenced by higher human activity and environmental stress. River habitats stand out for their specialized invertebrate communities adapted to aquatic life, highlighting the ecological specialization fostered by diverse environments.

The Games-Howell test underscores these differences in species distributions, particularly between natural and human-impacted areas, underscoring the profound impact of human activity on biodiversity. Rarefaction curves further emphasize these disparities, with forests exhibiting the highest species richness, especially among trees, while tourist areas demonstrate reduced richness across most taxonomic groups. NMDS analysis visually confirms these patterns, illustrating distinct clustering of species groups according to habitat type, aligning with our quantitative findings and showcasing the unique ecological niches and adaptive strategies of species.

To address these ecological insights effectively, we propose several recommendations. Conservation efforts should prioritize the protection of high-biodiversity habitats like forests and rivers. Restoration initiatives are critical in tourist areas to enhance biodiversity and restore ecosystem balance. Continuous ecological monitoring and research will facilitate adaptive management strategies in response to evolving conditions and challenges. Public education plays a crucial role in promoting awareness and responsible behavior towards natural habitats, supporting broader conservation objectives. Finally, stringent enforcement of environmental policies is essential to mitigate the negative impacts of tourism and urban development, ensuring the preservation of ecological integrity and promoting sustainable interactions with nature.

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