



Application of Island Biogeography Theory in Designing Urban Biodiversity Reserves

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Abstract

The application of Island Biogeography Theory (IBT) enhances urban ecological planning by offering a framework to promote biodiversity in fragmented urban landscapes. IBT was initially designed to explain species richness on isolated islands, but provides information about how size, isolation, and connectivity affect colonization and extinction rates of species—conditions that are relevant for urban green spaces functioning as habitat "islands". In this study, we investigate how the design of urban biodiversity reserves can be improved to incorporate IBT principles better, thereby increasing patch size, reducing isolation by implementing ecological corridors, and facilitating species migration to surrounding patches. Upon synthesizing existing case studies and performing spatial analyses of the existing urban green infrastructure, we demonstrate that, in general, larger and better-connected reserves are associated with higher species richness and greater robustness; smaller, isolated patches are more susceptible to extinction. This work compels us to emphasize that implementing ecological principles within an IBT

framework in urban planning can help mitigate habitat fragmentation and effectively utilize our green spaces for maintaining urban ecosystems. More broadly, we have also proposed a model for urban reserve network design that may help aggregate competing human ties while supporting ecological connectivity. Applying IBT principles to urban areas enables urban landscapes to play a crucial role in conserving native biodiversity and supporting global conservation objectives amid rapid urban development and climate change.

Keywords:

Island biogeography theory, urban biodiversity, reserves, habitat fragmentation, connectivity, ecological planning, species richness.

Article history:

Received: 18/04/2025, Revised: 20/05/2025, Accepted: 31/07/2025, Available online: 30/08/2025

Introduction***Fast Overview of Island Biogeography Theory***

Island Biogeography Theory (IBT), established in 1967 by Robert MacArthur and Edward O. Wilson, revolutionized the way people think about species distribution in isolated landscapes. It suggests that the number of species on any given island is a result of immigration and extinction equations, which are driven by the island's size and distance from the mainland (MacArthur & Wilson, 1967; Lomolino et al., 2010). Islands close to the mainland tend to receive higher immigration rates and therefore support a greater diversity of species. In contrast, small islands located farther away support fewer species due to lower migration rates, coupled with a higher risk of extinction. IBT was initially established for oceanic islands; however, it has been applied to terrestrial fragmented systems for conservation biology. Urban green areas, such as parks, remnant forests, and botanical gardens, represent green islands in an ocean of human-modified landscapes. The richness and sustainability of species in these areas are determined by their size, isolation, and connectivity to surrounding remnant habitats (Laurance, 2008). Although cities continue to grow and natural habitats continue to be fragmented, IBT is crucial for urban planners and ecologists to understand how urbanization and fragmentation can be managed to prevent further biodiversity losses in metropolitan areas (Dewangan et al., 2025).

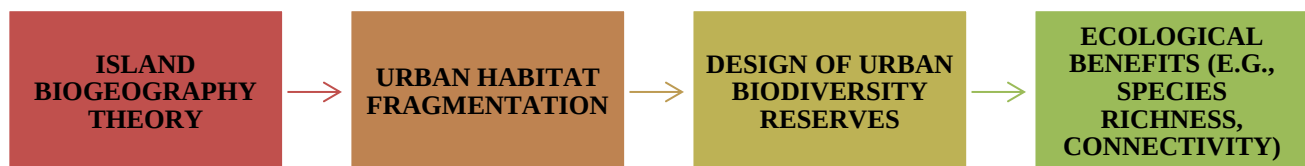


Figure 1(a). Conceptual Role of Island Biogeography in Urban Ecology

This diagram (Figure 1(a)) represents the flow of conceptual processes from the enabling body of theory: the Island Biogeography Theory, through its urban ecological application. The diagram begins with the Island Biogeography Theory, as it is a theoretical framework that pertains to the relationship between species distribution, habitat size, and habitat isolation. It then proceeds to urban habitat fragmentation, demonstrating how cities establish isolated green spaces that act as ecological islands. The design of urban biodiversity reserves represents a strategic application that incorporates aspects of spatial planning, connectivity, and habitat enhancements. The final block illustrates how this could potentially contribute to ecological outcomes by enhancing species richness and habitat connectivity. This visual framework illustrates how applying biogeographical principles can inform effective urban biodiversity policy.

Significance of Urban Biodiversity Reserves in Stabilizing Ecological Equilibrium

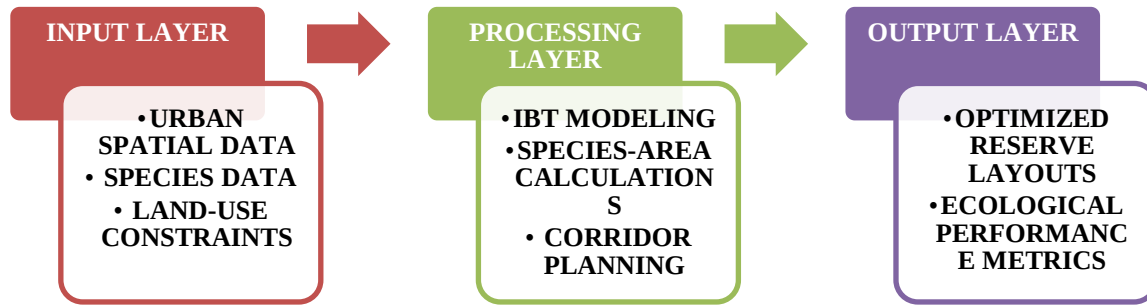


Figure 1(b). Framework for Applying IBT in Urban Reserve Design

This layered system (Figure 1(b)) architecture depicts the functional framework for incorporating Island Biogeography Theory (IBT) into urban biodiversity reserve planning. The Input Layer collects essential datasets, which include urban spatial arrangements, species occurrence data, and land use limitations. The inputs are processed in the Processing Layer, where IBT models are used to evaluate habitat fragmentation, calculate species-area relationships to assess biodiversity potential, and develop corridor planning to support ecological connectivity. In the Output Layer, optimized reserve forms that reflect conservation objectives and urban development are generated, along with a performance assessment to evaluate environmental resilience and species richness. This diagram illustrates a data-driven, theory-based process for designing more sustainable urban biodiversity reserves.

Urban biodiversity reserves play a crucial role in maintaining ecological balance as urbanization encroaches on wildlife habitats. Urban biodiversity reserves serve as havens for native flora and fauna, while also acting as barriers to the impacts of environmental degradation often associated with densely populated urban areas (Dearborn & Kark, 2010). Indigenous biodiversity reserves offer a diverse range of ecosystem services to urban dwellers, including air and water purification, pollination, temperature moderation, and mental health benefits (Aronson et al., 2017; Mishra et al., 2024). The contribution of biodiversity reserves in urban areas also influences the critical need to preserve genetic diversity for local species, and support species that may otherwise be driven to local extinction through habitat fragmentation (Beninde et al., 2015). Maintaining ecological networks and connectivity through green corridors and stepping-stone habitats can help mitigate the impact of isolation on species. Given that urban landscapes often encroach on biome regions of biodiversity (hot spots), maintaining and improving habitat association in urban biodiversity reserves supports broader conservation objectives ((Ives et al., 2016). Designing functional urban biodiversity reserves is not only a consideration for environmental sustainability, but also a part of socio-economic and public health strategy.

Thesis Statement: Application of Island Biogeography Theory in Designing Urban Biodiversity Reserves

This paper has argued that the Island Biogeography Theory has significant conceptual and practical applications in designing urban biodiversity reserves. By utilizing the main components of IBT - the importance of size, isolation, and connectivity of habitat, urban designers and managers conserve more resilient and functionally ecologically landscapes. This includes emphasizing larger patches of green space while simultaneously working to decrease the isolation of habitat remnants through ecological corridors to facilitate species migration and maintain biodiversity in this dynamic urban context. Essentially, we have integrated IBT into urban planning, adopting an enhanced scientific and data-

driven approach to mitigate biodiversity loss and create adaptable urban designs that support both human life and healthy habitats for other species (Al-Assadi & Al Kaabi, 2024). Through a synthesis of case studies, spatial modeling, and ecological analysis, this proposal seeks to demonstrate how IBT can be applied in an operational capacity to develop site-specific guidelines for biodiversity expectations in urban planning. By treating urban green areas as dynamic, ecologically isolated ecosystems intentionally embedded in an urban matrix, planners can encourage biological diversity and ensure meaningful ecological continuity in rapidly urbanizing settings (Wu, 2014). Therefore, this project aims to address the challenge of applying environmental theory to urban design, ultimately contributing to a more sustainable, biodiverse, and inclusive urban future.

This paper is presented in five distinct sections. In Section II, we elaborate on the Island Biogeography Theory, outlining its fundamental premises, introducing theoretical extensions of the concept as it relates to urban ecological planning, and providing examples of its application. In Section III, we explore the perspectives related to urban biodiversity reserves, discussing their environmental and functional value, obstacles to their design and implementation, and presenting a conceptual framework to maximize biodiversity utility using conceptual and mathematical models. In Section IV, we identify the practical implications of applying Island Biogeography Theory in the spatial planning of urban reserves, while addressing, in each series of applications, habitat fragmentation, connectivity, and species retention using data-driven performance metrics and graph representations. In Section V, we summarize our findings, reflect on the value of applying this knowledge in urban planning, and offer suggestions for future inquiry and potential conservation practices. The framework of this paper is designed to emphasize the coupling of ecological theory and urban biodiversity design.

Island Biogeography Theory

Description of Island Biogeography Theory and Its Components

Island Biogeography Theory (IBT) was developed by (MacArthur & Wilson, 2001) and refers to the relationship between species richness on islands and the equilibrium between the rates of immigration and extinction. Two primary parameters influence this equilibrium: the size of the island and the distance of the island from a source population (Vasquez & Mendoza, 2024). Larger islands can harbor larger populations and more habitat area (potential for diversity), thereby reducing extinction risk, while islands that are close to a mainland or other islands can facilitate the options for more immigration. The theory rests upon a dynamic equilibrium, which states that the number of species remains relatively consistent through time, while the species themselves constantly turn over (Brown & Lomolino, 2000). The theory also recognizes that small and isolated habitats are more susceptible to stochastic events, demographic uncertainty, and edge effects (Fahrig, 2003). While all turned over species may be equally vulnerable, over time, the theory shifted to include habitat quality factors, matrix permeability, and species-specific dispersal attributes (Krauss et al., 2004). This initial ecological framework has been applied to inform conservation practices in fragmented landscapes predominantly as ecologists began applying the IBT to terrestrial habitats fragmented by human activity (Kurian et al., 2018). IBT has become an important element of metapopulation theory and landscape ecology by emphasizing the significance of connectivity and scale for biodiversity conservation (Hanski, 1998).

Discussion of How to Apply the Theory in Urban Contexts

When we think of the urban context, natural green spaces such as parks, wetlands, and forest patches serve as ecological "islands" within an "ocean" of built infrastructure. The principles of IBT can help us to better

understand the distribution, persistence, and movements of species across fragmented ecological urban patches (Goddard et al., 2010). Similarly to oceanic islands, urban islands vary in size and connectivity, all influencing the outcomes related to biodiversity (Khazayi & Lotfi, 2017). Significantly, urban ecosystems are often negatively affected by habitat fragmentation increasing isolation and decreasing the size of patches to cause declines in overall species richness (Aronson et al., 2014; Shinde et al., 2018). By employing IBT, urban planners can help to conserve and design for larger, connected green spaces to allow for considerably higher levels of biodiversity. One example is to increase the size of habitat by allowing natural results when parks are expanded or merging green spaces together. Larger patches can decrease edge effects, increasing interior habitat conditions (Forman, 2014). Moreover, implementing green corridors or stepping-stone habitats can help to support permeability among species making dispersal easier while increasing gene flow among isolated patches (Haddad et al., 2015). Also, the theory supports strategies that integrate things like green roofs or tree-lined streets for increasing matrix permeability that will soften the urban matrix to reduce effective isolation (Hosseini & Jahaniyan, 2016).

Illustrations of Successful Application of Theory in Developing Biodiversity Reserves

Many applied urban planning initiatives have aimed to consider the tenets of IBT when developing green infrastructure that supports biodiversity. An example is Singapore's Park Connector Network. The Network consists of interconnected green corridors that provide routes linking the city's major parks, largely enhancing the diversity of birds and insects in Singapore (Tan et al., 2013). The city's planners have reduced patch isolation, and by mimicking natural systems, they have created a habitat network that connects the city much like natural ecological processes, increasing ecological resilience. In Berlin, Germany, planners used habitat connectivity models, structured on IBT, to incorporate green corridors linking habitats and convert them into the city land use plan. This project resulted in urban infrastructure that contained a greater richness of small mammals and birds (Abdulkareem, 2022). In addition, Portland, Oregon's Urban Wildlife Corridors Project followed IBT principles when prioritizing wildlife crossings and the development of stepping stone communities connected by rigorous urban habitat corridors (Beatley, 2016). Overall, these examples of urban green infrastructure demonstrate how theoretical models can provide guidance to real world urban design, creating sustainable urban environments that maximize ecological advances without diminishing human interests. The consistent outcome from these comparable scenarios are that urban biodiversity gains benefits when size, proximity and connectivity are incorporated in planning—hallmarks of Island Biogeography Theory.

Urban Biodiversity Reserves

Importance of Urban Biodiversity Reserves in Preserving Native Species and Promoting Ecosystem Health

Urban biodiversity reserves are essential for maintaining native species and having functional urban ecosystems. Biodiversity reserves provide suitable ecological habitats, for conserving regional plants and animals that are being displaced through urbanization. While conserving habitats, cities can maintain ecosystems, such as pollinators, water flow regulation, and microclimate stabilization. To estimate a reserve's species richness capacity, the species-area relationship can be used:

$$S = c * A^z \quad (1)$$

where S = number of species, A = area of the reserve, c , and z are taxonomic group and habitat constants. The equation presents evidence of spectrum of conservation needs for allocated areas large enough

for sustaining conservations, by suggesting that even small area allocations can have a benefit to biodiversity even despite the cost of time and energy. Biodiversity reserves also serve as biodiversity nodes that help the ecology of a spatial patterning and connectivity. This spatial patterning will impact species richness, biodiversity, and ecosystem health/stability through allotment, size, taxonomy, and surrounding matrix. Spatial analysis of the reserves, their design, has the benefits of informing urban planners to better estimate and measure the ecological capacity of the reserves being developed.



Figure 2. Methodological Flow of Urban Biodiversity Reserve Design Using Island Biogeography Theory

This figure (Figure 2) illustrates a laid out methodological workflow for urban biodiversity reserve design grounded in Island Biogeography Theory. The workflow commences with data collection. The process of data collection includes spatial, ecological, and land-use data for reserve planning. The second step is to identify the patches, where the areas of potential habitat are mapped and classified based on ecological value and potential to connect corridors. The third step is metric calculation, where important measures like isolation index, reserve area, and Diversity Potential Index (DPI) are calculated in order to analyze ecological viability. The metrics are inputted into the reserve network simulation, which is the modeling aspect of the process, investigating different spatial arrangements for the reserves, and corridors. The fourth step is performance evaluation of each scenario (based on the known criteria) to evaluate ecological effectiveness and sustainability. The final design proposal is developing the best and most resilient reserve configuration to be realized in an urban setting. This methodological flow facilitates a scientific, iterative, and data-based approach to urban biodiversity.

Difficulties and Limitations to Develop and Sustain Urban Biodiversity Reserves

Developing and sustaining biodiversity reserves in cities have some both logistical and ecological limitations. One typical issue is habitat isolation due to the increased infrastructure and limited open space in urban cores. Isolation reduces the opportunity for gene flow and species movement among patches, which can increase the potential for local extinction. To determine this, one can use the patch isolation index:

$$I_i = \sum_{j \neq i} \frac{A_j}{d_{ij}^k} \quad (2)$$

where I_i is the isolation for reserve i , A_j is the area of neighboring patch j , d_{ij} is the distance between them and k is a sensitivity factor for dispersal. Isolation values that are generally higher are associated with reduced connectivity, which reduces species populations' resilience. In addition to spatial fragmentation, ecological degradation in the reserve (pollution, invasive species and human activities) can

also represent a stressor at the internal design-level quality of the reserve. Stressors can decrease ecological value where the area could be sufficient, indicating that size is not a sufficient criterion for success.

Approaches to Maximizing Biodiversity in Urban Reserves

To address the spatial constraints and ecological stressors that typically constrain urban biodiversity planning, a system based, multi-metric approach should be adopted. One opportunity is greater connectivity between reserves through green corridors, stepping-stone habitats or ecological boulevards. The network connectivity among reserves can be mathematically modeled by:

$$C = \sum_{i=1}^n \sum_{j=1}^n \frac{S_i \cdot S_j}{d_{ij}^\alpha} \quad (3)$$

where S_i and S_j are species richness of patches i and j , d_{ij} is distance between patches, and α is a decay term that represents dispersal loss across distance. Maximizing C will create functional ecological flows within the urban matrix. To ensure that each patch can retain internal ecological value, we need to define a Reserve Quality Score (RQS):

$$Q_i = \beta_1 H_i + \beta_2 V_i + \beta_3 P_i - \beta_4 E_i \quad (4)$$

In this formula, Q_i measures reserve i 's ecological integrity as it relates to habitat heterogeneity H_i , vegetation cover V_i , presence of keystone species P_i , and detrimental edge-to-area ratio E_i , weighted by empirical parameters β . This will place constraints on bio-diversity planning so that it is not only spatially strategic but ecologically sensible. An integrated objective function to optimize biodiversity across an urban landscape can be written as follows:

$$Z = \sum_{i=1}^n \omega_1 S_i + \omega_2 Q_i + \omega_3 I_i + \omega_4 C \quad (5)$$

Subject to:

$$\sum_{i=1}^n A_i \leq A_{max} \text{ and } \sum_{i=1}^n B_i \leq B_{max} \quad (6)$$

where Z is total biodiversity utility, and available land space A_{max} and available budget B_{max} are constraints. This way, data-driven biodiversity planning can be done within urban land use and budget constraints. With an ecology-based framework and quantitative modelling in the project and strategic design of urban biodiversity reserves,⁵⁵ they can be planned not only as isolated green spaces, but as adaptive, integrated systems that can sustain both urban livelihood and ecological diversity for generations.

Designing Urban Biodiversity Reserves using Island Biogeography Theory

Including Habitat Fragmentation and Connectivity in Reserve Design

Urban biodiversity reserves cannot be designed without considering habitat fragmentation and ecological connectivity. This will also assure these reserves remain biologically viable and sustainable over the long-term. Habitat fragmentation happens when continuous natural habitat gets partitioned into smaller, less intact, and isolated patches caused by roads and buildings, and other urban development infrastructure. Often, these

fragmented patches are also patches that are too small or in edge habitat conditions to support viable populations, especially species that occupy large home ranges, or require specialized habitat conditions. To measure fragmentation, a Patch Integrity Index (PII) can be implemented:

$$PII_i = \frac{A_i}{1 + E_i} \quad (7)$$

where A_i is the area of the patch, and E_i is the edge-to-area ratio. A higher PII indicates more intact core habitat and lesser important habitat edge exposure. Equally important habitat attribute is the measure of ecological connectivity - how organisms can move between patches, and consequently migrate, disperse, and recolonize. Connectivity can also be modeled using a Functional Corridor Score (FCS):

$$FCS = \sum_{k=1}^m \left(\frac{L_k \cdot P_k}{D_k} \right) \quad (8)$$

where L_k is the length, P_k is the permeability, and D_k is the distance of corridor k . Reserves should not be designed or treated as isolated units, rather, they should comprise a larger habitat network that include corridors and buffer zones to facilitate ecological exchange.

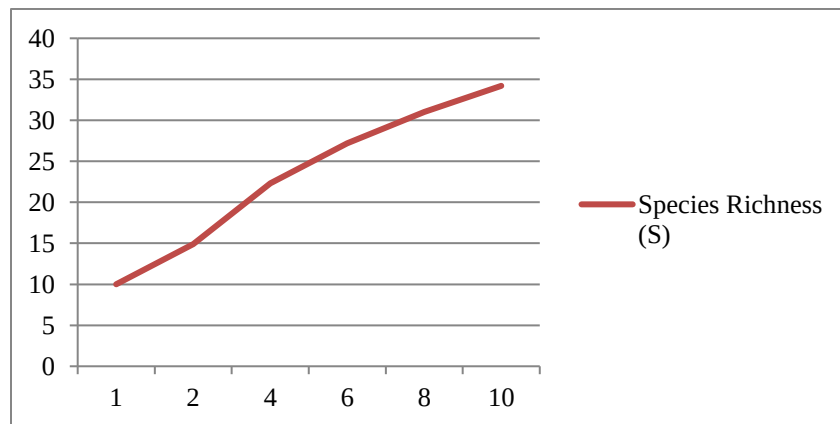


Figure 3. Effect of Reserve Size on Species Richness

This graph (Figure 3) exemplifies the classic species-area relationship where species richness is positively related to the area of the reserve. The values show an increase in species richness even with small reserves with small increases to reserve area, and these increases are most pronounced in the early stages of expansion. For example, an increase of area from 1 to 4 hectares resulted in an increase in species number of more than two times, from 10 to 22.3 species. The rate of increase in species richness tapers off when the area becomes larger, showing a natural diminishing returns, a well documented ecological pattern. This curve supports the ecological message of the benefits of larger reserves for maintaining species diversity, as described by the Island Biogeography Theory, while still not ignoring the tenet of maximizing the land available for ecological good.

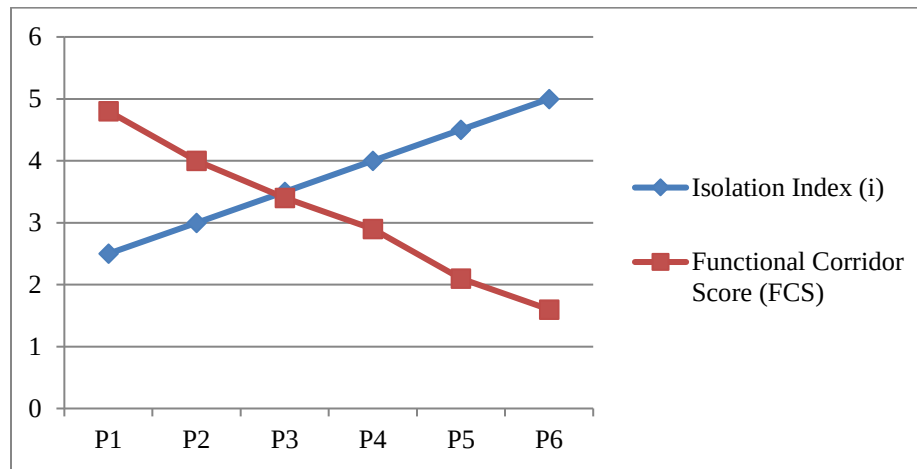


Figure 4. Patch Isolation vs. Functional Corridor Score

The graph (Figure 4), shows that functional connectivity is inversely related to the isolation of habitation. As the index of isolation of a habitat area increases (greater distance from other reserves), the score for functional corridor decreases, indicating the habitat area is less conducive to species movement and flux through it. For example, Patch P1 has a low isolation index of 2.5 as well as a high corridor score of 4.8; whereas, Patch P6 had the highest index of isolation at 5.0 and the lowest corridor score of 1.6. Therefore, this indicates that urban biodiversity reserves should be planned to be as contiguous as possible or they should be enhanced by well-designed ecological corridors so that they can maintain respect of species dispersal, gene flow and ecosystem resilience.

Improving Species Richness and Diversity in Urban Reserves

Using a few simple strategies for more effective management can lead to enhanced biodiversity in urban reserves through a spatial structured management approach, vegetative complexity, and microhabitat variability. Informed by island biogeography, one general finding is that large, well-connected reserves should allow for more species because of lower extinction and higher immigration. While metapopulation dynamics are less likely in urban reserves with limited landscape space, the reserve shape and internal heterogeneity of urban reserves are important. A Diversity Potential Index (DPI) can help assess reserve potential to sustain biodiversity:

$$DPI = \gamma S + \delta H + \epsilon R \quad (9)$$

where S is structural complexity (number of strata in the canopy), H is habitat heterogeneity (e.g., water bodies, grasslands, or patches of forest), and R is resource richness (food and nesting opportunities), with ecological importance weights γ, δ, ϵ . Generally, the higher the DPI, the more favourable the conditions for supporting a wider variety of species. An effective management approach will also include planting native vegetation, ecological zoning, seasonal dynamic disturbance schemes, and some form of adaptive monitoring programs. With consideration of natural processes in the management of urban reserves to replicate natural template conditions increases resilience to disturbance and climate change and supports both generalist and specialist species.

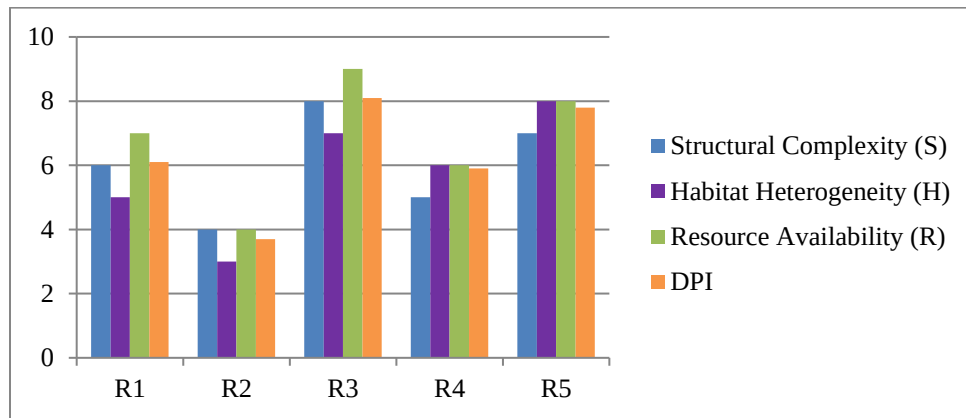


Figure 5. Diversity Potential Index Across Urban Reserves

This bar chart (Figure 5) shows the Diversity Potential Index (DPI) scores for various urban reserves derived from structural elements, habitat diversity and resources available. Reserves which scored higher on these score higher on the DPI Index, indicating that they have a greater potential to support a higher diversity of species. For example, Reserve R3 scored the highest DPI index, of 8.1, because it contained more complex vegetation layers, multi-species habitats and ecological resources. Reserve R2, by contrast, scored the lowest at 3.7, because of its relatively simple structuring and lack of habitat diversity. In summary, even though the urban reserves are small (e.g R2), they may still create ecological value for diversity if they are implemented with a lot of diverse microhabitats and ecological resources. This reiterates the aspect of not just considering the size of the reserves or the location but the state of internal habitat quality for biodiversity potential.

Case Studies that Evidenced the Successful Application of Island Biogeography Theory to Urban Biodiversity Reserve Design

There are a variety of examples of real-life applications that indicate an application of island biogeography theory into urban reserve design planning. While implementations can vary by geographic context, there are some overarching principles that tend to create positive outcomes, such as larger reserves, close inter-patch distance, and a greater functional effectiveness of corridors. We are able to create a Biodiversity Retention Score (BRS) over time to evaluate design effectiveness:

$$BRS_t = \frac{S_t}{S_0} \times 100 \quad (10)$$

where S_t is the species number of at time t, and S_0 is the number at baseline. This performance-oriented metric provides one perspective on how successful the reserve has been at supporting species richness over time. A Reserve Performance Index (RPI) can also integrate multiple dimensions of performance:

$$RPI = \eta_1 BRS + \eta_2 DPI + \eta_3 FCS - \eta_4 L \quad (11)$$

Where L indicates land use pressure or encroachment, and η values represent relative weights. This equation provides a reference for decision-makers to account for both ecological outcomes and human impacts, facilitating a more comprehensive performance assessment. Using such metrics as an accountability measure together with the principles of island biogeography, it is possible to design urban biodiversity reserves to maintain viable and adaptive ecological reserves despite the changing pressures of urban development.

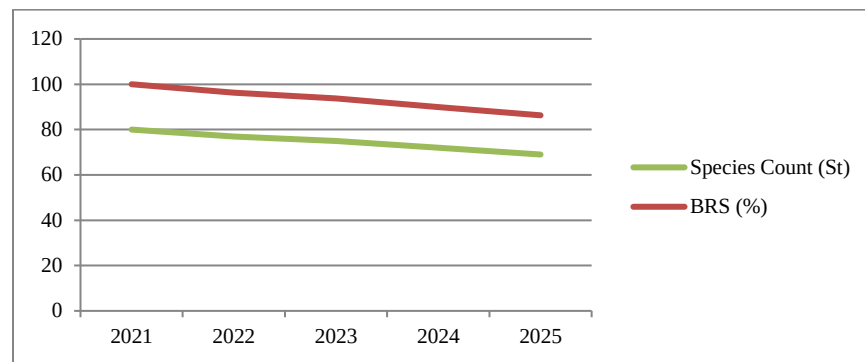


Figure 6. Biodiversity Retention Over Time

This illustration (Figure 6) shows the biodiversity retention score (BRS) in an urban designated biodiversity reserve over a period of five years and compares the species count on a yearly basis against a previous (baseline) value. An obvious declining trend is present, with species richness decreasing from 100% in 2021 to 86.3% in 2025. This indicates that regardless of having a biodiversity reserve as an ecological safeguard, other biological and ecological factors, such as habitat degradation, habitat encroachment, or climatic variations, are all commonplace in affecting the species within the reserve in due course. This illustrates an ongoing necessity for monitoring, as a drop in BRS will require some degree of ecological management, such as habitat restoration, predator management, or invasive species management (ecological interventions), to avert continued declines in biodiversity.

Conclusion

In conclusion, this research has illustrated how Island Biogeography Theory will aid in designing and reviewing urban biodiversity reserves. By being aware that species richness is correlated to reserve area, insularity, and connectivity, urban planners can systematically base their potential efforts to conserve species and promote overall ecosystem health in urban areas with fragmentation and urban development. The use of mathematical principles and a system for measuring and comparing the performance metrics — species area relationship, patch isolation index, and diversity potential scoring — will enable the implementation of a data driven plan that promotes ecosystem function across urban landscapes. The positive effects of implementing this type of approach is not limited to ecological metrics, but will also support climate resilience, enhance quality of life for urban inhabitants, and support the long-term sustainability of urban green infrastructure. In well-placed reserves connected by functional linkages, with habitat quality improvements, urban areas can develop into comprehensive ecological networks. The future of research should also look at integrating real time ecological monitoring with urban planning, evaluating the long-term effects of reserve configurations, along with adaptive management in a changing climate and land use. Some practical options also include policies favouring green infrastructure, urban ecological zoning, and community stewardship approaches that promote lasting conservation outcomes. However, importantly, the intersection of ecology and urbanism potentially creates a promising pathway to biodiversity resilient cities.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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