Research Paper

The Ecological Resilience Regulation Mechanism of Urban Morphology:

A Nonlinear Multi-scale Study on Avian Diversity

Yifan MU, School of Architecture and Design, Harbin Institute of Technology, Key Laboratory of National Territory Spatial Planning and Ecological Restoration in Cold Regions, Ministry of Natural Resources, China

Wei DONG, School of Architecture and Design, Harbin Institute of Technology, Key Laboratory of National Territory Spatial Planning and Ecological Restoration in Cold Regions, Ministry of Natural Resources, China

Yu DONG*, School of Architecture and Design, Harbin Institute of Technology, Key Laboratory of National Territory Spatial Planning and Ecological Restoration in Cold Regions, Ministry of Natural Resources, China

Zhuolin TAN, School of Architecture and Design, Harbin Institute of Technology, Key Laboratory of National Territory Spatial Planning and Ecological Restoration in Cold Regions, Ministry of Natural Resources, China

Abstract

Under the dual pressures of climate change and rapid urbanization, protecting urban biodiversity has become a key challenge for achieving sustainable development goals. This study focuses on residential areas in the central urban district of Harbin, Heilongjiang Province, China. Based on bird diversity data collected from 456 sample points, we used a boosted regression tree model to conduct a multi-scale nonlinear analysis. This approach allowed us to examine how urban morphology regulates bird diversity. The study finds that the influence of urban morphology on bird diversity shows a complex scale-dependent pattern. At the local scale, morphological parameters such as building density and floor area ratio generally suppress bird diversity. Of these parameters, the floor area ratio reaches a threshold near 1.5. At the landscape scale, the effects of these parameters change significantly. Building density shows a positive peak around 0.35, while the floor area ratio displays an inverted U-shaped relationship. Meanwhile, the research reveals saturation effects in both habitat and disturbance factors. The positive effect of NDVI slows down when it exceeds 0.5. The benefit of green space ratio stabilizes after reaching 40%. The influence of nighttime light intensity no longer increases significantly beyond a value of 80. Likewise, the impact of distance to large green spaces drops sharply beyond 2000 meters. Based on these findings, the study proposes differentiated planning recommendations. At the local scale, we suggest keeping the floor area ratio below 2.5. At the landscape scale, it is best maintained within the reasonable range of 0.5 to 2.5. Meanwhile, the green space ratio should be no less than 40%. Urban development projects should be prioritized within 2000 meters of large green spaces. These findings systematically explain the ecological resilience regulation mechanism of urban morphology. By identifying key ecological thresholds and their variations at different scales, our work gives a quantitative basis for establishing a multi-scale urban ecological management system. This advances urban planning from qualitative guidance toward quantitative design. Using a nonlinear multi-scale analysis method, this study clarifies how urban morphology affects bird diversity through ecological resilience pathways, offering an important scientific foundation for sustainable urban development.

ISOCARP World Planning Congress
RIYADH | الرياض
1 - 4 DECEMBER 2025
Cities & Regions in Action
Planning Pathways to
Resilience and Quality of Life

Keywords

Urban Morphology, Avian Diversity, Ecological Resilience, Nonlinear Multi-scale Analysis, Boosted Regression Tree, Sustainable Urban Growth

1. Introduction

Cities worldwide are growing faster than ever before in both speed and size. This trend is especially evident in China. According to data from China's National Bureau of Statistics, the country's urbanization rate surged from 36.2% to 63.89% between 2000 and 2020, and the number of cities reached 687 (Da, 2021). While this fast-paced urban growth has driven social and economic development, it has also triggered serious ecological problems. A pressing issue is the systematic decline of urban biodiversity. Many studies show that as urban density increases, natural vegetation and soil are increasingly taken over by buildings and impervious surfaces. This causes habitats to shrink and become fragmented (Liu et al., 2016), which profoundly affects bird communities (Xu et al., 2018). At high-density urban areas, bird species richness generally declines, while invasive and non-native species increase (Blair, 1996; Aronson et al., 2014). Furthermore, bird communities in built-up areas often show higher levels of biotic homogenization. These changes arise from various human-caused disturbances, with important drivers being simplified vegetation structure, noise pollution, and artificial light at night (Sidemo-Holm et al., 2022; Rodrigues et al., 2018).

Today's world confronts several connected challenges, as biodiversity decline, change of climate, and rapid urbanization create risk for urban sustainability. The urban heat island effect changes the local weather and influences bird breeding phenology and migration behavior (Sumasgutner et al., 2023). As extreme weather happens more often, its combination with habitat loss also greatly weakens species' capacity to recover (McCloy et al., 2022). The pressures not only directly reduce biodiversity but also weaken the ability of city ecosystems to resist disruptions while keeping their functions stable. Bird richness is a reliable indicator of environmental well-being, it can show how well these city ecosystems cope with stress (Smits and Fernie, 2013). Therefore, examining how urban form affects ecological resilience plays an important role in developing a sustainable urban during challenges.

We haven't fully known how urban morphology regulates ecological resilience. Existing research shows that morphological parameters like building density affect bird diversity in ways that strongly depend on scale (Choi et al., 2025). How this scale dependence translates into ecological resilience mechanisms is still not well understood. Specifically, high-density development often breaks habitats into smaller, disconnected pieces. At broader scales, however, a moderately clustered built environment may help species survive by creating varied microhabitats, as long as it remains connected to larger green networks (Norton et al., 2016). Current planning models, which mostly operate at a single scale, fail to properly address these scale-sensitive effects. This shortcoming cuts the effectiveness of using spatial design to strengthen ecological resilience. A separate issue is that planning practices often overlook the nonlinear response characteristics of nature. They have critical ecological thresholds in response to development pressure. For example, when road network density exceeds a certain level, biodiversity may decline rapidly (Ascensão et al., 2019). These nonlinear thresholds are key to understanding abrupt changes in ecological resilience. Nevertheless, most planning decisions are still based on linear assumptions (Dongchen et al., 2014). This neglect of ecosystems' threshold behavior makes it hard for spatial management measures to step in successfully at critical ecological tipping points.

These theoretical limitations have created a clear disconnect between planning policies and the goal of a sustainable city. There is a mismatch between regulatory standards and what ecosystems actually require. For example, current floor area ratio controls typically use one-size-fits-all standards and ignore the fact that different areas can tolerate different levels of ecological impact. Another problem involves scale mismatch in spatial governance. Green space planning tends to focus on large parks while paying insufficient attention to the pathways linking other green spaces. This led to a broken-up ecological network that has trouble dealing with the problem of habitat fragmentation.

Therefore, this study aims to reveal the ecological resilience regulation mechanism through a study of the multi-scale nonlinear effects of urban morphology on bird diversity, thereby providing a scientific basis for sustainable urban development. We employ boosted regression trees, a nonlinear machine learning approach, to look closely at how urban morphological parameters, habitat quality, climate factors, and human disturbances collectively influence avian diversity through nonlinear mechanisms and threshold characteristics. Using residential areas in Harbin, China, as our empirical case, this study tries to answer two questions: How does the urban morphology affect bird diversity through nonlinear relationships and threshold effects at different scales? How to use the result to make spatial management strategies to enhance urban ecological resilience? By answering these questions, this study aims to provide a theoretical foundation and practical pathways for enhancing urban ecological resilience through spatial planning and supporting sustainable urban growth in a world of multiple crises.

2. Methodology

2.1. Study Area and Bird Diversity Data Collection

This study focused on residential areas within Harbin's central city. We systematically selected 456 typical sample points to build the analytical framework, where the main variable of interest was bird species richness. Field surveys were conducted between July and September 2023. All surveys took place from 5:00 to 8:00 AM after sunrise. Each survey lasted 10 minutes, during which we recorded all bird species seen or heard within a 50-meter radius. To improve objectivity, this study also used BirdNET (Ware et al., 2023) to recognize bird species. This is an acoustic identification tool to analyze field recordings of birdsong. All automatically identified species were then manually checked. The bird species richness data were log-transformed to meet model assumptions.

2.2. Explanatory and Control Variables

This study adopted two spatial scales for collecting and processing environmental variables. These were a local scale, defined by a 250-meter radius buffer, and a landscape scale, defined by a 1000-meter radius buffer. The explanatory variables covered three main dimensions: urban morphology, habitat factors, and control variables. For urban morphology, we extracted spatial parameters at both scales. These included building density (BD), building height (BH), floor area ratio (FAR), and road density (RD). We also used Fragstats 4.3 (McGarigal and Marks, 1995) to calculate several landscape pattern indices. The data include the Shannon's Diversity Index (SHDI), Simpson's Diversity Index (SIDI), Shannon's Evenness Index (SHEI), and Simpson's Evenness Index (SIEI). We also computed the Aggregation Index for built-up areas (AIB) and for green spaces (AIGS). Habitat factors included the percentage of green space (PGS), the Normalized Difference Vegetation Index (NDVI), distance to large green space (DLGS), percentage of water (PW), distance to water source (DW), altitude (ALT), and slope (SLO). Control variables were incorporated to account for influences from climate and human activities. Included 19 bioclimatic factors

(BIO1-BIO19), population density (PD), nighttime lights (NTL), the percentage of built-up area (PB), distance to building (DB), and distance to roads (DR).

Table 1. Environmental variables data description (Source: created by the author).

Variable sets	Indicator	Specific explanation
Urban Morphology Factors	SHDI	Landscape shannon's diversity index
	SIDI	Landscape simpson's diversity index
	SHEI	Landscape shannon's evenness index
	SIEI	Landscape simpson's evenness index
	RD	Road density
	BD	Building density
	BH	Building height
	FAR	Floor area ratio
	AIGS	Aggregation index of Green space
	AIB	Aggregation index of built-up area
Habitat Factors	PGS	Percentage of green space
	NDVI	Normalized difference vegetation index
	DLGS	Distance to large green space
	PW	Percentage of water
	DW	Distance to water source
	ALT	Altitude
	SLO	Slope
Control Variables	BIO1-BIO19	Annual mean temperature, mean diurnal range, isothermality, etc., are all bioclimatic factors.
	PD	Population density
	NTL	Nighttime lights
	PB	percentage of built-up area
	DB	Distance to building
	DR	Distance to roads

2.3. Modeling and Analytical Methods

This study employed the boosted regression trees (BRT) model as its core analytical method. This model can handle complex interactions within high-dimensional data and identify nonlinear response patterns (Friedman, 2001). In contrast to linear methods, which can only identify a limited number of significant variables, the BRT model demonstrates a stronger capacity to find underlying mechanisms. It shows the relative importance of each variable in predicting bird diversity and uses a partial dependence curve to visually represent the threshold effects of morphological parameters. This method provides reliable methodological support for revealing how multi-scale urban morphology regulates biodiversity.

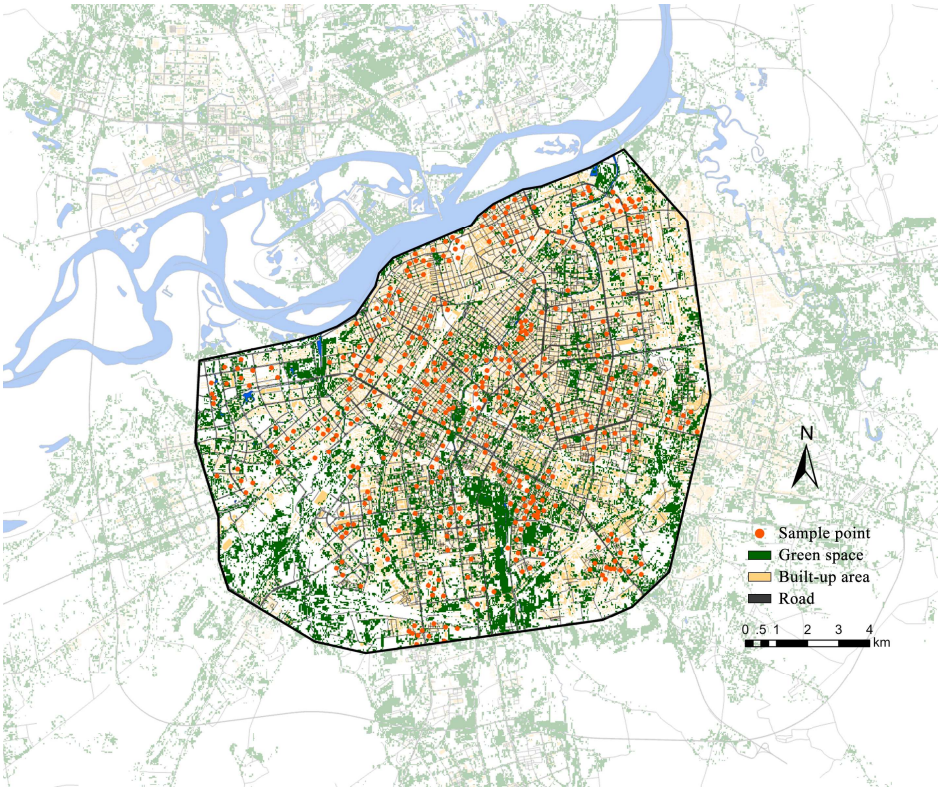


Figure 1. Research area and sample points (Source: created by the author).

3. Discussion

3.1. Relative Importance of Multi-scale Driving Factors

The relative importance analysis reveals that the dominant environmental factors affecting bird diversity differ significantly across spatial scales. At the 250-meter local scale, the environmental factors ranked by their relative contribution are NDVI, NTL, RD, AIGS, DLGS, Annual Mean Temperature (BIO1), and BD. Among these, NDVI shows the highest relative contribution, indicating that local habitat quality plays a vital role in maintaining bird diversity. NTL and RD capture the effects of light pollution and traffic disturbance on bird communities, respectively. Meanwhile, BD represents the degree to which the built environment compresses ecological space. These human-induced disturbance factors, together with NDVI, collectively create the key environmental gradients influencing bird communities at the local scale. This result aligns with niche theory (Leibold, 1995), showing that species distribution at the local scale depends on both available resources and how human disturbance filters out sensitive species.

At the landscape scale, when we rank environmental factors according to their relative importance, it shows notable changes. DLGS emerges as the most influential factor. It is followed by NTL, RD, DB, BD, BH, and PGS. This shift from local habitat quality to landscape connectivity indicates that ecological processes operate differently across spatial scales, consistent with patch dynamics theory (Leibold et al., 2004). Specifically, at the landscape scale, how accessible large green spaces are becomes the primary factor, replacing local vegetation conditions. This shows the movement of species and their selection of habitats operating dominantly over larger spatial areas. Meanwhile, building density, height, and their spatial distribution together define the structural character at the landscape level. They influence what habitats

are available to different species. Factors like nocturnal lighting and road networks continue to exert their disturbing effects, much as they do at the local scale. This indicates that the impact of human activities lasts through different scales. Compared to the local scale, the dominant mechanism at the landscape scale shifts from microhabitat quality to spatial configuration. This result highlights the essential value of a multi-scale approach to understanding urban ecosystems.

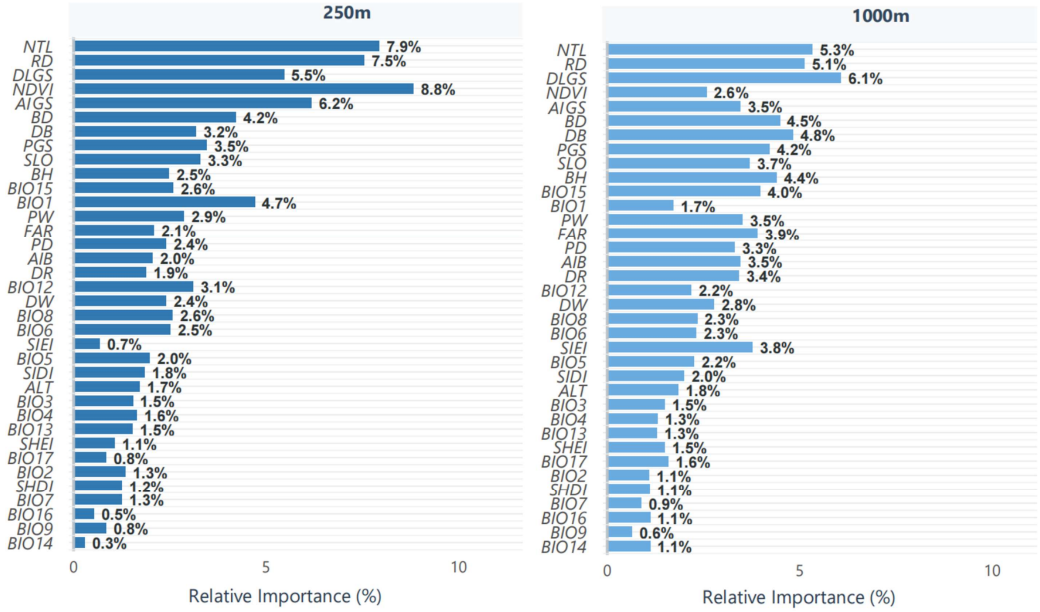


Figure 2. Relative importance of variables at two spatial scales (Source: created by the author).

3.2. Nonlinear Responses and Scale-Dependent Effects of Urban Morphology

The nonlinear effects plots generated by the BRT model (Figures 3 and 4) reveal the intricate connections between urban form and bird diversity that vary by scale. The response curves for the 250-meter scale (orange lines) and the 1000-meter scale (blue lines) differ greatly in both their direction and shape. These results confirm the presence of a strong scale reversal effect.

At the local scale, morphological parameters generally show suppressive threshold effects. BD reaches a brief peak near 0.26, after which its negative impact strengthens rapidly with increasing density. This pattern reflects how high building coverage significantly restricts habitat conditions past this point. The response curve for FAR shows a more typical pattern. It peaks around 1.5 before declining and then stabilizing. This suggests that 1.5 may represent a critical development intensity threshold needed to support local bird diversity. Beyond this value, further increases in FAR exert noticeably negative effects on diversity. Meanwhile, BH shows a stabilizing suppressive effect once it exceeds 10 meters, indicating that negative impacts, such as movement barriers and changed wind patterns, become consistent once buildings reach sufficient height.

At the landscape scale, morphological parameters show more complicated effects. As the spatial scale expands, the influence of BD on bird diversity reverses. Its relationship shifts from negative at the local scale to a positive correlation at the landscape scale, peaking when building density reaches approximately 0.35. This reveals that within a larger spatial context, a built environment having suitable density may support bird communities. It can form a mix of buildings with green spaces, encouraging a wider variety of microhabitats. The FAR shows an inverted U-shaped relationship. This finding supports

the view that a moderate development intensity could help support biodiversity levels. Both excessive concentration and excessive dispersion of development appear suboptimal. BH exhibits a unique non-monotonic pattern, initially decreasing and then increasing. This likely reflects the complex influence of buildings at different height levels on bird communities. Lower buildings might offer easier-to-reach nesting conditions, while a certain proportion of high-rise buildings may support species coexistence through the formation of varied vertical structures. These complex nonlinear responses clearly show that the relationship between urban form and its ecological effects goes beyond what conventional linear approaches can explain. They deepen our understanding of urban ecosystems toward a more refined, nonlinear regulatory paradigm.

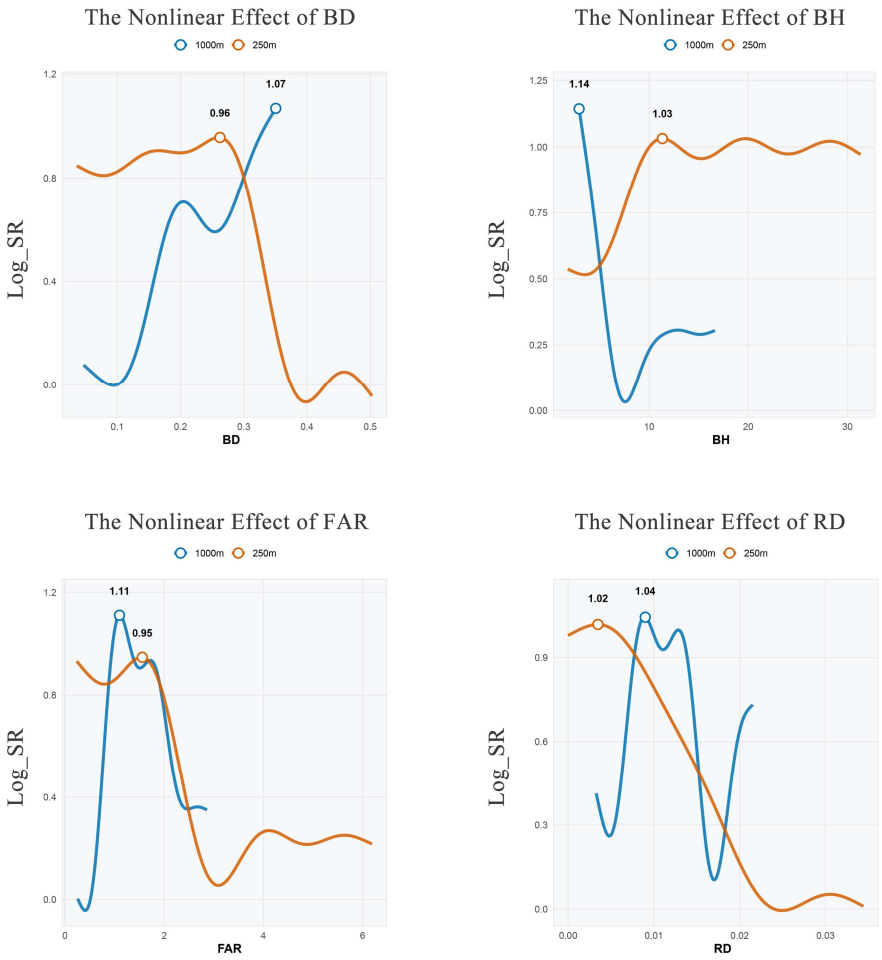


Figure 3. The multi-scale nonlinear impact of urban morphology on bird diversity (Source: created by the author).

3.3. Effects of Habitat and Human Disturbance with Saturation Thresholds

Apart from morphological parameters, the response patterns of habitat and disturbance factors also offer important guidance for planners. The NDVI has a strong positive relationship with diversity at the local scale, but its growth trend slows down noticeably after reaching 0.5. This implies that boosting vegetation cover is key to enhancing neighborhood biodiversity, yet beyond a certain level, the benefits begin to plateau. This saturation effect may reflect the limits of the local environmental carrying capacity. Once vegetation coverage reaches a high level, available ecological resources that help sustain a greater

number of species may become the new limiting factor. At the landscape scale, the PGS increases rapidly within the 30% to 40% range before stabilizing. This gives us an important ecological basis for scientifically setting the green space ratio in residential areas. DLGS exhibits a significant negative correlation at both the local scale and the landscape scale, with its effect stabilizing beyond 2000 meters. This shows the ecological value in placing residential areas within a reasonable distance from major ecological sources. This distance characteristic may reflect the effective range over which urban birds range, beyond which the supportive role of large green spaces for residential bird diversity diminishes noticeably. Furthermore, NTL shows a positive correlation with bird diversity at both scales, with the effect stabilizing after an intensity of 80. This phenomenon may indicate that moderate electric lighting and human activity extend activity time or create new feeding chances for some urban-adapted species. The urban ecosystem follows clear ecological thresholds, where different environmental factors show saturation or reversal effects at specific points. This pattern reflects how species compete for limited resources and respond differently to varied habitats (MacArthur, 1970).

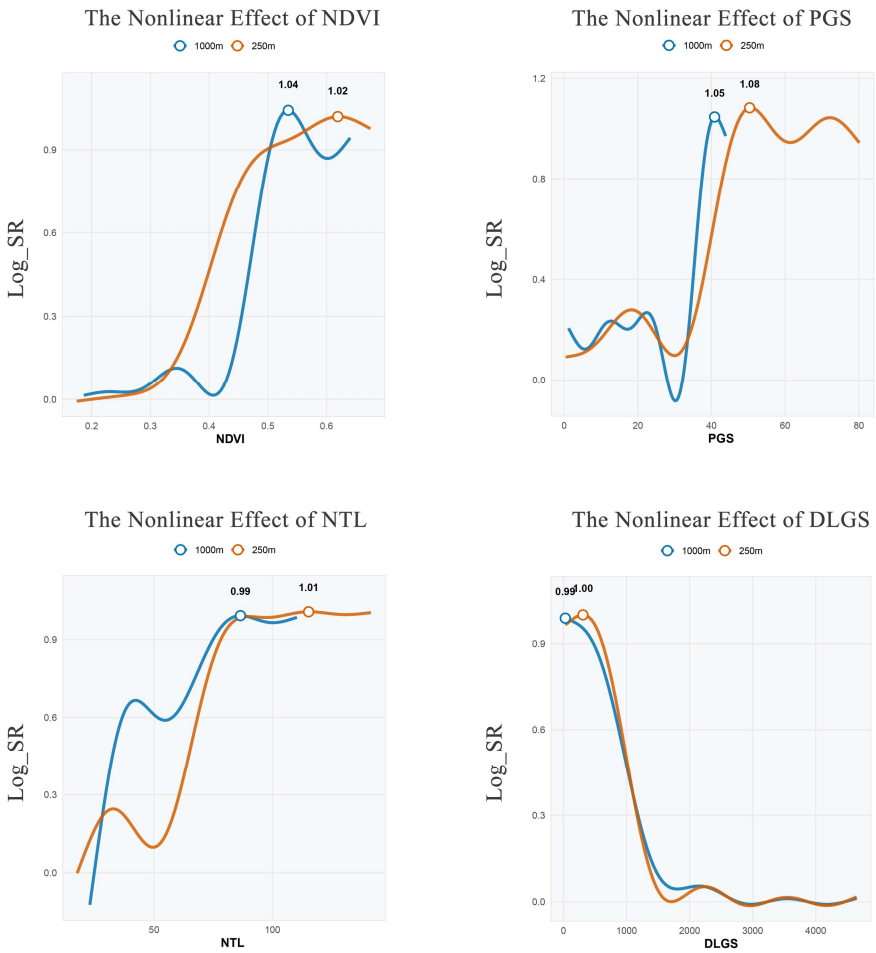


Figure 4. The multi-scale nonlinear effects of habitat and human disturbance on bird diversity (Source: created by the author).

3.4. A Conceptual Framework and Its Applications in Spatial Planning

Building on the analysis of relative importance and nonlinear effects, this study confirms that urban morphology plays a key role in shaping ecological outcomes. The framework developed here offers two

main contributions: it clarifies how ecological responses differ by scale, and it identifies ecological thresholds for key parameters. This advances urban planning as it moves away from qualitative guidance toward quantitative methods. Our framework repositions urban morphology from being a passive spatial container to serving as an active ecological regulator. It thereby promotes the integration of urban planning and ecology science.

Using this approach, this study proposes a spatial planning method that balances intensive land use with protecting nature. This path supports coordinated city growth and ecological protection through the management of morphological parameters. Management of development intensity should be based on identified ecological critical points. For instance, we recommend keeping the FAR below 2.5 at the local scale and maintaining it within the 0.5-2.5 range at the landscape scale. This helps balance development intensity with environmental benefits. This kind of differentiated management strategy reflects a scale-sensitive planning philosophy, going past the constraints of conventional one-size-fits-all approaches. Simultaneously, we suggest using 40% as a baseline for the PGS to ensure fundamental habitat quality. Furthermore, urban construction or renewal projects should be prioritized within a 2000-meter service radius of large green spaces, maximizing the beneficial spillover effects from these major ecological assets.

To put these recommendations into practice, several governance measures deserve attention. First, local planning authorities could integrate ecological thresholds into land-use zoning regulations, setting differentiated FAR limits for areas with varying ecological sensitivity. Second, cross-departmental coordination between urban planning, environmental protection, and parks management agencies would help ensure that green space targets and connectivity requirements are implemented consistently. Third, monitoring systems that track biodiversity indicators over time could provide feedback for adjusting threshold values as urban conditions change. These governance arrangements would help translate the scientific findings into enforceable planning standards.

We should recognize that the ecological thresholds identified in this study are context-dependent. Their specific values might change depending on local climate, vegetation types, and bird community composition. However, the methodological framework and the principle of scale-sensitive threshold management can be transferred to other high-density cities facing similar urbanization pressures, such as those in East Asia and rapidly growing metropolitan regions worldwide. Planners in different contexts could apply the same analytical approach while recalibrating threshold values according to local ecological and climatic conditions. Therefore, using these findings requires calibrating these parameters according to local characteristics and creating a system that can be updated over time.

4. Conclusion

This study employed a boosted regression tree model within a multi-scale analytical framework to look closely at the nonlinear regulatory mechanisms of urban morphology on bird diversity. Our results show that supporting bird diversity requires the joint support of ecological processes at different scales. At the local scale, habitat quality and human-induced disturbances serve as the primary limiting factors. Meanwhile, at the landscape scale, spatial configuration and how well ecosystems are connected play critical integrative roles. What we learned points out a major shortcoming in standard planning methods. Their single-scale approach and simple cause-and-effect assumptions are not enough to deal with the complex nature of city ecosystems. It is therefore necessary to establish a cross-scale collaborative

planning approach. Such a framework would help reconcile potential spatial conflicts between ecological processes operating at various scales.

Our work identifying ecological thresholds for important morphological and habitat parameters provides a scientific basis for shifting urban planning from qualitative guidance to quantitative design. Core parameters like BD and FAR exhibit scale-dependent reversal effects and nonlinear characteristics. These patterns show that the impact of urban morphology on biodiversity possesses significant dependence on local conditions and important transition features. Based on the research findings, a quantitative management system has been developed. This system establishes distinct control ranges for local and landscape scales. It gives specific rules for key parameters, including floor area ratio, green space percentage, and maintaining ecological connections. What we've set up shows that precise morphological regulation can effectively improve both development intensity and ecological function within limited space. This gives us a different way to think about the long-standing tension in conventional planning.

At the theoretical level, this study establishes a nonlinear "morphology-biodiversity" response framework. It repositions urban morphology from being a passive spatial carrier to serving as a useful means for ecological regulation. This shift helps us better understand how urban ecosystems function. At the practical level, the research confirms that precise spatial interventions can maximize environmental gains. It provides a new technical pathway for sustainable development in high-density urban residential areas. Together, these findings systematically explain the ecological resilience regulation mechanism of urban morphology through a multi-scale nonlinear perspective. While this study focuses on Harbin, the multi-scale nonlinear framework and the concept of ecological threshold-based planning offer transferable insights for other densely developed cities worldwide. The approach can inform urban sustainability practices in contexts where rapid growth threatens biodiversity. Our work gives a scientific basis for applying spatial plans that improve the capacity of city ecosystems to handle climate changes and support sustainable development.

5. References

Aronson, M. F., La Sorte, F. A., Nilon, C. H., Katti, M., Goddard, M. A., Lepczyk, C. A., Warren, P. S., Williams, N. S., Cilliers, S. & Clarkson, B. (2014) 'A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers'. *Proceedings of the Royal Society B: Biological Sciences* 281(1780):20133330.

Ascensão, F., D'amico, M. & Barrientos, R. (2019) 'Validation data is needed to support modelling in Road Ecology'.

Blair, R. B. (1996) 'Land use and avian species diversity along an urban gradient'. *Ecological Applications* 6(2):506-519.

Choi, D. H., Darling, L., Ha, J., Shao, J., Song, H., Fei, S. & Hardiman, B. S. (2025) 'Understanding the effects of spatial scaling on the relationship between urban structure and biodiversity'. *International Journal of Applied Earth Observation and Geoinformation* 138:104441.

Da, L. (2021) 'Urban Renewal from an Ecological Perspective: Construction of Near-Natural Urban Life Landmarks Based on the Restoration of Local Biodiversity'. *World Science*(12):30-31.

Dongchen, H., Qiuxiao, C. & Shuang, W. (2014) 'Urban planning formulation problems in China and the corresponding optimization ideas under the vision of the hypercycle theory'. *International Journal of Architectural and Environmental Engineering* 8:985-990.

Friedman, J. H. (2001) 'Greedy function approximation: a gradient boosting machine'. *Annals of statistics*:1189-1232.

Leibold, M. A. (1995) 'The niche concept revisited: mechanistic models and community context'. *Ecology* 76(5):1371-1382.

Leibold, M. A., Holyoak, M., Mouquet, N., Amarasekare, P., Chase, J. M., Hoopes, M. F., Holt, R. D., Shurin, J. B., Law, R., Tilman, D., Loreau, M. & Gonzalez, A. (2004) 'The metacommunity concept: a framework for multi-scale community ecology'. *Ecology Letters* 7(7):601-613.

Liu, Z., He, C. & Wu, J. (2016) 'The relationship between habitat loss and fragmentation during urbanization: an empirical evaluation from 16 world cities'. *Plos One* 11(4):e0154613.

Macarthur, R. (1970) 'Species packing and competitive equilibrium for many species'. *Theoretical Population Biology* 1(1):1-11.

Mccloy, M. W., Andringa, R. K. & Grace, J. K. (2022) 'Resilience of avian communities to urbanization and climate change: an integrative review'. *Frontiers in Conservation Science* 3:918873.

Mcgarigal, K. & Marks, B. J. (1995) 'FRAGSTATS: Spatial pattern analysis program for quantifying landscape structure.'. *Gen. Tech. Rep. PNW-GTR-351. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 122 p* 351.

Norton, B. A., Evans, K. L. & Warren, P. H. (2016) 'Urban biodiversity and landscape ecology: patterns, processes and planning'. *Current Landscape Ecology Reports* 1(4):178-192.

Rodrigues, A. G., Borges-Martins, M. & Zilio, F. (2018) 'Bird diversity in an urban ecosystem: the role of local habitats in understanding the effects of urbanization'. *Iheringia. Série Zoologia* 108:e2018017.

Sidemo-Holm, W., Ekroos, J., Reina García, S., Söderström, B. & Hedblom, M. (2022) 'Urbanization causes biotic homogenization of woodland bird communities at multiple spatial scales'. *Global Change Biology* 28(21):6152-6164.

Smits, J. E. & Fernie, K. J. (2013) 'Avian wildlife as sentinels of ecosystem health'. *Comparative Immunology, Microbiology and Infectious Diseases* 36(3):333-342.

Sumasgutner, P., Cunningham, S. J., Hegemann, A., Amar, A., Watson, H., Nilsson, J. F., Andersson, M. N. & Isaksson, C. (2023) 'Interactive effects of rising temperatures and urbanisation on birds across different climate zones: A mechanistic perspective'. *Global Change Biology* 29(9):2399-2420.

Ware, L., Mahon, C. L., Mcleod, L. & Jette, J.-F. (2023) 'Artificial intelligence (BirdNET) supplements manual methods to maximize bird species richness from acoustic data sets generated from regional monitoring'. *Canadian Journal of Zoology* 101(12):1031-1051.

Xu, X., Xie, Y., Qi, K., Luo, Z. & Wang, X. (2018) 'Detecting the response of bird communities and biodiversity to habitat loss and fragmentation due to urbanization'. *Science of the Total Environment* 624:1561-1576.