ASSESSING DIVERSITY RESPONSES FOR SUSTAINABLE LANDSCAPE MANAGEMENT: URBAN–RURAL GRADIENT IN DÜZCE

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Abstract

Urbanization substantially restructures landscape composition, yet fine-scale patterns of vascular plant diversity along urban–natural gradients remain insufficiently examined, particularly in ecologically heterogeneous, rapidly transforming Anatolian cities. This study explores floristic diversity across an urban–rural continuum in Düzce, a mid-sized city in the Western Black Sea region of Turkey, using a stratified design encompassing 397 vegetation plots across five ecologically informed transects. Each transect captured distinct land-use and topographic transitions—including forest interfaces, industrial zones, major roads, elevational shifts, and riparian corridors. Shannon diversity (H′) analyses revealed consistent declines in transitional areas, in contrast to elevated and stable diversity in forests, riparian margins, and steep slopes. Unexpectedly high diversity was also recorded in select urban sites, influenced by habitat mosaics and microclimatic variability. Species composition was dominated by disturbance-tolerant, cosmopolitan taxa such as *Festuca rubra*, *Cynodon dactylon*, and *Agrostis stolonifera*, reflecting strong ecological filtering across the urban matrix. Additionally, the persistent occurrence of native trees such as *Tilia tomentosa* across both urban and natural zones suggests the functional adaptability of certain mesophytic species to diverse urban contexts, while *Fagus orientalis* remained confined to interior forest sections, indicating sensitivity to fragmentation and disturbance.

Keywords: Landscape heterogeneity, Urban ecological gradients**,** Vegetation Dynamics

1. Introduction

Urbanization represents one of the most profound anthropogenic pressures on ecological systems, leading to habitat fragmentation, biotic homogenization, and the disruption of native plant communities (McKinney, 2006; Aronson et al., 2014). As cities expand into surrounding rural landscapes, they create complex spatial gradients where environmental stressors, land use intensity, and biodiversity patterns interact in multifaceted ways (Forman, 2008). Understanding how plant species diversity responds across such urban–rural gradients is crucial not only for conserving biodiversity in human-dominated landscapes but also for informing sustainable urban planning and green infrastructure development (Niemelä, 1999; Faeth et al., 2011). Floristic diversity is a vital component of urban ecosystem functioning (Doğan & Eroğlu, 2024; Weiskopf et al., 2024), influencing pollination (Loy & Brosi, 2022), microclimatic regulation, soil stabilization, and cultural ecosystem services (Terschanski et al., 2024). However, the mechanisms and spatial dynamics by which urbanization gradients impact vascular plant richness and composition remain insufficiently resolved, particularly in rapidly urbanizing regions with heterogeneous topographies and land-use legacies.

Recent studies have emphasized the need to move beyond simplistic urban–nonurban dichotomies and instead examine continuous spatial transitions from urban cores to rural peripheries (Müller et al., 2013; Beninde et al., 2015). While a growing body of research (Schmidt et al., 2014; Wang et al. 2020; English et al., 2022) has documented plant diversity patterns in metropolitan areas of Europe, America, and East Asia, significant geographic and methodological gaps persist (McKinney, 2008; Anderson et al. 2021). For instance, many studies employ coarse-resolution spatial sampling or remote sensing proxies without ground-truthed floristic data (Godefroid & Koedam, 2007; Williams et al., 2009). Others are confined to small sample sizes or limited to public greenspaces, neglecting the fine-scale heterogeneity of plant communities in residential and peri-urban zones (Kowarik, 2011). Furthermore, much of the literature focuses on large capital cities (Zerbe et al. 2003; Schmidt et al. 2014) leaving smaller urban centers—especially those in understudied biogeographic zones

such as the eastern Mediterranean and Black Sea regions—largely unrepresented in urban biodiversity science.

In the context of Turkey, the literature on urban biodiversity remains sparse and spatially biased. While major cities have received modest attention (e.g., Altay et al., 2012; Çoban et al., 2020), medium-sized cities with diverse ecological gradients and post-disaster urbanization dynamics, such as Düzce, are rarely investigated. Moreover, existing studies have seldom addressed the spatial continuity of plant diversity from urban cores to rural peripheries, thereby neglecting how ecological gradients intersect with urban morphology. In particular, there is a marked absence of studies that combine fine-scale, ground-verified floristic surveys with a continuous gradient perspective, capturing the full transition from dense urban fabric through transitional zones to natural habitats. Previous research has tended to concentrate on metropolitan contexts (e.g., Wang et al., 2020; Schmidt et al., 2014), rely heavily on coarse-resolution spatial data or remotely sensed proxies (e.g., Finizio, 2024; Zhu et al., 2019), and overlook medium-sized Anatolian cities where the juxtaposition of urban and rural land uses may produce distinctive biodiversity responses.This omission is particularly critical in regions where transitional zones act as ecological thresholds, mediating abrupt changes in land-use intensity, microclimatic conditions, and species composition—elements that are central to climate-resilient urban planning and biodiversity governance.

Düzce constitutes an especially compelling case study due to its unique convergence of post-seismic urban transformation, high landscape heterogeneity, and biogeographical significance within the Western Black Sea region. Following its elevation to provincial status after the 1999 earthquake, the city has experienced rapid yet spatially uneven urban expansion, embedded within a fine-grained mosaic of forests, agricultural lands, and semi-natural habitats (Kara, 2010). This intricate interplay between anthropogenic pressures and ecological heterogeneity offers an exceptional opportunity to examine how vascular plant diversity responds along a continuous urban–rural gradient in a medium-sized Anatolian city—an urban category largely absent from current biodiversity discourse.

Despite this ecological and urban complexity, no prior study has comprehensively assessed floristic diversity in Düzce with high spatial resolution and standardized botanical protocols. This research addresses that gap by providing the first fine-scale, ground-verified assessment of vascular plant diversity across the city's complete urban–rural continuum, thereby capturing patterns that remain unresolved in studies constrained to large metropolitan contexts or coarse spatial analyses. The unique contribution of this work lies in its explicit focus on a secondary urban center in an underrepresented biogeographical region, examining diversity not as a binary urban–nonurban contrast but as a dynamic continuum influenced by interacting environmental and morphological gradients.

Accordingly, this study pursues the following objectives: (i) to quantify spatial patterns of vascular plant diversity across urban, transitional, and natural zones in Düzce; (ii) to evaluate how land-cover composition, topography, and proximity to natural features influence these patterns; and (iii) to generate evidence-based insights to inform biodiversity-sensitive urban planning in ecologically heterogeneous and rapidly transforming secondary cities. The central research question guiding this study is: How does vascular plant diversity vary along the urban–rural continuum of Düzce, and to what extent are these patterns shaped by differences in land-cover composition and proximity to natural features?

2. Materials and Methods

This study was conducted within the administrative boundaries of the central district of Düzce, located in the Western Black Sea region of Turkey (Fig 1). Floristically, Düzce is situated within the A3 square of the Davis Grid System (Davis, 1965–1985), a widely used biogeographical framework developed by Peter H. Davis to standardize the spatial referencing of vascular plant taxa in Turkey. The city lies between the provinces of Sakarya to the west, Bolu to the east and southeast, and Zonguldak to the north, with the Black Sea coastline bordering the province's northern limits.

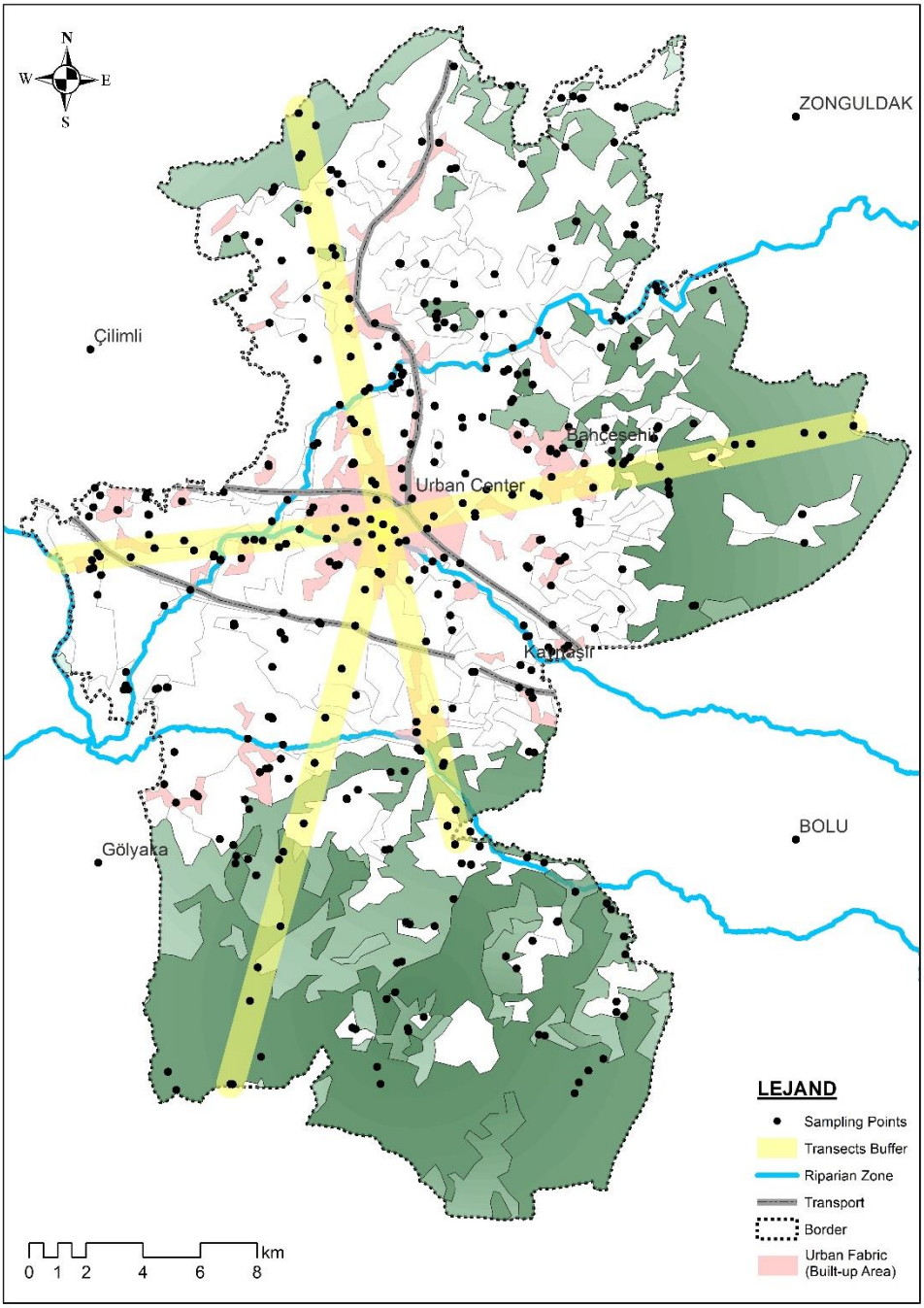

Fig. 1 Location Map of the Study Area

Covering an area of approximately 2,574 km², the province had a total population of 395,679 as of the end of 2021 (TUIK, 2021). Düzce was granted provincial status in 1999 following a major earthquake, which catalyzed significant infrastructural redevelopment and population influx, leading to fragmented and rapid urban expansion (Kara, 2010). Düzce exhibits a geomorphologically diverse and ecologically significant topographical structure, characterized by a broad elevation range extending from near sea level in the northern lowland plains to approximately 1,945 meters in the

Abant and Köroğlu mountain ranges to the south and east (Duzce Province EnvironmentalStatus Report, 2009). The provincial average elevation is around 500 meters above sea level, reflecting a transitional landscape composed of coastal plains, alluvial basins, foothills, and densely forested uplands, representative of the Western Black Sea biogeographical zone. Notably, the city center is situated within a fertile intramontane basin at approximately 120–180 meters elevation, encircled by forested mountain belts and high plateaus. This basin–mountain configuration not only governs the city's hydrographic and climatic variability but also contributes to its ecological heterogeneity, supporting a mosaic of urban, agricultural, and semi-natural habitats with high floristic potential (Görcelioğlu et al. 1999; Özmen et al. 2015).

Düzce features a transitional climate between the Black Sea oceanic and inland continental types, characterized by relatively high precipitation and humidity, particularly in the spring and autumn months. The annual mean temperature is around 13.5°C, while average annual precipitation exceeds 800 mm, supporting diverse vegetation types and land cover heterogeneity (Meteorological General Directorate, 2021). Düzce harbors a substantial diversity of both herbaceous and woody plant species, with a recorded flora comprising approximately 700 taxa, of which nearly 10% are endemic to the region (Aksoy et al. 2010; Aksoy et al. 2014).

A total of 397 vegetation subplots were selected across the central district of Düzce using a stratified random sampling method, which ensured the inclusion of varying urbanization intensities and land use categories. This method is widely recommended in ecological field research for its capacity to minimize sampling bias and enhance representativeness in heterogeneous landscapes (Krebs, 1999; Thompson, 2012). In order to secure a confidence level between 90 % and 95 % with a tolerable margin of error (~5 %–10 %) for estimating patterns of species diversity, the sampling framework adhered to the methodological recommendations of Bartlett et al. (2001) and Hansel and Hurwitz (1949). This statistical rationale confirmed the adequacy of the 397-point sample size. Plots devoid of vegetation or containing only a single plant taxon were omitted from subsequent analyses, as such sites fail to yield ecologically informative data for assessing Shannon diversity. In these cases,

alternative sites located nearby—sharing comparable degrees of urbanization but exhibiting greater floristic heterogeneity—were selected as substitutes. The final set of 397 sampling plots was systematically distributed across a broad spectrum of land-cover types classified according to the CORINE system, including urban, agricultural, forest, wetland, and riparian habitats, thereby ensuring comprehensive ecological representation (Table 1). While plot numbers differed slightly among land-cover categories owing to logistical limitations, the analytical design focused on modelling alpha diversity metrics—principally Shannon diversity (H′), along with species richness and evenness—as continuous responses to environmental predictors. Consequently, the variation in plot counts did not compromise either the validity or the statistical robustness of the models.

Table 1. Spatial Distribution of Sampling Sites According to Land Cover Categories

Land Cover (Level 2)	Land Cover (Level 3)	Subtype	No. of Plots	Minimum No. of Subplots
1.1. Urban Fabric	1.1.1 Continuous Urban Fabric	Park / Urban Green Space	29	1
	1.1.2 Discontinuous Urban Fabric	Residential Area / Orchard / Annual Crops / Urban Void / Coppice	29	≥ 2
1.2. Industrial, Commercial, and Transport Units	1.2.1. Industrial and Commercial Units	Industrial Site / University Campus	9	1
	1.2.2. Road and Rail Networks and Associated Land	Road Verge	11	1
1.3. Mine, Dump, and Construction Sites	1.3.1. Mineral Extraction Sites	Quarry	3	1
	1.3.3. Construction Sites	Urban Green Space	1	1
2.1. Arable Land	2.1.2. Permanently Irrigated Land	Coppice / Annual Crops	5	2
2.2. Permanent Crops	2.2.2. Fruit Trees and Berry Plantations	Orchard	18	1
2.3. Pastures	2.3.1. Pasture Land	Pasture	9	1
2.4. Heterogeneous Agricultural Areas	2.4.2. Complex Cultivation Patterns	Orchard / Coppice / Annual Crops / Irrigated Crops / Ornamental Plants	27	≥ 2
	2.4.3. Land Principally Occupied by Agriculture with Significant Areas of Natural Vegetation	Agricultural Use / Forest	10	2
3.1. Forests	3.1.1. Broad-leaved Forests	Broad-leaved Forest	45	2
	3.1.2. Coniferous Forests	Coniferous Forest	3	2
	3.1.3. Mixed Forests	Mixed Forest	11	2
3.2. Maquis and Herbaceous Vegetation	3.2.1. Natural Grasslands	Natural Grassland	1	1
	3.2.4. Transitional Woodland-Shrub	Forest / Shrubland	2	1
4.1. Inland Wetlands	4.1.1. Inland Wetlands	Inland Wetland	2	≥ 2
5.1. Inland Waters	5.1.1. Water Courses	Riparian Zone	15	1
Total			270	397

Field surveys were conducted during the vegetation periods of 2022, 2023, and 2024, covering the peak phenological stages of herbaceous and woody plants. All vascular plant species present within

each 20 m × 20 m plot were identified in situ using regional floras and taxonomic keys. When field identification was not possible, specimens were collected and subsequently verified at the Herbarium of the Faculty of Forestry, Düzce University (DUOF).

Urban transects were delineated via GIS-based spatial analysis and high-resolution imagery, structured to radiate from Düzce's geographic center toward five distinct directions—north, south, east, west, and southeast—to capture the full range of urban expansion gradients and adjacent ecological contexts. Each transect included 15–30 plots and covered a standardized width of 1,000 m (with 500 m buffers on either side), ensuring statistical robustness and ecological representativeness. Orientation was ecologically informed: the northern transect represented urban-forest transitions; the southern encompassed rural features and hydrological influence; the western targeted potential industrial impact; the eastern intersected zones of urban sprawl and major roads; and the southeastern followed the steepest terrain, enabling assessment of topographic effects. This multi-directional, gradient-based design maximized spatial, functional, and topographic coverage for subsequent diversity analyses.

For analytical purposes, the urban–rural gradient was operationally classified into three main zones—urban, transitional, and natural—based on a combination of spatial metrics and CORINE 2018 Level-3 land cover categories. Urban zone: plots located within continuous and discontinuous urban fabric, industrial and commercial areas, or transportation infrastructure (CORINE codes 1.1.1–1.2.3) within 0–1 km of the urban core boundary. Transitional zone: plots situated in ecotonal areas where urban land uses interface with agricultural or semi-natural habitats (e.g., pastures, orchards, mixed-use farmlands; CORINE codes 2.1.1–2.4.4), typically 1–3 km from the urban core. Natural zone: plots located in forest, natural grassland, shrubland, wetland, or riparian systems (CORINE codes 3.1.1–4.3.2) beyond 3 km from the urban core, with minimal direct anthropogenic land-use intensity. The classification process was implemented in a GIS environment, integrating high-resolution satellite imagery and official land-use datasets to ensure accurate spatial delineation of gradient categories.

This explicit zoning enabled subsequent statistical modelling of diversity patterns across a continuous urban–rural continuum, rather than as a binary urban–nonurban contrast.

Species diversity within each plot was quantified using the Shannon diversity index (H′), which accounts for both the number of species present and their proportional abundances (Whittaker, 1972), thus providing a robust measure of community complexity across anthropogenic gradients. The index was calculated as:

$$H' = -\sum_{i=1}^{s} p_i \, ln \, p_i$$

where p_i is the proportion of individuals belonging to species i relative to the total number of individuals recorded in the plot. The Shannon index was chosen for its sensitivity to both common and rare species, making it particularly suitable for detecting changes in community composition along urban–rural gradients (Peet, 1974; Spellerberg & Fedor, 2003). All calculations were performed in Python using the NumPy, Pandas, scipy, statsmodels, scikit-learn, Matplotlib, and Seaborn libraries.

To assess whether vascular plant diversity differed significantly across the five urban–rural transects, we applied the non-parametric Kruskal–Wallis H test, which is robust against deviations from normality and heteroscedasticity (McKight & Najab, 2010). The test compared Shannon diversity index values among transects, each representing distinct spatial and environmental contexts: (i) Northern gradient (urban–forest interface), (ii) Western gradient (industrial influence), (iii) Eastern gradient (urban sprawl and road infrastructure), (iv) Southwestern gradient (steep terrain), and (v) Southern gradient (rural–riparian mosaic).

All statistical analyses were conducted in Python, using the packages pandas for data handling, scipy.stats for Kruskal–Wallis and pairwise Mann–Whitney U tests, and scikit-posthocs for post-hoc comparisons with Bonferroni correction. Data visualisation was performed using matplotlib and seaborn to ensure high-quality and publication-ready figures. Where the Kruskal–Wallis test revealed

significant differences, post-hoc analyses were applied to determine which transect pairs differed statistically.

3. Results and Discussion

A total of 756 vascular plant taxa (Supplementary Table) were identified across the study area. Among these, the family Asteraceae was the most species-rich, represented by 84 taxa, underscoring its dominance in disturbed and urban-edge habitats. The most frequently recorded herbaceous species across sampling plots were *Trifolium repens* L. (42.17%), *Cynodon dactylon* L. (40.91%), and *Hedera helix* L. (36.11%). In the woody stratum, *Fagus orientalis* Lipsky (20.96%), *Carpinus orientalis* Mill. (20.19%), and *Corylus avellana* L. (19.95%) represented the most dominant taxa in terms of presence frequency. These patterns suggest that the aforementioned herbaceous species are capable of persisting across a wide range of microhabitat conditions and urban disturbance regimes, particularly within transitional and edge environments (McKinney, 2006; Vallet et al., 2010). Likewise, the observed dominance of native forest tree species in peri-urban zones underscores the ecological continuity between urban green infrastructures and surrounding semi-natural landscapes (Aronson et al., 2014; Zerbe et al., 2003). Analysis of Raunkiaer life forms revealed that the most prevalent biological type was Hemicryptophytes, comprising 33.73% of all recorded taxa, followed by Phanerophytes (20.24%) and Therophytes (18.92%). Additional contributions were made by Geophytes (8.60%), Chamaephytes (4.76%), and aquatic or semi-aquatic types such as Hydrophytes (0.53%), Helophytes (0.26%), and Holoparasites (0.40%). Regarding phenological leaf habit, deciduous species dominated the flora, accounting for 85.58% of all taxa. Evergreen species constituted 13.36%. These compositional patterns collectively underscore the ecological signature of a temperate mesophytic flora, shaped by the confluence of ruderal and forest-affiliated plant communities. The high proportion of hemicryptophytic and phanerophytic life forms aligns with functional syndromes typical of temperate deciduous forest biomes, wherein plant strategies are adapted to pronounced seasonality and intermediate disturbance regimes (Box, 1996; Weithoff et al. 2001; Pignatti et al., 2002). Furthermore, the overwhelming prevalence of deciduous taxa is

196 emblematic of the transitional ecological mosaic characterizing the Western Black Sea region, where
197 coastal, agricultural, and montane ecosystems intersect under complex climatic and topographic
198 gradients (Avcı, 2014).

199 The zonal transect analysis revealed consistent shifts in plant diversity along urban-to-natural
200 gradients, with marked increases and decreases observed depending on the landscape context and
201 transitional structure of each transect (Figure 2). Across all transects, transitional zones consistently
202 exhibited the lowest Shannon diversity values, indicating a general reduction in species richness and
203 evenness at the urban–natural interface. Conversely, zones associated with natural or semi-natural
204 features—such as forest areas, riparian strips, and high-elevation sites—tended to support higher
205 diversity levels, particularly when adjacent to roads or riparian. In several transects (e.g., Transect 1
206 and Transect 4), a clear increase in diversity was observed from the transitional zone toward forested
207 or highland areas, suggesting a positive relationship between ecological integrity and elevation or
208 canopy coverage. Similarly, in Transect 3, diversity increased sharply at the forest-road edge,
209 exceeding values recorded in both forest interior and urban zones, pointing to localized edge
210 enhancement effects. By contrast, Transect 2 displayed a notable decline in diversity within the urban-
211 industrial zone, where values dropped significantly below both urban residential and rural zones,
212 reflecting the suppressive ecological footprint of industrial land use. Taken together, these results
213 highlight distinct zonal effects on plant species diversity, with reductions frequently associated with
214 ecological transition or disturbance zones, and increases linked to elevation, edge structure, forest
215 continuity, or riparian connectivity. While the riparian zone in Transect 5 exhibited a relatively high
216 mean Shannon diversity value, this should not be interpreted as uniformly high diversity across all
217 riparian sampling points. In fact, greater heterogeneity was observed within the urban zone, which
218 included both sites of exceptionally low and notably high diversity, resulting in a broader distribution
219 and some urban sites exceeding the diversity levels found in the riparian zone. The higher consistency
220 of diversity within the riparian zone contributed to its elevated mean; however, the presence of highly
221 diverse urban microhabitats—potentially influenced by factors such as ornamental planting, habitat

mosaics, or microclimatic refugia—led to localized peaks that in some instances surpassed riparian values. This finding complicates the assumption that hydrological proximity alone guarantees superior biodiversity outcomes and instead emphasizes the role of site-level factors and spatial heterogeneity in shaping urban floristic diversity (Faeth et al., 2011; Aronson et al., 2014; Naiman & Décamps, 1997; Salinitro 2018). From an ecological perspective, these patterns suggest that riparian zones may serve as biodiversity stabilizers, while urban areas may function as reservoirs of floristic extremes—hosting both highly degraded and highly diverse patches depending on land management, disturbance regimes, and structural complexity. Similar to the findings of Kaya et al. (2025), who conducted a study in the same region with a different focus, this research also identified notably high plant diversity in riparian habitats. Despite variations in the sampling locations, the convergence of results underscores the capacity of wetland-associated areas to sustain elevated levels of biodiversity under ongoing urban pressures, highlighting the critical ecological role these zones continue to play within the urban landscape matrix.

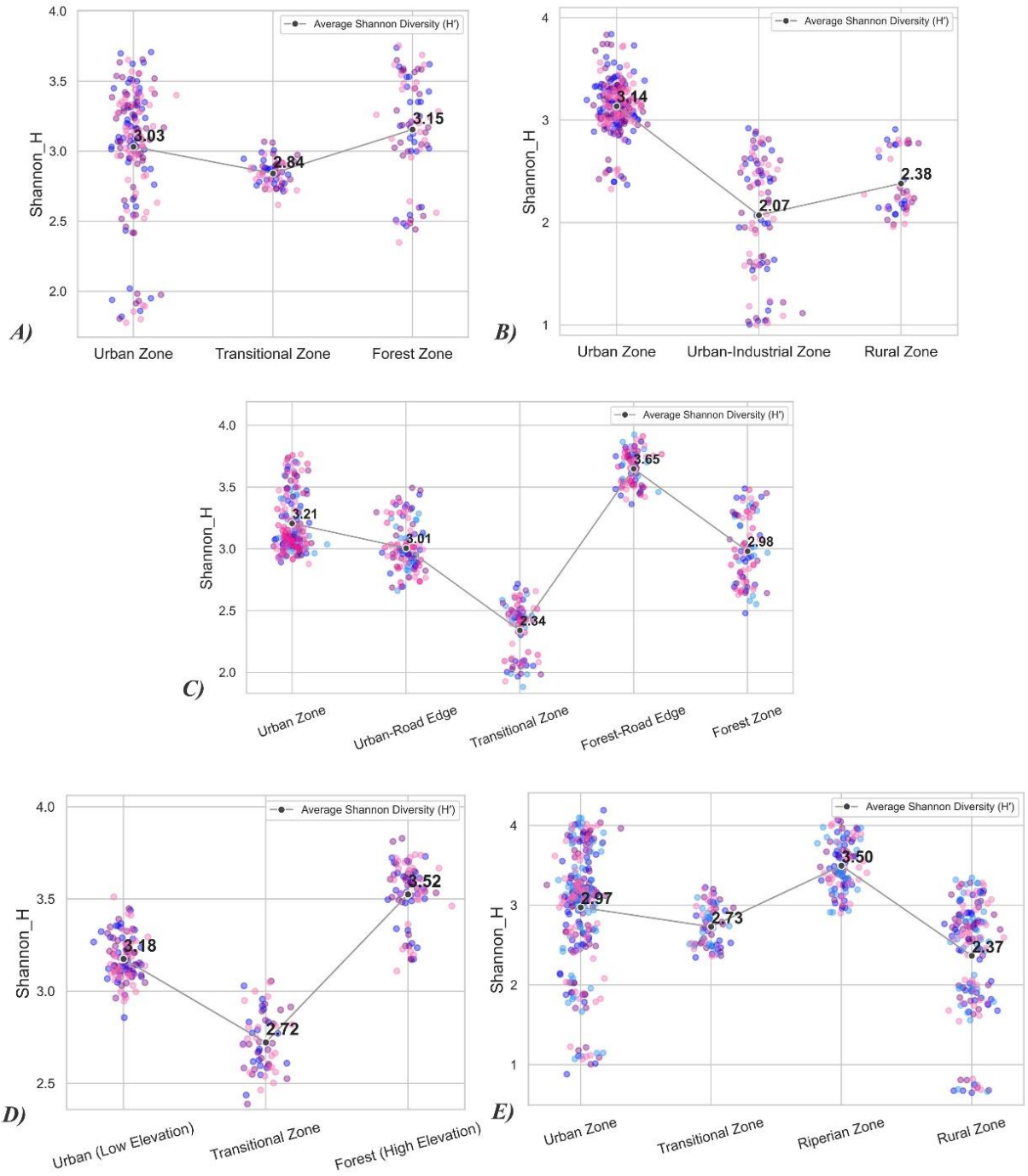

Fig 2. Zonal gradients in plant diversity (Shannon H′) across urban-to-natural transects (A: Transect 1 – Northern transect representing an urban–forest gradient; B: Transect 2 – Western transect reflecting industrial impact across the urban–rural continuum; C: Transect 3 – Eastern transect characterized by urban sprawl and road infrastructure; D: Transect 4 – Southwestern transect along steep terrain, capturing topographic influences; E: Transect 5 – Southern transect encompassing rural characteristics and riparian connectivity)

The patterns observed across the five transects indicate a nuanced and non-linear response of plant species diversity to urbanization and associated environmental gradients. Contrary to classical urban

ecology expectations which often posit a steady decline in biodiversity with increasing urban intensity (McKinney, 2008; Shochat et al. 2010), our results suggest that specific urban or edge conditions may foster unexpectedly high levels of floristic diversity, likely due to intermediate disturbance regimes (Bendix et al. 2017) or microhabitat heterogeneity (Jones et al. 2011; Kowarik, 2011; Alvey, 2006). The elevated diversity in urban zones across multiple transects (e.g., Transects 1, 2, and 3) may be attributed to the admixture of native and non-native taxa, frequent landscape interventions (Harper et al. 2005), and increased niche availability in fragmented and managed green spaces (Aronson et al. 2014; Hope et al., 2003; Wandl, 2019; Wang et al. 2024). Urban botanical heterogeneity can reflect both intentional design choices (e.g., ornamental plantings) and spontaneous colonization, especially in areas with varied substrate conditions and microclimates (Faeth et al., 2011). Conversely, urban-industrial zones, as evident in Transect 2, presented a sharp reduction in diversity, likely due to cumulative anthropogenic stressors such as pollution, impermeable surfaces, and habitat fragmentation (Pickett et al., 2011; Niemelä, 1999). These zones tend to lack ecologically functional green infrastructure, resulting in biotic homogenization and suppression of sensitive native flora. The consistently low diversity in transitional zones (all transects) reflects the ecological instability typical of edge habitats exposed to both biotic and abiotic stresses. Edge effects, including higher temperatures, increased wind exposure, and altered soil moisture, can negatively impact plant community stability (Murcia, 1995; Jacquemyn et al. 2001; Harper et al., 2005). Remarkably, the forest-road edge zone in Transect 3 demonstrated the highest diversity ($H' = 3.65$), suggesting a potential edge enhancement effect, where increased light availability and disturbed soils facilitate the coexistence of forest interior species with ruderal taxa (Haerdtle et al. 2003). However, such diversity peaks may be transient or dependent on early successional dynamics, necessitating temporal monitoring. In Transect 4, elevation emerged as a significant driver of plant diversity, with higher-elevation forests supporting richer assemblages than lower-elevation urban counterparts. This aligns with altitudinal diversity gradients observed in Mediterranean and temperate ecosystems (Rahbek, 2005), where elevational heterogeneity enhances beta diversity through microclimatic and edaphic

stratification. Lastly, the riparian zone in Transect 5 illustrated the role of hydrological proximity in sustaining elevated diversity. Riparian habitats are widely acknowledged as biodiversity hotspots due to their structural complexity, resource abundance, and buffering capacity (Prado et al. 2022; Sabo et al. 2005). Their integration into urban landscapes may provide critical ecosystem services while enhancing urban biodiversity resilience.

The floristic analysis across the urban–natural transects revealed a spatially structured but compositionally constrained pattern of vegetation dominated by disturbance-tolerant herbaceous taxa and a select set of woody perennials. Urban intensity, landscape context, and topographic features all contributed to the variation in species richness and frequency, shaping distinctive yet functionally convergent plant assemblages. Among herbaceous taxa, *Festuca rubra* L. and *Cynodon dactylon* L. were persistently observed across most transects. Their widespread occurrence in urban cores, transition zones, and rural margins reflects their ecological amplitude and compatibility with mown, compacted, or intermittently disturbed environments. These species serve as ecological constants in the urban matrix, particularly in areas influenced by regular anthropogenic maintenance. In more heavily altered zones, such as the industrial and roadside segments of Transects 2 and 3, *Cichorium intybus* L., *Convolvulus arvensis* L., and *Agrostis stolonifera* L. appeared with higher frequency, suggesting floristic shifts toward ruderal, early-successional communities. These taxa are indicative of fragmentation-prone interfaces where soil disturbance, elevated irradiance, and poor nutrient retention shape the ground vegetation. Woody species, while less frequent in absolute terms, were ecologically significant. The majority consisted of urban-tolerant or semi-naturalized taxa such as *Ligustrum lucidum* W.T.Aiton, *Prunus laurocerasus* L., and *Acer pseudoplatanus* L., often found in transition zones, institutional landscapes, and riparian buffers. Their spatial presence underscores landscape memory and the persistence of planted ornamental species in anthropogenic matrices. Importantly, *Tilia* species—primarily *Tilia platyphyllos* Scop. and *Tilia tomentosa* Moench—were detected consistently across multiple transects, including within urban parkland, along steep slopes (Transect 4), and notably within the riparian corridors of Transect 5. Their wide ecological amplitude

and cultural salience have made them not only functional elements in stormwater management and slope stabilization but also favored street and urban park trees. The continued presence of *Tilia* both within dense urban fabric and along ecological gradients illustrates its dual role as a native element and an intentional part of urban vegetation planning. Furthermore, *Fagus orientalis* Lipsky, while entirely absent from urban and transitional zones, was increasingly encountered toward the terminal forest sections of Transects 1 and 4. This spatial confinement to less-disturbed, canopy-dense areas reflects its sensitivity to light and soil compaction, as well as its status as a late-successional, mesophilic climax species typical of mature deciduous forests in the region. Its localized dominance in terminal zones signifies a threshold beyond which urban influence diminishes and forest integrity is reestablished. The floristic configuration along urban–natural transects in Düzce elucidates the profound ecological restructuring induced by urban expansion, manifesting as biotic homogenization and a decline in native forest integrity. This spatial gradient reinforces prior assertions that urban environments disproportionately favor disturbance-resilient, generalist taxa, while constraining the persistence of ecologically specialized species (Devictor et al.2008; Kowarik, 2011; Aronson et al., 2014). The omnipresence of *Festuca rubra* and *Cynodon dactylon*—both clonal, stress-tolerant grasses—exemplifies the ecological filtering mechanisms that underpin urban plant assemblages. Their dominance across structurally divergent zones reflects a functional convergence driven by anthropogenic pressures such as compaction, fragmentation, and mowing regimes (Ruas et al. 2008; Lososová et al., 2012). In contrast, the spatial recurrence of *Tilia* spp. across topographically complex and hydrologically buffered contexts, including riparian margins and slope forests, signifies the resilience and adaptability of select native trees when integrated into urban matrices. Beyond their spontaneous occurrence, the frequent cultivation of *Tilia* in managed landscapes underscores their dual ecological and cultural utility—linking biodiversity support with landscape functionality (Niemelä et al., 2011; Kendal et al., 2012). Conversely, the restriction of *Fagus orientalis* to terminal forest compartments delineates a threshold beyond which urban tolerance sharply declines. This pattern aligns with its late-successional status and stringent habitat requirements—mesic soils, low

light variability, and disturbance exclusion—rendering it emblematic of forest degradation gradients (Beninde et al., 2015; Jim & Chen, 2009). Furthermore, transects traversing hydrologically or geomorphologically complex zones revealed slightly elevated richness, suggesting that slope and riparian features serve as partial refugia for semi-sensitive taxa (Zhang 2020; Yangi 2009). Nevertheless, the absence of obligate forest or wetland specialists indicates functional erosion even within these buffers—likely due to edge effects, isolation, and anthropogenic runoff. The overall paucity of native woody species, with exceptions largely limited to ornamental introductions such as *Ligustrum lucidum* or *Prunus laurocerasus*, reflects a broader structural simplification of the urban flora. This phenomenon parallels a shift toward aesthetic-driven vegetation planning at the expense of ecological fidelity, as documented across temperate urban regions (Alvey, 2006; Anderson et al., 2021).

The Kruskal–Wallis H test revealed statistically significant differences in vascular plant diversity (Shannon H′) among the five land-use zones ($H = 85.42$, $p < 0.001$). Post-hoc pairwise Mann–Whitney U tests with Bonferroni correction demonstrated that all pairwise comparisons between zones were statistically significant ($p < 0.05$; Table 2), indicating distinct diversity profiles along the urban–rural gradient.

Table 2. Pairwise Mann–Whitney U test results for Shannon diversity across land-use zones.

Zone 1	Zone 2	U statistic	p-value
Urban	Industrial	670	<0.001 **
Urban	Transition	73	0.04 *
Urban	Rural	4	0.036 *
Urban	Forest	0	<0.001 **
Industrial	Transition	23	0.03 *
Industrial	Rural	1	0.006 *
Industrial	Forest	0	<0.001 **
Transition	Rural	78	0.009 *
Transition	Forest	0	0.041 *
Rural	Forest	82	<0.001 **

(All comparisons significant at $p < 0.05$ after Bonferroni correction.)

Diversity was lowest in the Industrial and Urban Core zones, intermediate in the Urban Fringe, and highest in the Rural and Forest Edge zones (Figure 3). This pattern reflects a progressive increase in species diversity with decreasing anthropogenic disturbance and increasing habitat heterogeneity.

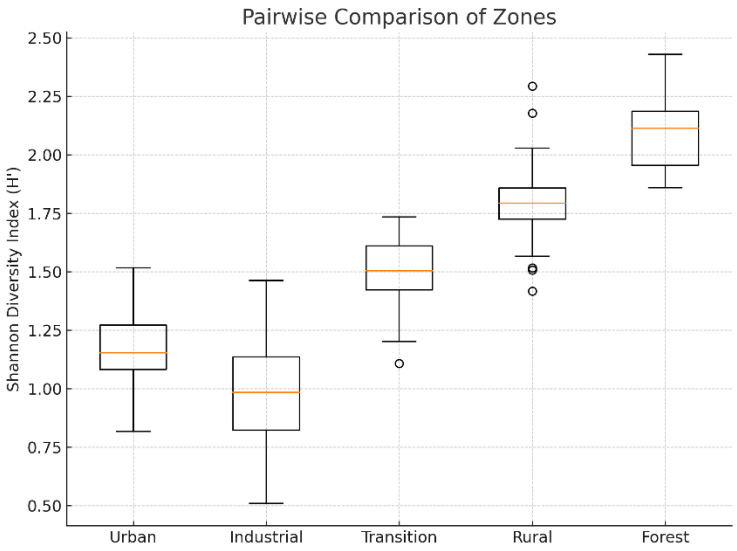

Fig 3. Distribution of Shannon diversity index (H') across land-use zones

The results demonstrate a clear and statistically robust zonal differentiation in vascular plant diversity across the urban–rural gradient in Düzce. The lowest diversity values in the Industrial and Urban Core zones are consistent with patterns reported in other urban ecology studies, where high levels of habitat sealing, fragmentation, and anthropogenic pressure limit both native species establishment and functional diversity (Aronson et al., 2014; McKinney, 2008). The Urban Fringe exhibited intermediate diversity, functioning as an ecological transition zone where remnant green spaces, spontaneous vegetation, and peri-urban agricultural plots provide refugia for both ruderal and native taxa (Muratet et al., 2007). These areas can act as biodiversity reservoirs if appropriately managed, highlighting their strategic role in biodiversity-sensitive urban planning. The Rural and Forest Edge zones recorded the highest diversity values. This can be attributed to a combination of reduced habitat disturbance, higher vegetation structural complexity, and proximity to source populations in semi-natural and forested areas (Niemelä, 1999). The elevated diversity at the forest edge aligns with edge ecology theory, which predicts increased species richness in ecotonal habitats due to the overlap of

357 species from adjacent ecosystems (Ries et al., 2004). Overall, the statistically significant differences
358 across all zones confirm that vascular plant diversity in Düzce responds strongly to the degree of
359 urbanization and associated environmental gradients. This finding underscores the need for integrated
360 spatial planning strategies that mitigate biodiversity loss in core urban and industrial zones while
361 leveraging the conservation potential of transitional and peri-urban areas. These findings are
362 consistent with, yet also extend, global urban ecology research. For example, studies in Shanghai,
363 China reported similarly complex diversity patterns along urban–rural gradients, where managed
364 green spaces and roadside verges contributed unexpectedly high richness (Wang et al., 2020). In Los
365 Angeles, USA, English et al. (2022) demonstrated that unmanaged grasslands within the urban fabric
366 retained substantial native diversity, indicating that even highly urbanized contexts can sustain
367 valuable plant assemblages when structural heterogeneity is maintained. Comparable results were
368 also observed in Berlin, Germany, where plant richness was influenced by fine-scale variation in
369 urban morphology and habitat mosaics rather than urban intensity alone (Schmidt et al., 2014).
370 Likewise, in South African cities, Anderson et al. (2021) emphasized that species responses are
371 strongly modulated by social-ecological drivers, underscoring the need for context-specific
372 management strategies. By integrating the Düzce case into this global discourse, our study reinforces
373 the view that medium-sized cities in biogeographically diverse regions can provide both challenges
374 and opportunities for sustaining vascular plant diversity under accelerating urbanization.

375 Collectively, these findings emphasize the importance of fine-scale zonal differentiation in urban
376 biodiversity planning. Urban landscapes are not ecologically uniform; instead, they comprise a
377 mosaic of zones with distinct ecological roles and conservation potentials. Effective biodiversity
378 management in cities must therefore go beyond a simplistic urban–rural dichotomy and consider the
379 multifactorial influences of elevation, hydrology, infrastructure, and edge dynamics.

380 **4. Conclusion**

381 This study highlights that plant species diversity across urban, transitional, and natural zones exhibits
382 fine-scale spatial variation that extends beyond the explanatory power of traditional urban–rural

dichotomies, thereby emphasizing the value of high-resolution, transect-based ecological assessments in urban landscapes. By incorporating multiple transects and detailed species occurrence data, the research captures the fine-scale floristic heterogeneity often overlooked in broader urban ecology models. The observed variation in Shannon diversity across transects highlights the ecological importance of microhabitat conditions, land-use intensity, edge effects, and topographic and hydrological gradients in shaping urban biodiversity. Transitional zones consistently exhibited depressed diversity levels, reinforcing their role as structurally and functionally unstable ecological interfaces. Conversely, areas proximate to natural features—such as forests, elevation gradients, and riparian corridors—supported greater and more stable diversity. For example, *Fagus orientalis* was restricted to forest interiors, reflecting sensitivity to disturbance and its dependence on mesic, shaded habitats, while *Tilia tomentosa* and *Tilia platyphyllos* persisted not only in natural areas but also within urban parks and steep urban slopes, highlighting their dual role as native elements and cultivated ornamentals. Likewise, the widespread occurrence of *Festuca rubra* and *Cynodon dactylon* across all transects illustrates the dominance of clonal, disturbance-tolerant grasses in both managed and spontaneous urban green spaces. These findings emphasize the need for spatially explicit biodiversity planning in urban environments, where both mean diversity values and within-zone floristic variability must be considered. Urban ecological management should prioritize not only the conservation of remnant native species but also the enhancement of structural and functional heterogeneity within the urban matrix. Recognizing the capacity of urban systems to simultaneously host both floristically impoverished and enriched microhabitats—often structured by the presence of ecologically significant species—can inform more nuanced, resilient, and context-specific conservation strategies in the face of accelerating urbanization. Incorporating adaptive management approaches that respond to local environmental conditions and social dynamics can further strengthen urban biodiversity outcomes. Additionally, promoting connectivity among green spaces and prioritizing species with key functional roles can enhance ecosystem services and long-term ecological resilience within cities.

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