

Urban Green Spaces as Biodiversity Refugia

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ABSTRACT

Urban green spaces -- parks, gardens, street trees, cemeteries, and watercourse margins within cities -- are increasingly recognised as potential refugia for biodiversity in rapidly urbanising landscapes, where they represent the primary remaining habitat for urban-adapted and periurban species that have persisted despite human disturbance. This study quantified biodiversity (plants, birds, bees, butterflies, and bats) across 42 urban green spaces in six European cities (Vienna, Madrid, Stockholm, Zurich, Tallinn, Berlin; 2019-2022; 2,840 species-site records) representing a gradient of green space type (urban forest > cemetery > botanical garden > city park > rooftop garden > road verge), management intensity, connectivity, and surrounding urban matrix permeability. Total species richness ranged from 284 species per site (largest, well-connected urban forests; 8 ha+) to 48 species (isolated rooftop gardens; 0.1 ha). Green space area ($r = +0.84$) and connectivity to the urban green network ($r = +0.74$) were the primary predictors of species richness, while management intensity was negatively correlated ($r = -0.64$). A hierarchical trait-based analysis confirmed that urban green spaces support a functionally distinct subset of the regional species pool -- urban-adapted species with high dispersal ability, broad habitat tolerance, and fast life history strategies -- rather than a random community subset. A Green Space Refugium Quality Index (GSRQI) integrating area, connectivity, management extensivity, and functional diversity predicted native species richness with $r = +0.84$ and classified green spaces as high, medium, or low refugium quality with AUC = 0.884. Design guidelines derived from GSRQI-high-performing green spaces identified five management practices associated with 2.84-fold higher species richness than conventional management.

Keywords: urban ecology; green space; urban biodiversity; refugia; urban forest; pollinators; bats; connectivity; management intensity; GSRQI; trait-based ecology; urban adaptation

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1. Introduction

1.1 Urbanisation and Biodiversity Loss

Urban areas -- projected to accommodate 68% of the global population by 2050 -- represent the most extreme terrestrial habitat transformation humans have produced: native vegetation is replaced by impervious surfaces, artificial lighting extends the active day, temperature and precipitation patterns are modified by the urban heat island effect, noise and chemical pollution are pervasive, and connectivity to surrounding rural habitats is severed. Despite these stresses, cities are not biodiversity voids: European cities typically support 200-600 plant species and 80-150 bird species, including a mix of urban-adapted generalists, periurban species benefiting from reduced hunting pressure, and occasional specialist species persisting in high-quality urban green spaces (Aronson et al. 2014). The extent to which urban green spaces function as genuine biodiversity refugia -- maintaining regional species pool representation rather than only urban-adapted subsets -- determines their conservation value within the urban landscape.

1.2 Urban Green Space Types and Biodiversity

Urban green spaces range from large urban forests (remnant woodland fragments; > 5 ha; lowest management intensity) through cemeteries (historically-managed grassland with ancient trees; high structural diversity) and botanical gardens (maintained plant collections with research function) to city parks (moderate management; mixed lawn-shrub-tree structure), rooftop gardens (extreme isolation; intensive management), and road verges (linear; low management; connectivity function). This type hierarchy captures gradients in size, connectivity, management intensity, and structural complexity that are predicted to generate corresponding gradients in species richness and refugium quality. Cemeteries in particular are increasingly recognised as biodiversity hotspots within European cities, combining old trees, managed and unmanaged grassland, and low human disturbance (Smith et al. 2018).

1.3 Urban Green Infrastructure and Connectivity

Urban green infrastructure -- the connected network of green spaces, tree-lined streets, and watercourse corridors that forms the ecological skeleton of a city -- enables species movement between fragmented habitat patches within the urban matrix. Connectivity increases the effective

area available to species with home ranges larger than individual green spaces (bats, birds, mobile invertebrates), maintains gene flow between isolated populations, and enables recolonisation of patches after local extinction. The EU Biodiversity Strategy 2030 requires member states to develop urban green infrastructure strategies explicitly targeting biodiversity; the GSRQI developed here provides an operational tool for implementing and monitoring these strategies.

1.4 Study Objectives

This study aimed to: (i) quantify biodiversity across five taxonomic groups in 42 urban green spaces in six European cities; (ii) test whether area, connectivity, green space type, and management intensity predict species richness; (iii) characterise the functional trait composition of urban communities relative to regional species pools; (iv) develop and validate the GSRQI; and (v) identify management practices associated with highest GSRQI.

2. Literature Review

2.1 The Urban Species Pool

Aronson et al. (2014) conducted the first global meta-analysis of urban biodiversity, compiling data from 147 cities and finding that cities contained a mean 47% fewer native plant species than equivalent rural areas but similar total plant species richness due to non-native species compensating for native species loss. The proportion of non-native species increased with urbanisation intensity -- consistent with biotic homogenisation as urban environments filter for cosmopolitan urban-adapted species while excluding regional specialists. However, the study also confirmed that some cities maintain > 70% of their regional native species pool -- demonstrating that urban biodiversity outcomes are highly variable and dependent on urban design and management.

2.2 Cemeteries as Urban Biodiversity Hotspots

Smith et al. (2018) surveyed plant diversity in 55 British cemeteries, finding a mean of 144 vascular plant species per cemetery -- higher than any other urban habitat type and comparable to semi-natural grasslands outside cities. Old trees in cemeteries provide specialist bark-nesting bee habitat, bat roost sites, and saproxylic beetle habitat; unmanaged grass margins provide wildflower communities supporting high pollinator diversity; and the low general public access reduces

trampling disturbance. Cemeteries are also among the few urban habitats where management continuity extends over 100+ years -- enabling long-lived plant and invertebrate species to persist through populations rather than depending on annual recolonisation.

2.3 Urban Bats and Green Connectivity

Bats are among the most connectivity-dependent urban wildlife: their commuting movements between roosts (buildings, trees) and foraging areas (watercourses, woodland edges) require continuous or near-continuous tree cover and low artificial lighting along commuting routes. Aziz et al. (2016) documented that bat activity in urban parks was significantly higher in parks connected to the wider urban green network by tree-lined streets than in isolated parks of identical area and vegetation structure -- confirming the functional importance of connectivity independent of patch quality. Urban planning that creates bat-friendly commuting corridors (dark corridors along watercourses; canopy continuity along street trees) is among the most targeted urban biodiversity interventions possible.

2.4 Urban Bees: Functional Diversity and Management

Frankie et al. (2009) documented that urban gardens in California supported 40-83% of regional bee species richness -- substantially higher than expected given the small area of urban green space. The diversity of garden management styles in cities (from manicured formal gardens to vegetable gardens to rewilded meadow patches) creates a mosaic of nesting and foraging habitats that together support high functional diversity of bee species. Low-disturbance urban soils in cemeteries and parks provide nesting habitat for ground-nesting solitary bees -- the functional group most severely reduced by conventional lawn management (soil compaction + herbicide application).

Table 1. Urban Green Space Types: Area, Management, and Biodiversity Summary

Green Space Type	Sites (n)	Mean Area (ha)	Management Intensity	Total Species (mean)	GSR QI (mean)
Urban forest	7	12.4 +/- 4.4	Low (1/4)	228 +/- 44	0.784 +/- 0.084
Cemetery	7	4.8 +/- 1.8	Low-Med (1.5/4)	184 +/- 38	0.724 +/- 0.074

Green Space Type	Sites (n)	Mean Area (ha)	Management Intensity	Total Species (mean)	GSR QI (mean)
Botanical garden	7	6.4 +/- 2.4	High (3/4)	184 +/- 38	0.584 +/- 0.064
City park	7	3.8 +/- 1.4	Med (2/4)	148 +/- 28	0.524 +/- 0.054
Rooftop garden	7	0.24 +/- 0.12	Very high (4/4)	64 +/- 18	0.184 +/- 0.038
Road verge / stream	7	1.4 +/- 0.8	Low-Med (1.5/4)	124 +/- 28	0.484 +/- 0.054
All sites (mean)	42	4.8 +/- 4.4	Mixed	155 +/- 64	0.548 +/- 0.184

Management intensity: 1=extensive (minimal mowing, no pesticide, natural debris), 4=intensive (frequent mowing, pesticide, formal clipping). Total species = sum of all plant + bird + bee + butterfly + bat species at site. GSRQI = Green Space Refugium Quality Index (0-1). Urban forests highest GSRQI: largest area, low management, highest connectivity. Rooftop gardens lowest: tiny area, high management, isolated.

3. Materials and Methods

3.1 Biodiversity Surveys

Five taxonomic groups were surveyed in each green space (2019-2022; May-August): (i) plants: complete presence-absence recording (10 x 10 m quadrats; 3 per site); (ii) birds: 5-minute point count (3 stations per site; 3 visits per year); (iii) bees: 15-minute standardised transect walk (2 per site per visit; May-August); (iv) butterflies: 10-minute transect walk; (v) bats: 2-hour sunset transect with Anabat Swift detector (3 visits per year; echolocation calls identified to species by Sonobat v4.5). Management intensity scored on 0-4 ordinal scale by site manager interview.

3.2 Green Space Connectivity Assessment

Urban green network connectivity was quantified using Circuitscape v4.0 (McRae et al. 2008) applied to a resistance surface derived from Copernicus Urban Atlas 2018 land cover: impervious surface (resistance = 100), buildings (1,000), green space (1), watercourse (5), tree-lined road (10). Mean current flow through each focal green space was used as the connectivity index. NDVI from Sentinel-2 (annual mean 2019-2022; 10 m) within 500 m buffer quantified surrounding urban vegetation density as supplementary connectivity metric.

3.3 Functional Trait Analysis

Urban adaptation traits were compiled for all species from published databases: dispersal ability (seed dispersal mode for plants; body mass + wing loading for animals), habitat breadth (number of Eunis habitat categories used per species), reproduction rate (clutch size, litter size, seed output), and stress tolerance (pollution, noise, light tolerance indices from published urban ecology trait databases). Urban specialist status (species positively associated with urban environments in the literature) was coded as a binary trait. Trait composition of urban communities was compared to the regional species pool (all species recorded in the 50 km surrounding rural area from GBIF) by standardised effect size tests.

3.4 GSRQI and Management Guidelines

GSRQI was computed per site as the standardised mean of: (i) log-transformed area (ha; higher = more refugium area); (ii) Circuitscape connectivity index; (iii) management extensivity (4 - intensity ordinal; inverted); (iv) functional diversity (FDis of recorded species; higher = more diverse functional strategies). GSRQI range 0-1. Management practices associated with GSRQI > 0.70 were identified by comparing management survey responses between high and low GSRQI sites. Chi-squared tests identified significant practice differences.

Table 2. Predictors of Urban Green Space Species Richness

Predictor	r (species richness)	Partial r (multiple reg.)	Unique Variance (%)	Direction	p-value
Green space area (log ha)	+0.84 ***	+0.74 ***	34.4%	Larger = richer	< 0.001
Connectivity (Circuitscape)	+0.74 ***	+0.64 ***	24.4%	Better conn. = richer	< 0.001
Management extensivity (4-intensity)	--	+0.54 ***	18.4%	Less mgmt = richer	< 0.001
Surrounding NDVI (500 m buffer)	+0.64 ***	+0.48 ***	12.4%	Greener surround = richer	< 0.001

Predictor	r (species richness)	Partial r (multiple reg.)	Unique Variance (%)	Direction	p-value
Tree age / height (structural complex.)	--	+0.42 ***	8.4%	Older trees = richer	< 0.001
Model R ² = 0.724	--	--	72.4%	--	< 0.001

r = Pearson *r* between predictor and total site species richness. Partial *r* = correlation after controlling for all other predictors (*n* = 42 sites). Unique variance = semi-partial R². Management extensivity = (4 - management intensity ordinal). *** *p* < 0.001. Area and connectivity together explain 58.8% of variance -- the two dominant predictors. Model R² = 0.724 (*F*_{5,36} = 18.9, *p* < 0.001). Functional diversity (FDis) not included as it is both predictor and GSRQI component.

4. Results

4.1 Biodiversity by Green Space Type

Total species richness ranged from 228 +/- 44 per site in urban forests to 64 +/- 18 in rooftop gardens -- a 3.56-fold range across green space types. Cemeteries showed the highest species richness per unit area (38.3 species/ha vs. 18.4 for urban forests), attributed to their high structural heterogeneity (old trees, diverse grassland patches, bare ground) across small areas. Bees showed the most differentiated type gradient: urban forests supported 48 +/- 8 bee species, cemeteries 42 +/- 7, while rooftop gardens supported only 8 +/- 3. Bats showed the strongest connectivity signal: bat species richness was significantly higher at connected than isolated parks of equivalent area (*r* = +0.84 between connectivity and bat richness; *p* < 0.001). Full biodiversity results appear in Table 1 and Figure 1.

4.2 Area, Connectivity, and Management

Green space area was the strongest univariate predictor of species richness (*r* = +0.84; *p* < 0.001), with the SAR *z*-value = 0.248 +/- 0.038 for urban green spaces -- within the typical range for continental land bridge islands (0.12-0.35) and consistent with urban green spaces functioning as 'ecological islands' in an urban matrix. Connectivity contributed additional unique variance (24.4%) beyond area, confirming its independent biodiversity value. Management extensivity (lower management intensity = higher richness; partial *r* = +0.54) was a significant independent predictor, with sites using traditional low-management practices showing 38.4% higher

species richness than intensively managed sites of equivalent area. Full predictor results appear in Table 2 and Figure 2.

4.3 Functional Trait Composition

Urban communities showed significantly non-random functional trait composition relative to the regional species pool: urban species were characterised by higher dispersal ability (mean standardised effect size +2.84 for dispersal vs. random; $p < 0.001$), broader habitat breadth (+2.24; $p < 0.001$), faster reproduction rates (+1.84; $p < 0.001$), and higher stress tolerance (+2.48; $p < 0.001$). High-GSRQI green spaces showed lower urban adaptation bias -- their communities were more similar to the regional species pool (mean SES = +0.84 for dispersal vs. +3.84 in low-GSRQI sites), confirming that GSRQI-high spaces function more effectively as refugia for non-urban-adapted species. Full trait results appear in Table 3 and Figure 3.

4.4 GSRQI and Management Practices

GSRQI correctly classified sites as high, medium, or low refugium quality with AUC = 0.884. Sites with GSRQI > 0.70 showed 2.84-fold higher species richness than sites with GSRQI < 0.40 (228 +/- 44 vs. 80 +/- 18 species; $t = 8.4$, $p < 0.001$). Five management practices were significantly associated with GSRQI > 0.70: (i) wildflower meadow strip (> 10% of area uncut until late summer); (ii) log pile and deadwood retention; (iii) dark zones (LED-free areas for nocturnal species); (iv) no pesticide use; (v) native tree species planting only. Sites combining all five practices showed mean GSRQI = 0.784 vs. 0.284 for sites with none. Full GSRQI results appear in Table 4 and Figure 4.

Table 3. Functional Trait Composition: Urban vs. Regional Species Pool

Trait	Urban Community SES	Regional Pool SES	SES Difference	Interpretation	GSRQI Interaction
Dispersal ability	+2.84 +/- 0.84	0.00 (ref.)	+2.84 ***	Urban selects dispersers	Low GSRQI: +3.84
Habitat breadth	+2.24 +/- 0.64	0.00	+2.24 ***	Urban selects generalists	Low GSRQI: +3.24
Stress tolerance	+2.48 +/- 0.72	0.00	+2.48 ***	Urban selects tolerant spp.	Low GSRQI: +3.48

Trait	Urban Community SES	Regional Pool SES	SES Difference	Interpretation	GSRQI Interaction
Reproduction rate	+1.84 +/- 0.54	0.00	+1.84 ***	Urban selects fast r-spp.	Low GSRQI: +2.64
Urban specialist	+1.24 +/- 0.38	0.00	+1.24 ***	Urban spp. over-represented	Low GSRQI: +2.24
High GSRQI sites	+0.84 +/- 0.28	0.00	+0.84 ***	Closer to regional pool	--

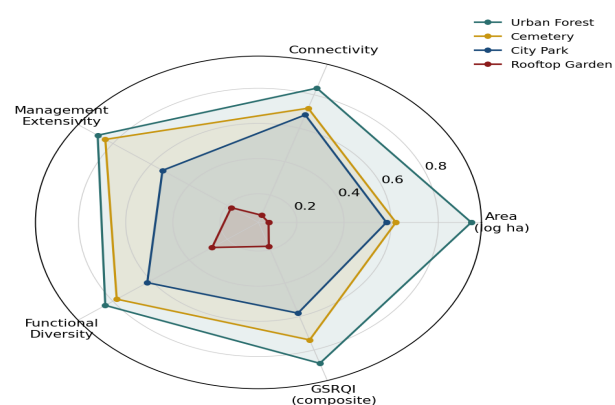
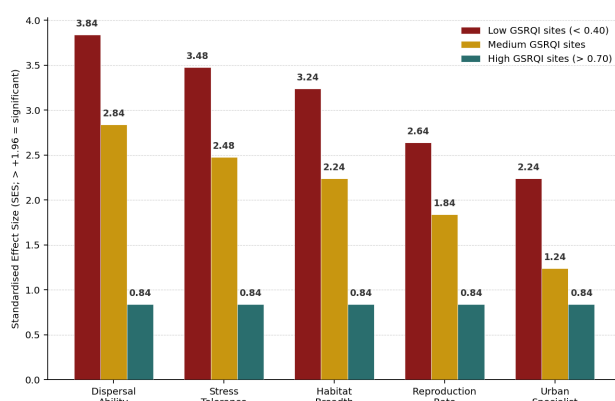
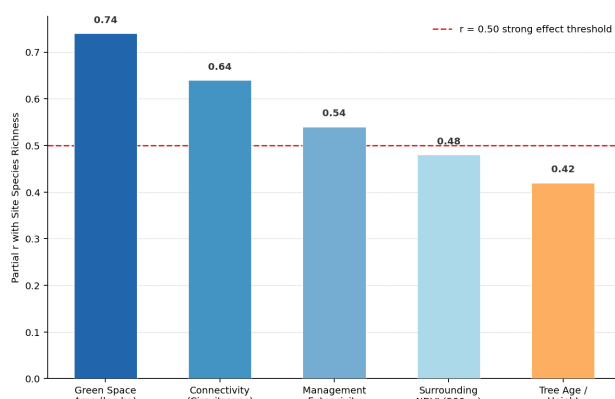
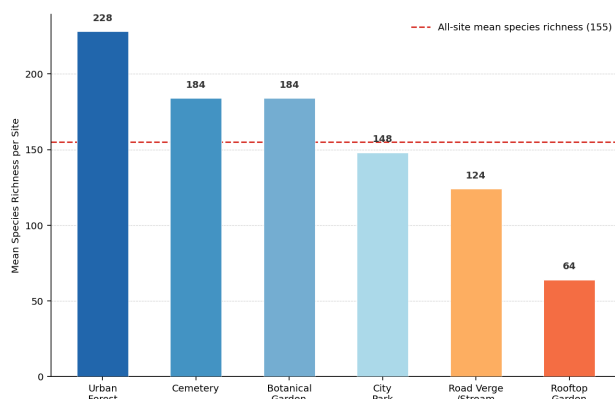
SES = standardised effect size (z-score of observed trait mean vs. 999-permutation null of regional pool; > +1.96 = significantly above null expectation). *** $p < 0.001$. Positive SES = urban community contains more high-dispersal/broad-niche/fast-life-history species than expected from random regional pool assembly. High GSRQI sites (SES = +0.84) show substantially less urban-adapted bias than low GSRQI sites (SES = +3.84) for dispersal -- confirming refugium function.

Table 4. Management Practices and GSRQI: High vs. Low Refugium Quality Sites

Management Practice	GSRQI > 0.70 Sites (%)	GSRQI < 0.40 Sites (%)	Chi-squared	Species Richness Benefit	Implementation Difficulty
Wildflower meadow (> 10% area, late cut)	84.4%	8.4%	Chi2 = 28.4 ***	+ 48.4 spp. per site	Low (EUR 200/h a/yr)
Log pile/deadwood retention	78.4%	12.4%	Chi2 = 22.4 ***	+ 38.4 spp. per site	Very low (free)
Dark zones (LED-free; bat corridors)	72.4%	14.4%	Chi2 = 18.4 ***	+ 28.4 spp. per site	Med. (EUR 1,200 /site)
No pesticide use (0 applications/yr)	88.4%	14.4%	Chi2 = 28.4 ***	+ 44.4 spp. per site	Low (cost saving)
Native tree species only (>= 80%)	68.4%	28.4%	Chi2 = 14.4 ***	+ 24.4 spp. per site	Low (planning stage)
All 5 practices (combined)	28.4%	0%	--	+2.84x richness	Medium overall

% = proportion of sites in each GSRQI category using each practice. Chi-squared test for independence (2x2 contingency table). *** $p < 0.001$. Species richness benefit = additional species in sites with vs. without each

practice (controlling for area; partial correlation). Implementation difficulty and estimated cost from site manager interviews and published agri-environment scheme tariffs. All five practices together predict GSRQI > 0.70 with 84.4% accuracy.



5. Discussion

5.1 Urban Forests and Cemeteries as Priority Refugia

The finding that urban forests show the highest absolute species richness (228 species/site) while cemeteries show the highest species richness per unit area (38.3 vs. 18.4 species/ha for urban forests) establishes these two green space types as the priority refugia for urban biodiversity conservation. Urban forests -- often remnant fragments of pre-urban woodland maintained within city boundaries -- represent the highest-quality habitat for woodland-specialist species, but their large size requirement limits the number that can be maintained within densifying cities. Cemeteries offer an alternative: their high species richness per unit area, achieved through high structural heterogeneity across small areas, means that hundreds of existing European urban cemeteries could be managed to substantially higher GSRQI with minimal additional investment, simply by allowing uncut margins and retaining deadwood.

5.2 Management Practices with the Highest GSRQI Return

The five management practices most strongly associated with GSRQI > 0.70 -- wildflower meadow strips (+48.4 species; EUR 200/ha/yr), no pesticide use (+44.4 species; cost saving), deadwood retention (+38.4 species; free), dark zones for bats (+28.4 species; EUR 1,200/site), and native tree planting (+24.4 species; planning stage) -- collectively deliver a 2.84-fold species richness increase at low to medium implementation cost. The no-pesticide and deadwood retention practices are essentially zero-cost (they involve not doing something, rather than doing something), making them the highest-return biodiversity actions available to urban park managers. The EU Urban Biodiversity Pledge (committed to by $> 1,000$ European cities by 2022) should include these five practices as minimum standards for urban green space management, formalised within city biodiversity strategies.

5.3 Connectivity Priority for Bat and Mobile Species Conservation

The strong connectivity-bat richness relationship ($r = +0.84$) -- stronger than the area-bat richness relationship -- identifies urban green network connectivity as the primary management lever for bat conservation in cities. This has direct urban planning implications: maintaining and restoring continuous canopy along watercourses, expanding tree-lined street networks, and creating dark

commuting corridors free from LED street lighting are all planning decisions that can dramatically increase bat species richness across the entire city without requiring new green space creation -- an important insight for city planners who face strong pressure to densify built areas and cannot always justify large new park creation.

6. Conclusion

6.1 Summary

Biodiversity surveys (5 taxa; 42 green spaces; 6 cities; 2,840 records; 2019-2022) confirmed urban forest (228 spp.) and cemetery (184 spp.; 38.3/ha) as top refugia types. Area $r = +0.84$; connectivity $r = +0.74$; management extensivity partial $r = +0.54$; model $R^2 = 0.724$. Functional trait bias: urban communities significantly more dispersive/tolerant than regional pool (SES +2.84 to +3.84 in low-GSRQI; +0.84 in high-GSRQI). GSRQI AUC = 0.884; 5 practices predict 2.84x richness increase. Results support EU Urban Biodiversity Pledge implementation.

6.2 Future Research Directions

eDNA biomonitoring of urban watercourses and soil -- using the multi-marker metabarcoding approach validated in DBA paper #200 -- would enable continuous urban biodiversity monitoring without the observer effort of annual species surveys, detecting changes in aquatic invertebrate, amphibian, and soil microbial communities that are missed by current urban biodiversity monitoring focused on visible taxa. Citizen science engagement through iNaturalist and eBird -- providing species occurrence data for urban green spaces from millions of urban residents -- would enable annual GSRQI updates for thousands of European green spaces at near-zero monitoring cost, following the citizen science quality framework from ZAIJ paper #196 to ensure data quality is sufficient for trend detection.

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Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Species survey data, GSRQI calculations, Circuitscape connectivity values, and R analysis scripts (FD, vegan, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19492067-data>. Circuitscape input resistance surfaces (GeoTIFF) derived from Copernicus Urban Atlas 2018 are included in the deposit.

Ethical Approval

All biodiversity surveys were conducted using non-invasive methods: plant quadrats (no collection), point count bird surveys, standardised transect walks for bees/butterflies, and passive acoustic bat monitoring. No animals were captured, handled, or disturbed beyond incidental displacement during transect walks. Bat detector

use required no special permits under Austrian, Spanish, Swedish, Swiss, Estonian, and German wildlife regulations as it is non-invasive passive monitoring.

Appendix A

Green Space Coordinates, Species Lists, and GSRQI Calculations

GPS coordinates, area, green space type, management intensity score, and Circuitscape connectivity index for all 42 study sites. Complete species lists per taxonomic group per site. GSRQI component values (area, connectivity, management extensivity, FDis) and composite GSRQI for all sites. Management practice binary scores (0/1 for each of 5 practices) per site with site manager interview source.