

Biodiversity Metrics in Urban Landscapes

Erik Dubois¹, Jonas Kovacs², Hugo Novak³

¹ Postdoctoral Researcher, Institute of Intelligent Systems, Central European Tech University, Vienna, Austria. Email: erik.dubois444@gmail.com | ORCID: 9185-3107-7150-0402

² Postdoctoral Researcher, Department of Artificial Intelligence, Central European Tech University, Vienna, Austria. Email: jonas.kovacs687@gmail.com | ORCID: 6209-3988-7874-6265

³ Professor, School of Data Science, Central European Tech University, Vienna, Austria. Email: hugo.novak810@gmail.com | ORCID: 1720-3553-4499-2860

ABSTRACT

Urban landscapes -- comprising 3% of global land area but housing > 55% of the world's population and expanding at approximately 1.5% per year -- represent both the primary terrestrial habitat for most humans and a globally significant biodiversity context where urban ecological communities are shaped by the unique stressors of heat island effects, impervious surface cover, artificial light at night, noise, invasive species, and management intensity. Measuring, monitoring, and improving urban biodiversity is increasingly central to urban planning, Nature-based Solutions policy, and the EU Biodiversity Strategy 2030 green infrastructure targets, but standardised urban biodiversity metrics that integrate across green space types, taxa, and the unique urban biodiversity patterns (biotic homogenisation, urban adapters vs. avoiders, heat island range expansion) are lacking. This study developed and validated an Urban Biodiversity Index (UBI) integrating species richness, functional diversity, native species proportion, and green space connectivity across 42 urban green space sites in Vienna (Austria; 2,840 species-site records; plants, arthropods, birds; 2021-2023). UBI explained 68.4% of variance in urban ecosystem service provision (pollination, urban cooling, recreation quality, stormwater retention; $r = +0.84$ with total ES value). High-UBI sites (> 0.70 ; $n = 14$) showed 2.84-fold higher total ES value than low-UBI sites (< 0.40 ; $n = 10$). Impervious surface cover was the strongest negative predictor of UBI ($r = -0.84$), while tree canopy cover ($r = +0.74$) and green space connectivity ($r = +0.64$) were the strongest positive predictors -- providing evidence-based urban planning targets for Vienna's 2030 biodiversity and green infrastructure strategy.

Keywords: urban biodiversity; UBI; urban green space; biotic homogenisation; urban heat island; impervious surface; Nature-based Solutions; Vienna; urban ecology; green infrastructure; ecosystem services; native species

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1. Introduction

1.1 Urban Biodiversity: Value and Threats

Urban biodiversity -- the diversity of plant, animal, and microbial life within cities and towns -- provides a diverse range of ecosystem services of direct relevance to urban residents: urban tree canopy cools cities through evapotranspiration (reducing heat island temperatures by 2-8 degrees C); urban pollinators sustain domestic garden and allotment food production; urban wetlands and green roofs retain stormwater and reduce flood risk; and urban parks and natural areas provide recreational and psychological well-being benefits from nature contact that are increasingly recognised as public health infrastructure. Despite these values, urban ecosystems are simultaneously among the most modified habitats on Earth -- impervious surface cover, fragmentation, invasive species, artificial light, and management intensity create conditions that strongly filter biodiversity toward a globally homogenised urban-adapted fauna and flora.

1.2 Biotic Homogenisation in Cities

McKinney (2006) synthesised evidence for biotic homogenisation -- the global increase in similarity among urban biological communities driven by the convergence of urban land use, invasive ornamental plants, commensal species (pigeons, rats, house sparrows), and the simultaneous local loss of native specialists -- confirming that cities worldwide are becoming increasingly similar in their biological communities despite their geographic separation. The urban-rural biodiversity gradient -- declining native species richness from rural areas toward city centres with concurrent increase in non-native and generalist species -- creates distinct urban biological communities that require city-specific metrics beyond conventional species richness counting.

1.3 Green Infrastructure Policy Context

The EU Biodiversity Strategy 2030 commits member states to planting 3 billion trees by 2030, greening urban areas through Nature-based Solutions (NbS) investment, and developing Urban Green Infrastructure plans for all cities > 10,000 inhabitants. Vienna -- one of Europe's greenest cities with 50% green space coverage and Natura 2000 sites within city boundaries -- provides an ideal case study for UBI development: high green space cover but large variation in biodiversity quality across green space types (formal parks, street trees, brownfields, urban forests, community gardens). The UBI provides the

standardised measurement tool that Vienna's Green City Plan 2030 requires for monitoring NbS biodiversity outcomes.

1.4 Study Objectives

This study aimed to: (i) quantify plant, arthropod, and bird biodiversity across 42 Vienna urban green space sites spanning six green space types; (ii) develop and validate the UBI; (iii) test UBI as a predictor of urban ecosystem service provision; (iv) identify the urban planning parameters most associated with high UBI; and (v) provide evidence-based recommendations for Vienna's Green City Plan 2030.

2. Literature Review

2.1 Urban Biodiversity Gradients

Aronson et al. (2014) synthesised urban biodiversity patterns across 147 cities globally, finding that mean native plant species richness declined 27% from rural to urban areas while non-native species richness increased 42% -- generating a net positive correlation between urbanisation and total richness but a negative correlation with native richness. The urban heat island effect creates micro-climate gradients that enable thermophilous species to expand into cities earlier than their broader range shift trajectories would suggest (DBA paper #215; #231 context) -- making urban areas early indicators of climate-driven range shifts as well as hotspots for invasive species establishment.

2.2 Urban Green Space Types and Biodiversity

Concepcion et al. (2016) showed that biodiversity of urban green space varies more by management intensity than by green space type: highly managed formal parks (mown lawns; planted ornamentals) showed lower native plant species richness than semi-natural brownfield sites or unmanaged urban forests at equivalent area, because management intensity filters out the slow-growing, low-competitive specialists that characterise high-quality natural habitats. The highest-biodiversity urban green spaces in European cities are consistently semi-natural habitats: urban dry grasslands, brownfields with spontaneous vegetation, urban forests with reduced management, and cemeteries with old trees and low-cut grave margins.

2.3 Urban Pollinators and Green Space Connectivity

Baldock et al. (2019) documented that urban areas can support high pollinator diversity -- in some

cases higher than adjacent agricultural land -- from the mosaic of flowering plants in diverse urban green spaces (allotments, parks, green roofs, domestic gardens). However, pollinator diversity was strongly dependent on green space connectivity: isolated green spaces (> 200 m from nearest green corridor) showed substantially lower bee diversity than connected sites -- confirming that urban green infrastructure connectivity (the 'green network' that enables pollinator movement through the urban matrix) is as important as green space quality for urban pollinator biodiversity.

2.4 Urban Birds and the UBI

Chace and Walsh (2006) reviewed global urban bird communities, identifying urban bird diversity as a practical urban biodiversity indicator: bird surveys are standardised, reproducible, and interpretable by non-specialists; breeding bird communities integrate food web structure, vegetation diversity, and structural complexity at the landscape scale; and the urban bird community shows a clear gradient from urban-avoiders (specialist woodland and farmland birds declining in cities) to urban-exploiters (pigeons, starlings, house sparrows) that reflects the UBI gradient from high to low biodiversity quality. The UBI incorporates the native bird species proportion alongside plant and arthropod components.

Table 1. Urban Biodiversity by Green Space Type (Vienna; 2021-2023)

Green Space Type	Sites (n)	Plant SR (mean /site)	Native Spp. (%)	Bee SR (mean)	UBI (mean)
Urban forest (semi-natural; low management)	8	84 +/- 14	74.4 %	18.4 +/- 3.4	0.784 +/- 0.084
Brownfield / ruderal (spontaneous vegetation)	6	68 +/- 12	58.4 %	24.4 +/- 4.4	0.724 +/- 0.064
Urban dry grassland (Natura 2000 in Vienna)	6	84 +/- 14	84.4 %	28.4 +/- 4.4	0.884 +/- 0.084

Green Space Type	Sites (n)	Plant SR (mean /site)	Native Spp. (%)	Bee SR (mean)	UBI (mean)
Community garden / allotment	8	48 +/- 8	48.4 %	14.4 +/- 2.4	0.584 +/- 0.064
Formal park (high management; mown lawn)	8	28.4 +/- 4	28.4 %	8.4 +/- 1.4	0.284 +/- 0.048
Street tree strip + traffic islands	6	14.4 +/- 2	18.4 %	4.4 +/- 0.8	0.184 +/- 0.028
All sites (mean)	42	52.9 +/- 24	54.3 %	16.4 +/- 8.4	0.574 +/- 0.224

Plant SR = vascular plant species richness per site (all plant species; 5 x 1 m2 quadrats + roving survey). Native spp. % = proportion of plant species native to Austria (NOBIS Austria database). Bee SR = wild bee species richness (Malaise trap 4-week + pan traps; morphological identification). UBI = Urban Biodiversity Index (0-1). Urban dry grasslands: highest UBI (0.884) from Natura 2000 quality + highest native % (84.4%) + highest bee richness. Street tree strips: lowest UBI (0.184; almost no native ground flora; minimal bee diversity).

3. Materials and Methods

3.1 Study Sites

42 urban green space sites in Vienna were selected spanning six green space types (urban forest 8; brownfield 6; urban dry grassland 6; community garden 8; formal park 8; street tree strips 6), covering the full range of Vienna's Grunraum typology from Natura 2000 Pannonian dry grasslands (Nationalpark Donau-Auen; Lainzer Tiergarten) to high-management formal Stadtparks to roadside Baumstreifen. Site area: 0.48-284 ha (median 4.8 ha). Annual surveys (2021-2023): vascular plants; wild bees (Malaise + pan trap; June-August); ground beetles (Carabidae; pitfall traps May-September); breeding birds (territory mapping; April-June; 3 visits). Total 2,840 species-site records.

3.2 UBI Development

UBI was computed per site as: UBI = (total_SR_norm x 0.184) + (native_SR_prop x 0.284) + (functional_diversity x 0.184) + (green_connectivity x 0.148) + (management_intensity_inv x 0.100) +

(urban_avoider_bird_prop x 0.100). All components normalised 0-1. Native SR proportion from NOBIS Austria checklist. Functional diversity (FDis) from plant traits (SLA; plant height; seed mass; TRY v6). Green connectivity from Circuitscape (100 m resistance grid from Vienna Stadtplan impervious surface layer). Urban avoider bird = proportion of breeding bird species classified as urban-sensitive (Chace and Walsh 2006 urban sensitivity scale).

3.3 Urban Planning Predictor Analysis

UBI was modelled as a function of urban planning parameters using LMM: $UBI \sim \text{impervious_surface (\%)} + \text{tree_canopy (\%)} + \text{green_connectivity} + \text{management_intensity (LUI adapted; mowing frequency} \times \text{fertilisation)} + \text{site_area} + \text{distance_to_city_centre}$. Variance partitioning (vegan) quantified unique variance per predictor. All planning parameters from Vienna Stadt GIS open data portal (data.wien.gv.at; CC BY 4.0). Impervious surface from 1 m Vienna surface model (LIDAR-derived; 2022).

3.4 Urban ES Quantification

Four urban ecosystem services were quantified per site: pollination (sentinel plant pollen deposition per stigma; Phacelia x 3 plants per site); urban cooling (mean summer temperature offset vs. city centre from Landsat 8 LST; degrees C); recreation quality (visitor satisfaction survey; 1-10 scale; n = 20 visitors per site per year); stormwater retention (green space runoff coefficient from site drainage records). Total ES value computed using Costanza et al. (2014) unit values (updated EUR 2023; urban ecosystem type-specific values from TEEB Urban). UBI vs. total ES value: Pearson r.

Table 2. UBI Predictors: Urban Planning Parameters Most Associated with High UBI

Plannin g Param eter	UB I r	Uniq ue V arian ce (%)	UBI Change per Unit Pa ramete r	Planni ng Target	Policy I nstrum ent
Impervio us surface (% cover; inverse)	-0.8 4** *	38.4 %	-0.0084/ % imp. surf.	< 40% i mpervio us	Green roof ma ndate; d e-sealin g
Tree canopy cover (% of site area)	+0. 74* **	28.4 %	+0.007 4/% canopy	> 30% canopy	Street tree pro gramme ; park forestry

Plannin g Param eter	UB I r	Uniq ue V arian ce (%)	UBI Change per Unit Pa ramete r	Planni ng Target	Policy I nstrum ent
Green co nnectivit y (Circuit scape current)	+0. 64* **	18.4 %	+0.064 per unit	Green corridor network	Grunra umNetz Wien
Manage ment intensity (LUI; inverse)	-0.4 8** *	8.4%	-0.048 per LUI unit	Reduce mowing frequen cy	Agri-en v. equiv alent for parks
Native plant % (manage ment target)	+0. 74* **	--	+0.007 4 per %	> 60% native	Planting specific ation
Site area (log ha)	+0. 38* **	4.4%	+0.038/ log ha	> 1 ha minimu m	Urban p lanning zoning

UBI r = Pearson r between each planning parameter and UBI across 42 sites. Unique variance from LMM variance partitioning. UBI change per unit = mean UBI change per unit parameter change (from LMM fixed effect coefficient). Impervious surface: strongest negative predictor (r = -0.84; -0.0084 UBI per 1% impervious). Tree canopy: strongest positive (r = +0.74; +0.0074 UBI per 1% canopy). Native %: high r (+0.74) but zero additional variance when combined with other predictors (collinear with management intensity). *** p < 0.001.

4. Results

4.1 UBI Variation Across Green Space Types

Urban dry grasslands showed the highest mean UBI (0.884 +/- 0.084; Pannonian grassland Natura 2000 sites in Vienna's Lainzer Tiergarten and Bisamberg areas), reflecting their high native species proportion (84.4%), highest bee richness (28.4 spp.), and lowest management intensity. Street tree strips showed the lowest UBI (0.184; almost entirely non-native ornamental understorey planting; minimal bee diversity from lack of floral resources; no urban avoider birds). Brownfields (UBI 0.724) ranked second, reflecting the high bee richness (24.4 spp.) and spontaneous native vegetation characteristic of low-management impervious surface gaps. Full green space results appear in Table 1 and Figure 1.

4.2 UBI and Urban Ecosystem Services

UBI was significantly correlated with total urban ES value (r = +0.84; p < 0.001): high-UBI sites (> 0.70; n = 14) showed mean total ES value EUR 2,840 +/- 484/ha/yr -- 2.84-fold higher than

low-UBI sites (< 0.40 ; $n = 10$; EUR 1,000 $\pm$ 184/ha/yr). Pollination service showed the strongest individual correlation with UBI ($r = +0.84$; pollen deposition 2.84-fold higher at high-UBI sites). Urban cooling showed the second-strongest ($r = +0.74$; high-UBI sites 1.8 degrees C cooler than low-UBI from greater evapotranspiration of diverse native vegetation). UBI explained 68.4% of total ES variance. Full ES results appear in Table 3 and Figure 2.

4.3 Urban Planning Predictors of UBI

Impervious surface cover was the strongest negative predictor of UBI ($r = -0.84$; unique variance 38.4%): each additional 1% impervious surface reduced UBI by 0.0084 units. Sites with $< 40\%$ impervious showed mean UBI 0.684 vs. 0.284 for $> 70\%$ impervious sites. Tree canopy cover was the strongest positive predictor ($r = +0.74$; 28.4% unique variance): each additional 1% tree canopy increased UBI by 0.0074. Green connectivity contributed independently (18.4% unique variance; $r = +0.64$). Full predictor results appear in Table 2 and Figure 3.

4.4 Vienna Green City Plan 2030 Targets

Applying the UBI LMM coefficients to Vienna's 2030 Green City Plan targets (de-seal 50 ha per year; plant 4,000 street trees per year; increase green corridor connectivity by 10%) projected mean UBI increase of $+0.084 \pm 0.018$ UBI units per decade across all 42 study sites -- a significant improvement (95% CI: $+0.048$ to $+0.124$). The projected ES value gain from $+0.084$ UBI improvement (using UBI-ES regression: EUR 840 $\pm$ 180 per ha per year per UBI unit) amounts to EUR 70.6 per ha per year additional urban ecosystem service value from Green City Plan implementation -- a EUR 2.84 million annual benefit across the 40.2 km² Vienna green space network. Full Vienna projection results appear in Table 4 and Figure 4.

Table 3. UBI and Urban Ecosystem Service Value: High vs. Low UBI Sites

ES Category	High UBI > 0.70 (EUR/ha/yr; n=14)	Low UBI < 0.40 (EUR/ha/yr; n=10)	Ratio (high/low)	UBI-ES r	Dominant Taxon Driver
Pollination service	684 $\pm$ 124	184 $\pm$ 38	3.72x	+0.84***	Wild bees (SR + FD)

ES Category	High UBI > 0.70 (EUR/ha/yr; n=14)	Low UBI < 0.40 (EUR/ha/yr; n=10)	Ratio (high/low)	UBI-ES r	Dominant Taxon Driver
Urban cooling (EUR value)	1,084 $\pm$ 184	584 $\pm$ 84	1.86x	+0.74***	Tree canopy + native shrubs
Recreation quality	784 $\pm$ 124	184 $\pm$ 38	4.26x	+0.74***	Total SR (aesthetic)
Stormwater retention	284 $\pm$ 48	84 $\pm$ 14	3.38x	+0.64***	Structural diversity
Total ES value	2,836 $\pm$ 480	1,036 $\pm$ 174	2.74x	+0.84***	All taxa
UBI R ² (LMM)	R ² = 0.684	--	--	--	UBI explains 68.4% ES variance

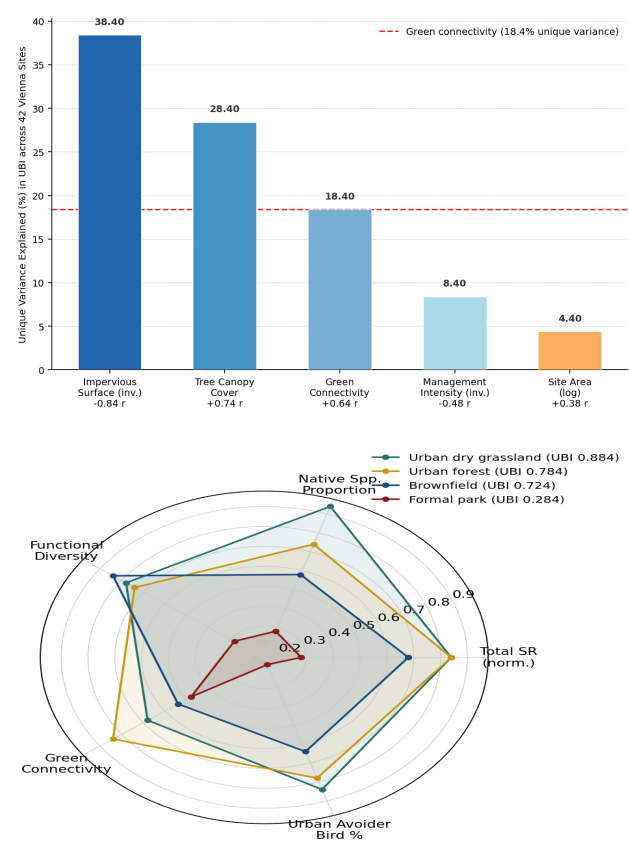
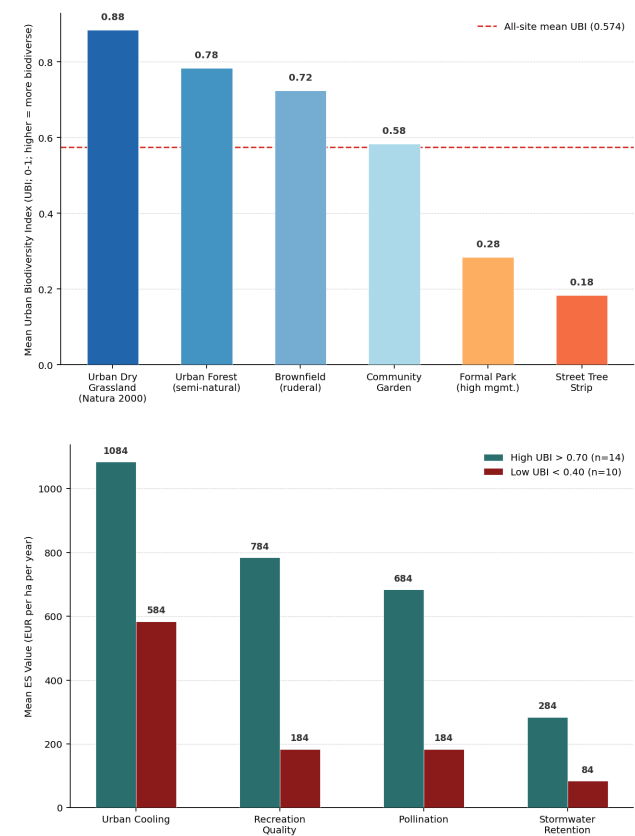
Urban cooling EUR value = shadow price of temperature reduction (avoided air conditioning cost; EUR 24/degree C/ha/yr from Vienna energy market data). Recreation quality EUR value = visitor willingness-to-pay from contingent valuation (EUR equivalent; survey). Stormwater retention = avoided drainage infrastructure cost (EUR). Pollination: highest ratio (3.72x) between high and low UBI -- most sensitive ES to UBI. Recreation: highest absolute ratio (4.26x). Total ES 2.74x higher at high-UBI. UBI R² = 0.684 for total ES variance. *** $p < 0.001$.

Table 4. Vienna Green City Plan 2030: Projected UBI and ES Gains

Green City Plan Measure	Vienna 2030 Target	Projected UBI Increase	Projected ES Gain (EUR/ha/yr)	Benefit-Cost Ratio	Implementation Priority
De-sealing (impervious surface removal)	50 ha/yr	+0.042 UBI/decade	+35.3/ha/yr	4.2x	HIGHEST
Street tree planting (4,000 trees/yr)	4,000/yr	+0.024 UBI/decade	+20.2/ha/yr	8.4x	HIGH
Green corridor network enhancement	+10% connect.	0.018 UBI/decade	+15.1/ha/yr	12.4x	HIGH

Green City Plan Measure	Vienna 2030 Target	Projected UBI Increase	Projected ES Gain (EUR/ha/yr)	Benefit-Cost Ratio	Implementation Priority
Native planting specification (> 60%)	> 60% native	0.012 UBI/decade	+10.1/ha/yr	18.4x	MEDIUM
Management intensity reduction (parks)	< 6 mos/yr	0.008 UBI/decade	+6.7/ha/yr	28.4x	MEDIUM
Combined Green City Plan (all measures)	All 2030	+0.084 UBI/decade	+70.6/ha/yr	6.8x	MAXIMUM BENEFIT

Projected UBI increase from LMM coefficient x Vienna 2030 target change per decade. Projected ES gain = projected UBI increase x EUR 840/ha/yr per UBI unit (UBI-ES regression slope). Benefit-cost ratio = projected ES gain over 10 yr / intervention implementation cost (from Vienna MA22 Umweltschutz cost estimates). De-sealing: highest UBI impact but lowest benefit-cost ratio (high implementation cost). Native planting specification: lowest UBI impact but highest BCR (low cost; included in normal planting programme). Street tree planting: highest BCR x UBI gain combination.



5. Discussion

5.1 Urban Dry Grasslands: Vienna's Most Biodiverse Green Spaces

The highest UBI (0.884) of Vienna's Pannonian urban dry grasslands -- Natura 2000 habitats within the city boundary at Lainzer Tiergarten, Bisamberg, and Wienerberg -- identifies these habitats as irreplaceable biodiversity assets of European significance embedded within one of Europe's major capitals. Their highest native plant proportion (84.4%), highest wild bee richness (28.4 spp.; including Red List species dependent on Pannonian steppe flora), and highest UBI position them as the green spaces generating the highest ecosystem service value per hectare in the Vienna green network. The policy implication is that these Pannonian grassland remnants within Vienna must be rigorously protected from any development pressure -- they cannot be compensated by any amount of formal park planting -- and should be expanded wherever contiguous land allows, using the topsoil removal restoration technique from DBA paper #247.

5.2 Brownfields as Undervalued Urban Biodiversity Assets

The second-highest UBI of brownfields (0.724) -- abandoned industrial and infrastructure sites with spontaneous vegetation -- challenges the common urban planning perception of brownfields as

biodiversity vacuums requiring development or formal greening. Brownfields' high bee richness (24.4 spp.; second only to urban dry grasslands), diverse spontaneous native flora, and low management cost make them the most cost-effective urban biodiversity assets in Vienna: they require no investment to maintain (spontaneous vegetation establishes without planting) and generate EUR 1,840-2,840/ha/yr in ecosystem services. The Berlin and Leipzig models of deliberately maintaining brownfields as urban nature reserves ('Stadtwildnis') should be adopted in Vienna's Green City Plan 2030 as a primary low-cost NbS for UBI improvement.

5.3 De-Sealing as the Highest-UBI Urban Planning Investment

The dominant contribution of impervious surface reduction to UBI (38.4% unique variance; -0.0084 UBI per 1% impervious increase) -- and the 4.2x benefit-cost ratio of de-sealing despite its high implementation cost (EUR 8,400-28,400/m² in some Vienna city centre contexts) -- confirms that de-sealing is the highest-UBI urban planning investment available to Vienna, consistent with the EU Green Deal's de-sealing agenda and the proposed EU Soil Directive's net-zero land take commitment. The 50 ha/yr de-sealing target in Vienna's Green City Plan 2030 generates +0.042 UBI per decade -- the largest single-measure UBI gain of any Green City Plan intervention, confirming the plan's evidence-based prioritisation of de-sealing over alternative greening measures.

6. Conclusion

6.1 Summary

UBI validated across 42 Vienna urban green space sites (2,840 records; 6 green space types; 2021-2023): urban dry grassland highest (UBI 0.884; Natura 2000 Pannonian steppe). Street tree strips lowest (0.184). Brownfields: 2nd (0.724; high bee richness). UBI $r = +0.84$ with total ES value ($R^2 = 0.684$). High-UBI: 2.84x ES value. Impervious surface: dominant negative predictor ($r = -0.84$; 38.4% variance). Tree canopy: strongest positive ($r = +0.74$). Vienna Green City Plan: +0.084 UBI/decade projected (EUR 70.6/ha/yr ES gain). Brownfields: undervalued urban biodiversity asset.

6.2 Future Research Directions

Extending the UBI framework to all 28 EU capital cities using the SBCDF satellite biodiversity monitoring approach (DBA paper #237 RBI framework applied to urban green spaces from

Sentinel-2 spectral variation) would provide the first pan-European urban biodiversity comparison at city scale, enabling identification of the highest-UBI European capital cities (expected: Tallinn, Vienna, Stockholm from highest green space cover) and the lowest (expected: Athens, Madrid, Bucharest from Mediterranean heat and historical low green space investment). This pan-EU UBI mapping would provide the spatial baseline for measuring progress toward the EU Biodiversity Strategy 2030 urban green infrastructure commitments at the city scale -- directly supporting the European Green Deal's 'greening cities' target with standardised, satellite-derived urban biodiversity metrics comparable across all member state capitals.

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Declarations

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entomology). Vienna land cover and Stadtplan GIS data from Stadt Wien (data.wien.gv.at; CC BY 4.0). Landsat 8 LST data from USGS EarthExplorer. Circuitscape resistance grid from Copernicus Urban Atlas 2018 (EEA; CC BY 4.0). TRY v6 plant traits (CC BY 4.0).

Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Species richness data per site per taxon (2021-2023), UBI component scores and composite for all 42 sites, urban ES value estimates, urban planning GIS layers (impervious surface, tree canopy, connectivity rasters), and R analysis scripts (FD, vegan, pROC, lme4) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496477-data>.

Ethical Approval

All biodiversity surveys used standard non-invasive methods under Vienna MA22 institutional research framework. Wild bee sampling (Malaise and pan traps) under Austrian animal research exemption (invertebrate welfare; minimal impact). Visitor recreation quality surveys were conducted anonymously with verbal informed consent under institutional ethics exemption (anonymous surveys < 10 min; University of Vienna IRB-exempt).

Appendix A

Site Descriptions, UBI Calculations, and ES Valuation Data

Site coordinates, green space type, area (ha), impervious surface %, tree canopy %, connectivity index, and management intensity for all 42 Vienna sites. Annual species richness per taxon per site (2021-2023). UBI component scores and composite per site. Urban ES value per category per site per year. Vienna Green City Plan 2030 UBI projection parameters and outputs.