Hungarian University of Agriculture and Life Sciences
Doctoral School of Environmental Sciences

Aspects of urban floristic research in Budapest

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1. Background and objectives

The ecological consequences of urbanization are extremely complex: fragmentation of natural habitats, loss of biodiversity, habitat disturbance, and various types of pollution—such as air pollution, heavy metals, and light pollution—all contribute significantly to the transformation of urban ecosystems (Szlavecz et al. 2011; Wilson et al. 2016; Zipperer et al. 2020). The disturbance of urban habitats and their specific microclimatic conditions—such as the urban heat island effect—directly influence species composition, often favoring alien, disturbance-tolerant, or drought-tolerant plant species (Ariori et al. 2017; Nowak 2010; Xiao et al. 2005). At the same time, these urban ecosystems can also provide unique species pools and ecosystem services that promote human well-being and contribute to environmental sustainability (Kowarik 2011). The so-called "novel ecosystems" (Kowarik 2011; Ahern 2016) that emerge as a result of urbanization offer opportunities to explore new theoretical and practical research questions, such as biotic homogenization or evolutionary processes of adaptation (McKinney 2002; Woudstra et al. 2024).

Research of urban flora has become particularly important in an era of declining natural habitats, as cities play an increasingly significant role in shaping regional biodiversity (Lososová et al. 2012). Research in Central Europe has also confirmed that some cities contain habitat mosaics that can provide refuge for rare or endangered species (Kowarik 2011; Wirth et al. 2020b). The ecological assessment of urban vegetation is therefore not only descriptive in nature, but also of decisive importance from a nature conservation and urban ecology perspective. Urban flora research is also playing an increasingly important role in addressing issues of nature conservation practice and sustainable urban planning (Cadenasso & Pickett 2012). These research typically focuses on the study of cities and their surroundings, mapping the rough patterns of plant species distribution (e.g., Lososová et al. 2012; Pyšek 1998). However, with a few exceptions (e.g., Salinitro et al. 2018), detailed exploration of urban (micro)habitats has largely been neglected (Čeplová et al. 2017). Urban ecosystems – with their complex structure, heterogeneous and often disturbed habitats, and numerous practices that facilitate species introduction – can be hotspots for plant species introduction and starting points for subsequent invasions (Francis & Chadwick 2015; Gaertner et al. 2017).

In Hungary, the study of urban flora has long been overshadowed by research of natural habitats, even though significant floristic data on certain urban areas were already published in the 19th and 20th centuries (e.g., Priszter 1944). Modern urban floristic research in Hungary has mostly taken the form of small-scale, local studies (e.g., Tamás et al. 2017). It is only in the last decade that methodologically uniform and complex urban floristic researh have begun, for example in the city of Pécs (Wirth et al. 2020a, 2020b), which can provide a basis for comparative analyses of urban flora in Hungary.

The main objectives of the dissertation are as follows:

1. To provide a comprehensive overview of the composition of the urban flora of Budapest and to compile a floristic inventory of the capital;
2. To explore the city's neophyte flora in detail, with particular emphasis on garden escapees and other newly appearing alien species;
3. To examine and evaluate the number of species in each urban habitat type;
4. To examine and evaluate the species composition of urban habitat types and explore the floristic differences and similarities between them;
5. To explore the background variables that influence the number of plant species in urban areas on a small scale (street section, square).

2. Materials and methods

Study area

Budapest covers an area of 525.11 km^2, of which 388.02 km^2 is urban area, with a permanent population of 1,623,343 in 2023 (Központi Statisztikai Hivatal 2025). The survey of urban habitats in the capital took place between September 2018 and December 2024, during more than 250 field days. The study focused exclusively on urban areas under human influence, excluding natural and semi-natural habitats.

Data collection and processing

The research used two data collection methods:

1. Detailed, small-scale, habitat-based survey using our own methodology in 16 defined urban habitats to explore floristic diversity and the impact of habitats on species numbers;
2. Coarse-scale supplementary data collection without detailed methodology, with the aim of compiling the most complete species list possible for Budapest.

During the detailed data collection, we examined small, easily identifiable territorial units (e.g., street sections, squares), in which we separated distinct habitats (survey units). Within the surveyed territorial units, a list of spontaneously occurring plant species presence/absence was recorded for each habitat (survey unit). Cultivated species (sub)spontaneous individuals and populations were also included in the study. The selection of territorial units was random. A total of 4,143 survey units (habitats) were surveyed within 1,566 territorial units, with the aim of covering as much of the city as possible.

The established habitat category system

During the preparation of the research, we defined the (micro)habitats suitable for plants occurring in the city. When separating habitat categories, we took into account the urban structure, the characteristics of the built environment, the spatial (vertical and horizontal) organization of habitats, their accessibility (public or private areas), the type of disturbance, and the nature of their surface (paved/unpaved). Based on these factors, we developed a (micro-)habitat classification system applicable to urban environments, with 16 separate habitat categories, which can be classified into the following main groups:

1. Roadside habitats: roadside grasslands, roadslopes, ditches;
2. Grasslands: urban grasslands, lawns;
3. Horticultural areas: flower beds, flower boxes, tree planting pits;
4. Gardens: front gardens, private gardens;
5. Woody vegetation: shrubs, hedges;
6. Other types: cracks, ruderal areas, railways, walls.

Sources of species data

I determined the status and origin of the species found in Budapest primarily based on Balogh et al. (2004) and Csiky et al. (2023), supplemented by data from Pyšek et al. (2022), Verloove (2006), and my own field observations.

Geoinformatic methods

I performed the spatial analysis of the data using QGIS 3.36.1 software. I calculated the size, length, width, and distance of the territorial units from the center of Budapest (Clark Ádám Square, 0 kilometer marker). Based on the GIS datasets received from the Municipality of Budapest, I used two main layers of data: (1) urban land use map, (2) green space intensity point map. I grouped the more than 60 categories of the land use map into five functional groups: (1) metropolitan, densely built-up central areas; (2) areas used for transportation; (3) institutional, industrial, and commercial areas; (4) residential areas; (5) parks and public green spaces.

Statistical analyses

I processed and filtered the data and calculated the relative frequency of species per habitat using MS Excel. I performed statistical tests and data analysis in R version 4.3.3, applying a significance level of $\alpha = 0.05$ to interpret the analysis results.

Statistical analysis of species numbers in urban habitats

The aim of the analysis was to compare the average species numbers of different urban habitat types. I calculated the species numbers (total, native, archaeophytes, neophytes) for each survey unit (habitat patch). The species numbers were not normally distributed, so it was appropriate to use non-parametric statistical methods. The main analytical procedure was the Kruskal–Wallis test, followed by Dunn's post hoc test (with Bonferroni correction). Since the sample sizes for the habitats differed significantly, I validated the results using the bootstrap method. The analysis was performed separately for the total number of species, for each native group (native, archaeophyte, neophyte), and for unique species found in each habitat (species that occurred in only one habitat within a given territorial unit).

Statistical analysis of species composition in urban habitats

The aim of this analysis was to explore the floristic similarities and differences between individual urban habitats. This was done by compiling a relative frequency matrix based on the frequency of occurrence of each species in each habitat, derived from the presence/absence data for all survey units (habitats) studied, by calculating for each species the percentage of survey units belonging to each habitat in which that species was present. Based on this, I created a Bray–Curtis dissimilarity matrix. Using the dissimilarity matrix, I performed hierarchical cluster analysis (using the complete linkage method) to group habitats that are floristically similar.

Exploring variables influencing the number of native, archaeophyte, and neophyte plant species at the level of territorial units

The aim of the analysis was to determine which environmental and structural factors influence the number of species in territorial units. I first transformed the data (logarithmization, standardization) and then removed the outliers. To explore the relationships, I used a negative binomial model and then built generalized linear mixed models (GLMM) taking spatial autocorrelation into account. The explanatory variables were: distance from the city center, proportion of green space, number of habitats, area, length/width ratio, and land use type. I modeled the total number of species, native species, archaeophytes, and neophytes separately.

3. Results and discussion

Urban flora of Budapest

Between 2018 and 2024, 1,021 spontaneously or subspontaneously occurring plant species were found in Budapest's secondary urban habitats, 50% of which are native (509), 20% are archaeophytes (207), and 30% are neophytes (305). The 1,021 taxa represent 33% of the Hungarian flora (Bartha et al. 2025), while Budapest covers only 0.5% of the country's territory. The national ratio of native–archaeophyte–neophyte species is 7:1:2 (Csiky et al. 2023), while in Budapest it is 5:2:3, which clearly indicates the spread of alien species in the urban flora. A floristic study of the city of Pécs (Wirth et al. 2020a, 2020b) included 1,641 species, with a significantly different native-archaeophyte-neophyte ratio (7:1:2) compared to Budapest, which can be partly explained by the fact that the study in Pécs also included (semi-)natural habitats found in the city.

Distribution of different life form types in the urban flora of Budapest: 35% annual (Th), 49% herbaceous perennial and biennial (HT, HH, He, Ge, Ch), 16% woody (E, N, M-MM). This ratio is 20-67-13 for native species, 70-23-7 for archaeophytes, and 36-38-26 for neophytes. The 1021 taxa belong to 106 families. The families with the most species are: Asteraceae (125), Poaceae (100), Brassicaceae (62), Fabaceae and Rosaceae (50-50). In terms of chorological types, most of the native and archaeophytic species are widespread, with Eurasian (205 species), European (82), circumpolar (55), cosmopolitan (91), and sub-Mediterranean (87) elements dominating.

Neophytes in Budapest

During the research, 305 neophytes were found in Budapest. The neophytes belong to 77 families, the most populous being Asteraceae (39 species), Poaceae (26), Brassicaceae and Rosaceae (15-15), Amaranthaceae and Lamiaceae (13-13). Of the 26 species of Poaceae, 24 are still rare in Budapest. Among the (currently) rare species of the Poaceae family are several perennial grasses (e.g., *Cenchrus alopecuroides*, *Nassella tenuissima*), which pose a global invasion threat (Musarella et al. 2024; Brunel et al. 2010).

By region of origin, most neophytes come from Asia (24%), North America (23%), and the Mediterranean region (16%). By invasion status, 63% of species are casuals, 19% are naturalized, 13% are invasive, and 5% are transformers. By mode of introduction, 74% of species were introduced deliberately, 21% accidentally, and 5% by both modes. The majority of deliberately introduced species are ornamental plants (210 species), while 25 of the accidentally introduced species are also linked to the ornamental plant trade, a trend that is characteristic throughout Europe (Arianoutsou et al. 2021).

It is important to regularly update the neophyte checklist of defined geographic areas, as these contribute to long-term comparative research and the early detection of rare species (Čeplová et al. 2017). Historically, the number of neophytes has increased dramatically in Budapest: Sadler (1840) mentions 8 species, Borbás (1879) 34, and Hegedüs (1994) 116.

New and significant floristic data from Budapest

Regular field surveys have yielded a great number of valuable floristic data. Eight species were found that are new to the flora of Hungary: *Campanula portenschlagiana*, *Clinopodium nepeta*, *Chasmanthium latifolium*, *Cyrtomium fortunei*, *Linaria maroccana*, *Nicotiana sylvestris*, *Sabulina tenuifolia*, and *Talinum paniculatum*. Three species were also found for which there were no recent data from Hungary: *Glebionis coronaria*, *Lagenaria siceraria*, and *Sisymbrium irio*. In addition, the significant spread of several species was documented (e.g., *Erigeron sumatrensis* and *Euphorbia prostrata*).

Urban habitats of Budapest

During the mapping, I recorded and evaluated a total of 4,143 survey units, i.e., species lists for specific habitat patches, in 1,566 territorial units. The most frequently recorded habitats were cracks, which were included in the survey a total of 1,476 times. Other common habitats were roadside grasslands (541 occurrences), urban grasslands (376 occurrences), hedges (351 occurrences), tree planting pits (292 occurrences), flower boxes (228 occurrences), and front gardens (207 occurrences). In addition to these, there are also very rarely sampled habitats such as ditches (32 occurrences), lawns (41 occurrences), railways (44 occurrences) and roadslopes (56 occurrences). As can be seen from the above, the frequency of individual urban (micro)habitats varies greatly in Budapest.

Number of native, archaeophyte and neophyte species in urban habitats in Budapest

The average total number of species in urban habitat patches showed significant differences, indicating biologically relevant differences. The highest number of species was found on roadslopes (average: 24.3 species), urban grasslands (18.7), roadside grasslands (18.5), railways (17.6), and lawns (16.2). The fewest species were found on walls (3.4), in flower boxes (4.6), in tree planting pits (5.5) and in hedges (5.7). In terms of native species, the habitat types with the highest average number of species were also roadslopes (11.7), urban grasslands (8.4) and roadside grasslands (7.5), while on average the fewest species were found in flower boxes (1.2), walls (1.7) and tree planting pits (1.8). The number of archaeophyte species also proved to be habitat-dependent. Roadslopes (8.4) and railways (8.1) were the habitats with the highest average number of species, while walls (0.9), hedges (1.2), and shrubs (1.3) hosted the fewest species on average. The average number of neophytes also differed between habitat types, although the effect was smaller, i.e., neophytes are less sensitive to habitat type. The highest average species numbers were found in ditches (4), railways (3.9), ruderal areas (3.4), cracks (3.1) and flower beds (3.2). The fewest neophytes occurred on walls (0.6). The number of unique species also showed significant differences. Roadslopes (8.6), roadside grasslands (8.1), and urban grasslands (8.3) had the highest values. Walls again had the lowest value (0.8).

Species with different residence times react differently to habitat conditions. All groups are present in large numbers on roadslopes, while on walls they are uniformly low in number. At the same time, several habitat types – such as railways, flower beds, ditches, and cracks – provide favorable conditions primarily for alien species and are therefore the sites of their introduction and spread.

While urban species richness has often been studied on a large scale (e.g., Pyšek 1998; Lososová et al. 2012; Ariori et al. 2017), finer-scale analyses (e.g., Chang et al. 2022; Solomou et al. 2022) show that the heterogeneity of urban structure is an even more important factor at smaller spatial scales. Our results confirm this: the number of plant species occurring in urban areas is strongly dependent on habitat diversity (cf. Deutschewitz et al. 2003; Liu et al. 2023; Wirth et al. 2020a).

Species composition of urban habitats in Budapest

As a result of hierarchical clustering, the 16 urban habitat types were divided into five clusters: (1) shrubs; (2) private gardens, hedges; (3) ditches, front gardens, urban grasslands, flower beds, lawns, cracks, roadslopes, ruderal areas, roadside grasslands, railways; (4) tree planting pits, flower boxes; (5) walls.

It can be concluded that the species composition of urban habitats is often similar, typically dominated by generalist species that are tolerant to disturbance and trampling (cf. Čeplová et al. 2015; Kühn & Klotz 2006). At the same time, several habitat types – such as walls, shrubs, private gardens, and hedges – have unique species compositions and are well separated from other types. The study confirmed that individual habitats play different roles in urban biodiversity. Cracks, ruderal areas, ditches, flower beds, and flower boxes are home to numerous alien species, supporting the concept of "novel urban ecosystems" (Ahern 2016; Kowarik 2011). Roadslopes and different grassland patches showed a more natural character, with rare, specialist species also occurring, similar to other cities (e.g., Salinitro et al. 2018). We confirmed that both floristic homogenization (e.g., roadside grasslands, cracks, ruderal areas) and specialization (e.g., walls, shrubs) are present in urban vegetation (Kühn & Klotz 2006; McKinney 2002). This duality reflects the diversity of urban vegetation.

Variables influencing the number of native, archaeophyte, and neophyte plant species at the level of territorial units

In terms of total species number, the size of the surveyed territorial unit and the number of habitats occurring within the unit had the strongest positive effect on species number, followed by the proportion of green areas and then distance from the city center. For native species, the proportion of green areas and the number of habitats were the most significant positive background variables. In contrast, the size of the surveyed territorial unit had less influence on the number of native species, while there was no significant correlation between the distance from the city center and the number of native species. In the case of archaeophytes, the factors that had the most positive effect on species number were the size of the territorial unit and the number of habitats, followed by the proportion of green areas. However, distance from the city center had no significant effect on the number of archaeophytes. The number of habitats had the most significant positive effect on the number of neophytes, and a positive significant correlation was also observed with distance from the city center. The size of the area had only a moderate positive effect on the number of neophyte species. The shape of the studied territorial units (length/width ratio) had no significant effect on either the total number of species or the number of species in each group. When analyzing different types of urban land use, it appears that, using industrial and commercial areas as a reference, the total number of species was significantly lower in metropolitan and transportation areas. This effect was even more pronounced in the case of archaeophytes, while the number of native species showed a significant decrease only in metropolitan areas. There was no significant difference in the number of neophytes between the different urban land use types.

It is important to note that similar studies generally deal with species numbers in urban areas on a larger scale and with lower resolution, usually examining differences on a landscape scale or based on a grid projected onto the area.

The strong positive correlation between total species number and the territorial unit size is consistent with classical biogeographical theories (Kilburn 1966; Lomolino 2000). The positive effect of area size was true for all groups, but it was strongest for archaeophytes, which fits well with their synanthropic nature and urban adaptability (Lososová et al. 2012). Native species were less affected by unit size than by the number of habitats or the proportion of green areas, and showed no correlation with distance from the city center. This suggests that locally suitable habitats are necessary for their survival (cf. Kowarik & Lippe 2018). Only in heavily urbanized areas did the number of native species decrease significantly, which is supported by previous, larger-scale studies (e.g., Afonso et al. 2020). The number of neophytes was most strongly correlated with the number of habitats and distance from the city center, while area size had only a moderate influence. Surprisingly, neophytes were present in greater numbers in the outer parts of the city, contrary to the findings of Kowarik (2011). This may be because many alien species are planted in private gardens in the suburbs, which can easily escape from cultivation (Guo et al. 2019), making these areas potential hotspots for invasion.

4. Conclusions and recommendations

A study of the urban flora of Budapest has shown that urbanized areas – despite being subject to significant anthropogenic influences – are capable of maintaining considerable floristic diversity and exhibiting a unique species composition. The 1,021 vascular plant species found, representing one-third of the Hungarian flora, prove that the urban environment is a complex ecological system in which species of different origins and ecological requirements can coexist. The distribution and number of native, archaeophyte, and neophyte species show significant differences depending on habitat characteristics, disturbance levels, and spatial and structural features. This emphasizes the need to focus on further detailed studies in addition to treating and evaluating urban flora as a single entity.

The results of my research highlight that it is worthwhile to examine urban plant species richness at different scales, as this allows us to discover different patterns that can better help us understand the richness and composition of spontaneous vegetation in urban ecosystems. By exploring the processes affecting urban biodiversity as broadly as possible, researchers can contribute to understanding urbanization as a complex process and, through this, to making cities more livable and preserving urban biodiversity. A better understanding of urban microhabitats helps to identify urban areas that are valuable from a nature conservation perspective.

The floristic and ecological study of cities faces numerous difficulties, mainly due to the significant size of private areas. It would be worthwhile to involve the population in urban floristic and ecological research. This would have two positive outcomes: (1) researchers would obtain biotic data from places that are inaccessible to them; (2) the population would become more involved in exploring urban biodiversity, thereby becoming interested in its conservation..

During the research, the most important and critical issue appeared to be the large number of alien, mainly neophyte species occurring and spreading in the city. However, studying these species is difficult because the occurrence of most species is so random that they rarely come to the attention of researchers without a systematic search of urban habitats. Most of these species are only noticed when they have already established populations.

Therefore, it is particularly important to systematically search as many urban areas as possible in order to detect newly emerging neophytes in time. Plants that escape from horticultural cultivation often form self-sustaining populations in and around settlements. The horticultural trade plays a key role in the spread of potentially invasive species. It is important to initiate consultation with gardeners, landscape architects, and urban planners, both in the municipal and private sectors. As a first step, consultations with landscape architects began at a conference workshop on February 28, 2025, at the First Hungarian Invasion Biology Conference, entitled "How not to plant invasive plants?".

5. New scientific results

The new scientific findings of the thesis are summarised as follows:

1. Based on my testing and further development, I have implemented a novel habitat-based urban floristic survey method and recommend its use.
2. I have compiled a current inventory of Budapest's urban flora, which contains 1,021 species.
3. I have contributed significant floristic data to the Hungarian flora and have detected eight vascular plant species new to the flora of the country.
4. I have documented the spread of neophytes and assessed their invasion potential.
5. I determined the contribution of individual urban habitats to the number of plant species in well-defined urban areas.
6. I developed a manageable system for urban habitats based on their species composition.
7. I identified the background variables that influence the number of species in urban areas on a small scale.

6. Publications related to the topic of the dissertation

Journal articles in English:

Rigó, A., Malatinszky, Á., Barina, Z. (2023): Inventory of the urban flora of Budapest (Hungary) highlighting new and noteworthy floristic records. *Biodiversity Data Journal* 11: e110450. https://doi.org/10.3897/BDJ.11.e110450 [IF: 1,0; Q2]

Rigó, A., Barina, Z. (2020): Methodology of the habitat classification of anthropogenic urban areas in Budapest (Hungary). *Biologia Futura* 71: 53–68. https://doi.org/10.1007/s42977-020-00011-x [Q3]

Journal articles in Hungarian:

Rigó, A. (2025): Új jövevényfaj Magyarországon: a *Sabulina tenuifolia* előfordulása Budapesten. *Kitaibelia* 30(1): 15–26. https://doi.org/10.17542/kit.30.063 [Q2]

Conference abstracts in English:

Rigó, A., Malatinszky, Á., Barina, Z. (2023): The non-native flora of Budapest (Hungary). In: Pérez-Diz, M., Núñez González, N., González, L., Rodríguez-Addesso, B. (szerk.): *Book of Abstracts. – III. International Young Researchers Conference on Invasive Species*. Czech Academy of Sciences & Universidade de Vigo, Vigo, Spanyolország, pp. 41–42.

Conference abstracts in Hungarian:

Rigó, A., Kröel-Dulay, Gy., Botta-Dukát, Z., Malatinszky, Á., Barina, Z. (2024): Növényi diverzitás Budapesten. In: Lőrinczi, G., Tölgyesi, Cs. (szerk.): *13. Magyar Ökológus Kongresszus. Előadások és poszterek összefoglalói*. Szegedi Tudományegyetem, Szeged, pp. 67.

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