



A shifting floral bounty in urban ruderal vegetation: implications for pollinator conservation in Bratislava

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Abstract

Urban ecosystems are undergoing changes due to biological invasions and climate change. In this study, we compare shifts in the species composition of ruderal plant communities in Bratislava, with a particular focus on honey-bearing plant species in four phytosociological classes of ruderal herbaceous vegetation. Our comparisons indicate that while plant species richness has remained stable, the presence of invasive species has increased, especially in the *Artemisietea vulgaris*, *Galio-Urticetea*, and *Stellarietea mediae* classes. Native species such as *Carduus crispus*, *Centaurea scabiosa*, and *Epilobium dodonaei* have declined, while invasive species such as *Solidago canadensis*, *Solidago gigantea*, *Reynoutria × bohemica*, and *Symphytotrichum lanceolatum* have expanded their range and increased in cover. Regardless of these changes, the mean melliferous potential of weedy plant communities has remained almost unchanged. Even the spread of melliferous invasive species has contributed to a slight increase in nectar-producing and pollen-producing potential, especially in the *Galio-Urticetea* class. The potential has also increased in the *Stellarietea mediae* class due to the more frequent occurrence of native melliferous species. An important finding is that the abundance of honey-bearing species flowering in late summer and autumn, when few species of trees and agricultural plants flower in and around the city, has remained unchanged despite climate change. Our findings highlight the importance of continuous monitoring and adaptive urban planning to sustain pollinator resources amidst changing species compositions, particularly as invasive species continue to shape urban plant communities.

Keywords Urban ecosystems · Invasive species · Melliferous plants · Pollinator resources · Climate change impacts

Introduction

Urban landscapes are dynamic ecosystems where nature and human activity continuously reshape plant communities (de Barros et al. 2022). Within these landscapes, ruderal urban vegetation plays a crucial role in supporting biodiversity and providing essential ecosystem services (Guo et al. 2018; Mogîldea and Biță-Nicolae 2024). Among these services, pollination—an important regulating ecosystem

service (Haines-Young and Potschin 2018)—is vital not only for humans but also for the survival of many other organisms, particularly insect-pollinated plants. These plants offer essential nectar and pollen resources that sustain and enhance pollinator communities (Nicholls and Altieri 2013).

Despite the prevalence of human infrastructure, urban areas can still serve as important habitats for pollinators. Studies suggest that urban green spaces, such as community gardens with ornamental and functional plants, and urban parks dominated by native or non-native shrubs and trees, are important foraging habitats for pollinators, supporting greater pollinator abundance and diversity (Daniels et al. 2020; Majewska and Altizer 2020; Marquardt et al. 2021; Poole et al. 2025) compared to urban ruderal vegetation. Although urban ruderal vegetation is often perceived negatively (e.g., Brun et al. 2018; Mathey et al. 2018), it can provide a diverse and balanced food source for insect species compared to plantings designed specifically for certain pollinator groups (Lerch et al. 2024; Ulrich and Sargent 2025). Plants in ruderal vegetation thrive in urban

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environments—such as vacant lots, roadsides, and abandoned lands—where they establish rapidly (Robinson and Lundholm 2012; Tabašević et al. 2021) and offer abundant floral resources (Lowenstein and Minor 2016). Research on native ruderal vegetation has primarily focused on its ecological benefits, including biodiversity support, mitigation of urban heat islands, improvement of air quality, and water retention (Mogîldea and Biță-Nicolae 2024). The conservation of biodiversity in urban ecosystems requires not only the protection of pollinators, but also the promotion of ecological stability under conditions of environmental change (Artamendi et al. 2024; Magrach and Montoya 2024). A key strategy to achieve this goal is long-term monitoring of species composition, with particular emphasis on the melliferous potential of urban vegetation.

Previous research has focused on the dynamics of ruderal plant communities in urban environments, showing their crucial role in biodiversity conservation and the provision of essential ecosystem services (Chen et al. 2014; Guo et al. 2018; Torija et al. 2025). In these plant communities, the species richness and their cover are influenced by various factors, such as urbanization (Beninde et al. 2015; de Barros et al. 2022; Hou et al. 2023), the surrounding landscape (Brown and Anand 2024), climate change (Li et al. 2020; Ortega-Rosas et al. 2020; Franceschi et al. 2023), and the spread of alien invasive plants (Rendeková et al., 2017, 2018). However, there is still limited understanding of how these factors jointly influence the melliferous potential of ruderal vegetation. Since any changes in plant communities can disrupt the balance between plants and pollinators, research on urban vegetation should investigate these interactions. Understanding these changes may be key to promoting biodiversity and ensuring the long-term sustainability of green spaces in an increasingly urbanized world (Daniels et al. 2020; Silva et al. 2021).

To assess the ability of plants to provide forage for pollinators, we use the concept of melliferous potential. However, this term can be defined in different ways depending on the context. One widely used definition quantifies melliferous potential as the amount of nectar secreted by a flower, measured either under field conditions or under optimal laboratory conditions (Crane 1975; Ion et al. 2018; Sarvia et al. 2023). This quantitative approach is particularly suited for agricultural or monotypic landscapes where honey production is directly measured. In contrast, another interpretation of melliferous potential focuses on the capacity of a plant to produce nectar and pollen under optimal conditions, which can be utilized by a wide range of pollinators. This method uses a non-parametric scale to assess melliferous potential, rather than a quantitative yield (Jurko 1990; Jarić et al. 2013; Mačukanović-Jocić and Jarić 2016). This approach is mainly applied when evaluating the melliferous potential of grassland and forest communities (Jurko and Fajmonová

1988; Zlinská and Kubalová 2001; Jarić et al. 2013; Eliáš and Mariničová 2017). It may be useful for assessing plant communities that are diverse and dynamic, where species composition and abundance can change significantly over time. Given the diversity and variability of urban ruderal vegetation, we prefer this qualitative approach for our study. By employing this method, we aim to capture changes in the species composition of melliferous plants, rather than directly quantifying nectar production, which may vary significantly across years and environmental conditions. Finally, the use of an established scale allows for comparing historical and contemporary vegetation records, making it more suitable for assessing melliferous potential in urban environments (Hrabovský et al. 2025).

This study analyzes the changes in the representation of honey-bearing plants in the ruderal vegetation of Bratislava by comparing the species composition in two different time periods, with an average difference of 35 years between them. In addition, it assesses changes in the melliferous potential of this vegetation and identifies the plant species responsible for these changes. By focusing on long-term vegetation changes, this study contributes to the broader understanding of how urbanization and environmental changes influence floral resources for pollinators. Finally, long-term monitoring of vegetation that supports pollinators is essential for biodiversity conservation. To achieve these objectives, this study aims to answer the following questions: (i) What changes have occurred in the species composition of ruderal vegetation? (ii) Has the melliferous potential increased or decreased during the study period? (iii) Do invasive species play any role in providing food resources for pollinators?

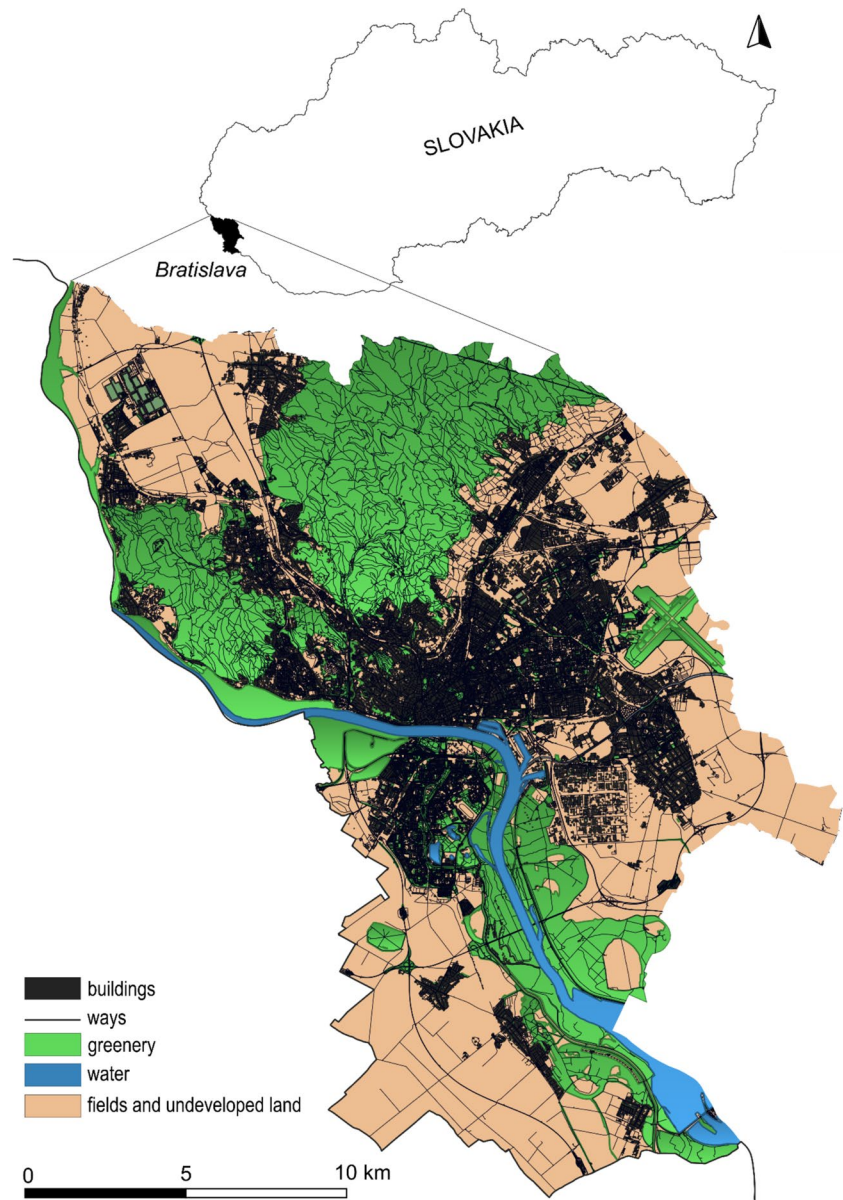
Material and methods

Study area

The capital of Slovakia, Bratislava (48.14944° N, 17.07333° E), was chosen for this study due to its diverse vegetation in both urban and suburban zones (Fig. 1). Like many other cities, Bratislava is a typical urban area featuring various types of greenery, such as forests, parks, gardens, cemeteries, lawns, and ruderal vegetation (Belčáková et al. 2022). In addition to the wild-growing vegetation, a variety of annuals, perennials, and nectar-producing trees are cultivated here, but these are not the subject of this work; we focused only on ruderal plant communities.

The city is located in western Slovakia, where it sits in a transition temperate zone between continental and oceanic climates (Metzger et al. 2005). In recent decades, the average annual temperature has increased, indicating the broader impact of climate change in the area. When comparing the

Fig. 1 Map of Bratislava with land use



different periods (1975–1982 and 2011–2014), the increase was from 9.8 to 11.6 °C. Annual precipitation varies between 500 and 700 mm, signifying moderate rainfall; however, droughts and heatwaves have become more common. Again, over the same time periods, the precipitation totals increased from 548 to 561 mm (Slovak Hydrometeorology Institute). The combination of urbanization and climatic shifts makes Bratislava an ideal location for analyzing vegetation changes, e.g., the spread of melliferous plant species.

Vegetation data

Vegetation changes were assessed using data (phytosociological relevés) recorded from plots with a size of 1–25 m², in accordance with the Zurich-Montpellier school approach

(Braun-Blanquet 1964). The Braun-Blanquet scale modified by Barkman et al. (1964) was used for assessing the values of abundance and dominance of species. We gathered the phytosociological relevés across two different time periods (1975–1982 and 2011–2014), aiming to collect data from approximately the same areas. Maintaining fixed plots over long periods in a dynamic urban setting is challenging due to significant changes in the urban landscape, such as new infrastructure, building projects, and urban expansion. As a result, while we aimed to collect data from the same general locations, there may have been slight shifts of a few meters between the original and newer plots. To ensure data comparability, we focused on capturing the same types of ruderal vegetation rather than insisting on identical plot replication. The relevés were conducted in locations that

broadly matched the original settings, such as roadsides, abandoned lots, and construction sites. Maps with the exact locations and distribution of relevés, including both periods, were published in Rendeková et al. (2017).

The data were recorded in TURBOWIN (Hennekens and Schaminée 2001) and analyzed using JUICE (Tichý 2002), where values of abundance and dominance were converted into percentage cover. The categorization of the relevés was done through clustering methods. Four phytosociological classes were identified: *Artemisietea vulgaris* Lohmeyer et al. in R. Tx. ex von Rochow 1951 (AV), *Galio-Urticetea* Passarge ex Kopecký 1969 (GU), *Polygono arenastri-Poetea annuae* Rivas-Martínez 1975 corr. Rivas-Martínez et al. 1991 (PP), and *Stellarietea mediae* R. Tx., Lohmeyer et Preising in R. Tx. ex von Rochow 1951 (SM).

The AV class includes xerothermic plant communities dominated by biennial and perennial plants, which grow in dry, sunny anthropogenic or semi-natural habitats. The GU class consists of ruderal and semi-natural perennial hemicryptophyte communities that prefer humid nitrogen-rich substrates. The PP class consists of annual plants that thrive in frequently compacted ruderal areas. Lastly, the SM class encompasses annual therophytes that establish themselves in newly disturbed or recently developed areas, including construction sites (Jarolímek et al. 1997; Chytrý 2009). Invasive plant species were classified according to the *Inventory of the Alien Flora of Slovakia* (Medvecká et al. 2012).

Melliferous potential

The melliferous potential of vegetation is influenced by several factors, including the nectar and pollen production of individual plants, their flowering patterns, their proportion and cover within the plant community, and various biotic and abiotic environmental conditions. When a plant grows under optimal conditions and produces its usual number of nectar- and pollen-rich flowers, the honey potential of the plant community primarily depends on species composition and their percentage cover (Jurko 1990; Jarić et al. 2013). Nectar and pollen production of individual species may be assessed using quantitative (Ion et al. 2018; Sarvia et al. 2023) or qualitative scales that are derived from quantitative data (e.g., Ricciardelli D'Albore 1997; Jarić et al. 2013). To evaluate melliferous potential, we applied a qualitative five-level scale established for Slovak flora by Jurko (1990): 0—non-melliferous species without nectar or pollen production, 1—poor melliferous species with minimal nectar or pollen production, 2—good, 3—very good, and 4—excellent. The melliferous potential values assigned to ruderal plant species by Jurko (1990) are based on earlier works, including Jurík (1979), Saury (1981), and Hoepfner (1986), and are comparable to other qualitative scales used in similar studies (e.g., Ricciardelli D'Albore 1997; Jarić et al. 2013),

ensuring methodological continuity and comparability. A list of melliferous species identified in the ruderal vegetation of Bratislava, along with their classification into quality categories, is provided in Table S1. This qualitative method for assessing melliferous potential has its limitations and is not intended to replace quantitative measurements of nectar and pollen yields, which can vary significantly across years due to environmental factors and plant phenology. Instead, it is suitable for determining whether the number of melliferous species is increasing or decreasing, as well as distinguishing between species with low versus high nectar and pollen production (Jurko 1990).

Unlike previous studies (e.g., Jurko and Fajmonová 1988; Zlinská and Kubalová 2001; Jarić et al. 2013), which assessed the melliferous potential of entire plant communities (groups of relevés), we performed a more detailed analysis. Just as we calculated the allergenic potential for the same type of vegetation (Hrabovský et al. 2025), we also assessed the following melliferous characteristics of the 695 relevés individually: (i) nectar-producing and pollen-producing species richness—the number of nectar-producing or corbicular pollen-producing melliferous species, considering both overall diversity and diversity specific to the flowering period; (ii) nectar-producing and pollen-producing species proportion—the ratio of nectar-producing or corbicular pollen-producing melliferous species to all recorded plant species; (iii) nectar-producing and pollen-producing species cover; and (iv) nectar-producing and pollen-producing species cover proportion to total vegetation cover. Nectar-producing and pollen-producing species cover (c) and cover proportion were calculated based on the method of Chytrý et al. (2005) using the formula published by Hrabovský et al. (2025).

We then calculated the nectar-producing potential (NPP) and pollen-producing potential (PPP) of the stand as a weighted average

$$NPP = \frac{\sum_{i=1}^n (c_i \times NPP_i)}{\sum_{i=1}^n c_i}, PPP = \frac{\sum_{i=1}^n (c_i \times PPP_i)}{\sum_{i=1}^n c_i},$$

where c_i may be percentage cover (e.g., 68%) or decimal cover value of each species (e.g., 0.68), and NPP_i and PPP_i are the species-specific melliferous potentials assigned on a five-level scale. The resulting value estimates the nectar- and pollen-producing potential of the stand represented by the recorded relevé, ranging from 0 to 4 (0–0.4—non-melliferous stand, 0.5–1.4—poor melliferous stand, 1.5–2.4—good melliferous stand, 2.5–3.4—very good melliferous stand, and 3.5–4—excellent melliferous stand).

To compare the species spectrum between older (1975–1982) and more recent (2011–2014) periods, we calculated the following metrics for each melliferous species across all relevés: (i) periodical proportion—the proportion of relevés in which the species appeared during a specific

period; and (ii) periodical cover—the average cover of the species in the relevés where it was present within a specific period. These metrics were compared to assess temporal trends in the distribution of melliferous species according to Hrabovský et al. (2025).

Data analysis

R software was used for dataset analysis. Changes in the abovementioned four melliferous characteristics and melliferous potential (NPP and PPP) between older and more recent relevés, as well as among different phytosociological classes, were evaluated by the Kruskal–Wallis test. The periodical proportion and cover of melliferous species were compared using the paired Wilcoxon test. Spearman's correlation was applied to examine relationships between meteorological data (series of mean annual air temperatures and annual precipitation totals) recorded over two periods (1975–1982 and 2011–2014) and four melliferous characteristics and melliferous potential. The meteorological data were obtained from the Slovak Hydrometeorological Institute.

Results

During the period 1975–1982 (historical period), 387 stands of ruderal vegetation were recorded, of which 181 belong to the AV class, 51 to the GU class, 16 to the PP class, and 139 to the SM class. The number of relevés in the recent period (2011–2014) was 308 (AV, 123; GU, 89; PP, 29; SM, 67). In both periods, plant communities of the AV class were the most abundant, which means that ruderal vegetation of dry and warm habitats with moderate disturbance prevailed in Bratislava.

In total, we identified 458 herbaceous plant species, of which 229 (50.0%) are considered melliferous. All of them produce pollen, and only 205 species produce nectar. Specifically, 70 species are poor, 104 good, 25 very good, and 6 excellent nectar-producing plants. For pollen production, 131 species are poor, 77 good, 19 very good, and 2 excellent producers (Table S1).

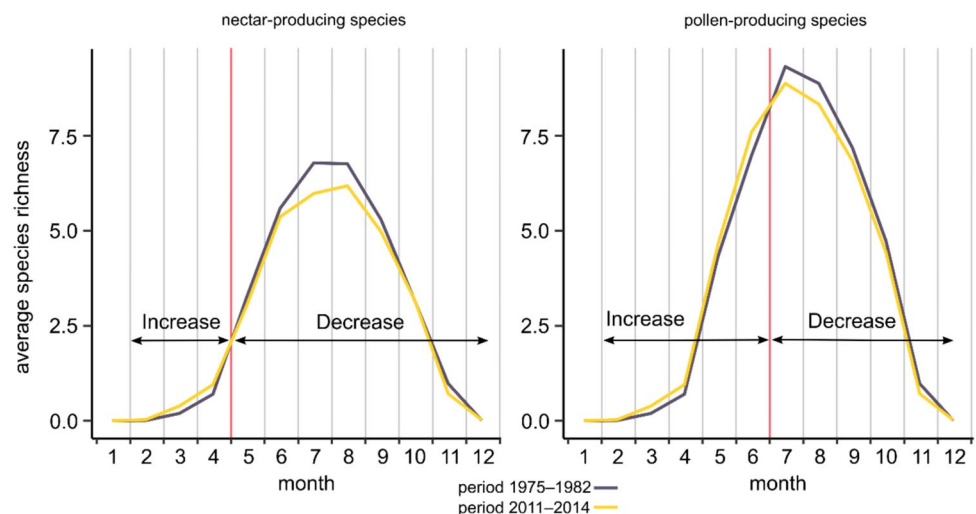
The melliferous characteristics of ruderal vegetation across individual phytosociological classes are summarized in Table S2.

The species richness of nectar- and pollen-producing plants remained largely unchanged in 2011–2014 compared to 1975–1982 (Fig. S1). The only exception was the SM class, where a significant increase was observed in both nectar-producing ($\chi^2 = 28.03$, $p < 0.001$) and pollen-producing species ($\chi^2 = 32.00$, $p < 0.001$) according to the Kruskal–Wallis test. When assessing the number of melliferous species across different stands based on their flowering period, changes were mainly observed in the species composition of spring- and summer-flowering plants. The number of nectar-producing species in March–April and pollen-producing species in March–June increased significantly ($\chi^2 = 6.26$ – 9.81 , $p < 0.05$). In contrast, a decrease in both categories during summer and autumn was observed (Fig. 2), but this decline was not statistically significant compared to the spring increase.

The proportion of nectar-producing species did not change significantly when considering all stands (Fig. S2). However, it decreased in the AV ($\chi^2 = 15.94$, $p < 0.001$) and GU ($\chi^2 = 7.56$, $p < 0.01$) classes, while it increased in the SM class ($\chi^2 = 27.43$, $p < 0.001$). The proportion of pollen-producing species showed a slight decline in the AV class ($\chi^2 = 5.12$, $p < 0.05$), whereas the SM class exhibited the opposite trend ($\chi^2 = 27.3$, $p < 0.001$).

Statistically significant changes were observed in the cover and cover proportion of melliferous species

Fig. 2 Comparison of the average number of flowering nectar-producing species (left) and pollen-producing species (right) in specific months during two periods: 1975–1982 and 2011–2014



(Figs. S3, S4). Both the cover and cover proportion of nectar-producing ($\chi^2 = 12.86\text{--}20.52$, $p < 0.001$) and pollen-producing species ($\chi^2 = 18.28\text{--}32.96$, $p < 0.001$) increased. The average cover and cover proportion of nectar-producing species grew mainly in the GU ($\chi^2 = 5.44\text{--}6.13$, $p < 0.05$) and SM ($\chi^2 = 17.71\text{--}24.25$, $p < 0.001$) classes. Meanwhile, the average cover and cover proportion of pollen-producing species increased across all classes (AV: $\chi^2 = 4.33\text{--}9.48$, $p < 0.05$; GU: $\chi^2 = 7.79\text{--}9.99$, $p < 0.01$; PP: $\chi^2 = 4.25\text{--}4.51$, $p < 0.05$; SM: $\chi^2 = 8.76\text{--}14.52$, $p < 0.01$).

The nectar-producing ($\chi^2 = 4.99$, $p < 0.05$) and pollen-producing potential ($\chi^2 = 10.89$, $p < 0.001$) of stands has increased in the recent period compared to the historical period (Fig. 3). The increase in nectar-producing potential is particularly significant in the SM class ($\chi^2 = 21.6$, $p < 0.001$). Pollen-producing potential has risen mainly in the GU ($\chi^2 = 5.97$, $p < 0.05$) and SM ($\chi^2 = 16.24$, $p < 0.001$) classes.

The paired Wilcoxon test indicates no significant changes in the averaged periodical proportion of species among all melliferous species. However, the average periodical cover proportion (Fig. 4) has increased in favor of melliferous species ($V = 16,808$, $p < 0.001$). Six invasive species—*Bunias orientalis*, *Reynoutria × bohemica*, *Reynoutria japonica*, *Helianthus tuberosus*, and *Solidago canadensis*—have shown an average cover increase of more than 20%. Additionally, three other invasive species—*Atriplex tatarica*, *Solidago gigantea*, and *Symphotrichum lanceolatum*—have

expanded their cover by more than 10%. Many of these invasive species possess good melliferous potential.

Mean annual air temperature (Table 1) showed a significant positive correlation with nectar-producing species, including their cover ($\rho = 0.149$, $p < 0.001$), cover proportion ($\rho = 0.119$, $p < 0.001$), and potential ($\rho = 0.071$, $p < 0.01$). Similarly, it was positively correlated with pollen-producing species cover ($\rho = 0.180$, $p < 0.001$), cover proportion ($\rho = 0.137$, $p < 0.001$), and potential ($\rho = 0.100$, $p < 0.001$). Annual precipitation totals (Table 1) also had a positive correlation with nectar-producing species, specifically their cover ($\rho = 0.099$, $p < 0.001$), cover proportion ($\rho = 0.104$, $p < 0.001$), and potential ($\rho = 0.087$, $p < 0.01$). Additionally, precipitation was positively associated with pollen-producing species cover ($\rho = 0.069$, $p < 0.01$), cover proportion ($\rho = 0.078$, $p < 0.01$), and potential ($\rho = 0.062$, $p < 0.05$).

Discussion

Changes in the number of phytocoenological records and the diversity of ruderal communities in Bratislava were analyzed in a previous study (Rendeková et al. 2018), which found that these shifts were largely driven by land use changes, increased building activity, and alterations in abiotic factors, particularly rising temperatures. In this study, we further examined changes in the species spectrum in greater detail. Since up to 50% of the recorded species are melliferous,

Fig. 3 Boxplots showing the median melliferous potential—nectar-producing potential on the left and pollen-producing potential on the right—of communities in four phytosociological classes (AV, *Artemisietea vulgaris*; GU, *Galio-Urticetea*; PP, *Polygono are-nastri-Poetea annuae*; SM, *Stellarietea mediae*) during two periods: 1975–1982 and 2011–2014. Statistically significant changes in the community are indicated in bold

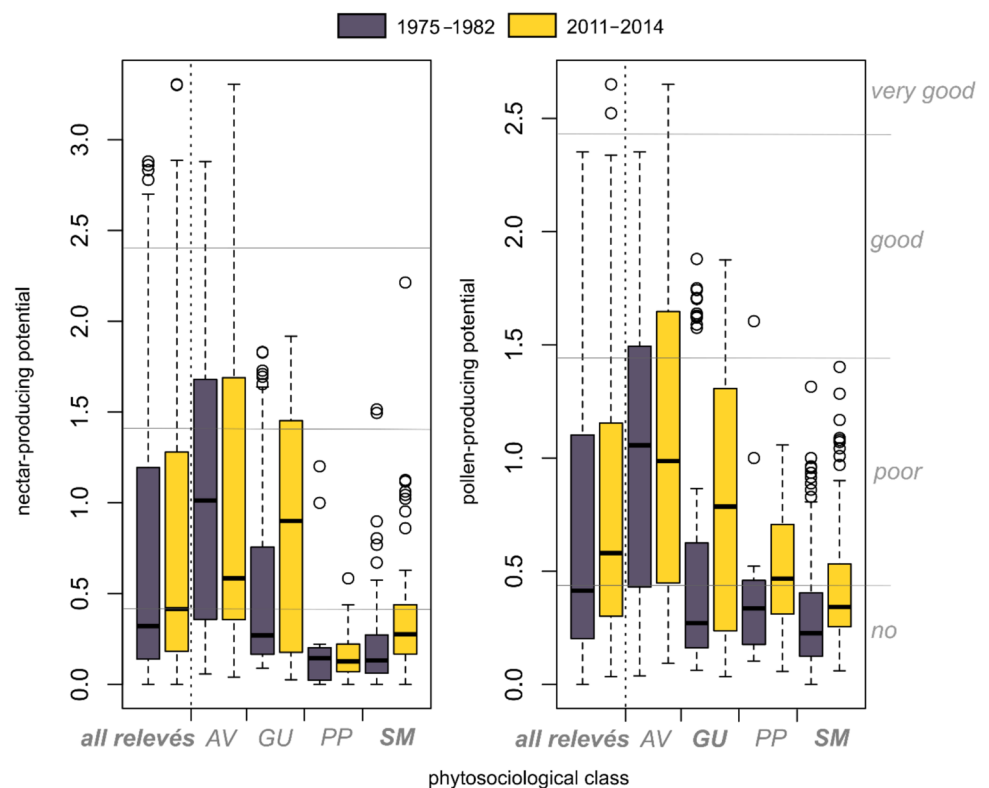


Fig. 4 Changes in the spectrum of melliferous species in Bratislava between the periods 2011–2014 and 1975–1982. The chart displays percentage changes in the averaged periodical cover of the most affected species. Invasive species are indicated in bold

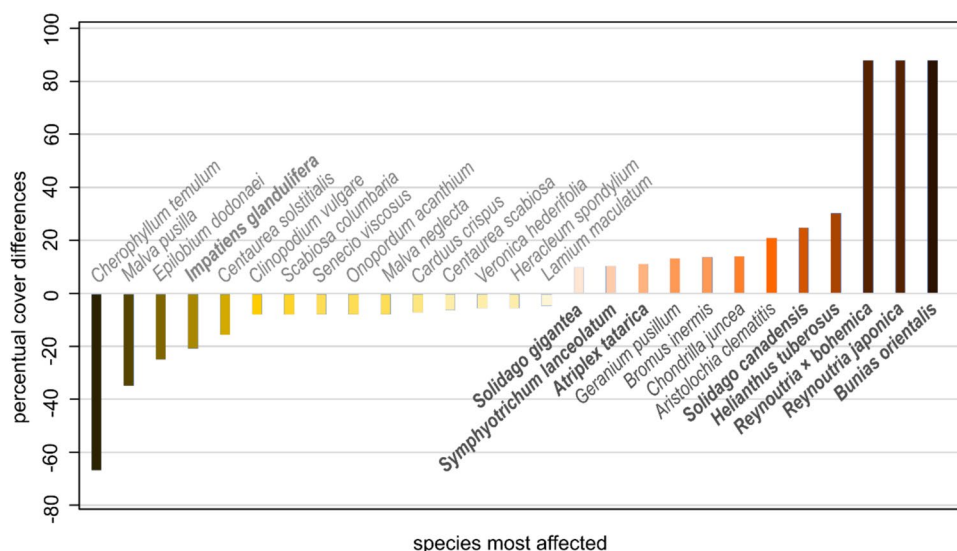


Table 1 Spearman's correlation coefficients between melliferous characteristics of nectar-producing (NP) and pollen-producing (PP) species and meteorological variables

Characteristics	Mean annual air temperature	Annual precipitation totals
NP species richness	0.012NS	0.032NS
NP species proportion	−0.028NS	0.027NS
NP species cover	0.149***	0.099***
NP species cover proportion	0.119***	0.104***
NP species potential	0.071**	0.087**
PP species richness	0.039NS	0.038NS
PP species proportion	0.027NS	0.044NS
PP species cover	0.180***	0.069**
PP species cover proportion	0.137***	0.078**
PP species potential	0.100***	0.062*

* $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$; NS non-significant

these changes inevitably affected the composition of melliferous species as well. However, the extent of these changes varied across phytosociological classes. The most noticeable changes occurred in the AV and SM classes, while they were less pronounced in the GU class and remained comparable in the PP class. Factors such as climate change (Wiegmanns et al. 2024), changes in land use and green space management (de Barros et al. 2022), and biological invasions (Świercz et al. 2024) can be responsible for the shifts in the species spectrum of urban weedy vegetation. The fact that species richness of plants remained stable is often linked with the resilience and stability of plant communities. More diverse plant communities tend to be more adaptable to ecological shifts and disturbances (Dietrich et al. 2024). On the contrary, shifts in species cover led to a slight increase in nectar- and pollen-producing potential.

The mean melliferous potential remained consistently at a “poor” level (ranging from 0.5 to 1.4) according to the established scale.

In the AV class, the most significant changes were observed, with 91 species affected. Several native species, such as *Arctium tomentosum*, *Carduus crispus*, *Centaurea scabiosa*, *Clinopodium vulgare*, and *Epilobium dodonaei*, declined in occurrence and abundance. On the contrary, invasive species such as *Bunias orientalis*, *Helianthus tuberosus*, and *Solidago canadensis* established new populations, and the cover of *Solidago gigantea* increased. These changes suggest a shift towards a more invasion-prone vegetation structure. A possible cause of the spread of invasive plants could be climate change, as the abovementioned invasive species thrive in warming conditions (Cao et al. 2018; Jovanović et al. 2018; Agapie et al. 2022; Michalová et al. 2024). The melliferous potential of this class has remained stable despite the changes, as native species have been replaced by invasive honey-bearing species.

In the GU class, 67 species were affected. Notable declines were recorded for cover of *Heracleum spondylium*, *Chaerophyllum temulum*, and invasive *Impatiens glandulifera*. Similar to the AV class, invasive species such as *Reynoutria japonica*, *Reynoutria x bohemica*, *Helianthus tuberosus*, and *Solidago canadensis* spread into the communities of this class, and the cover of *Solidago gigantea* and *Symphyotrichum lanceolatum* increased. These trends indicate an ongoing homogenization of ruderal communities, where aggressive non-native species are outcompeting native flora (Arévalo et al. 2010; Ondeková and Renčo 2017). Nevertheless, the invasive species are responsible for the enhanced melliferous potential of this class.

In contrast, the PP class experienced relatively minor changes, with only 23 species affected, but it had no effect on the melliferous potential of this group of plant communities.

This suggests that the vegetation dynamics in this class remain relatively stable, possibly due to the persistent nature of short-lived ruderal species adapted to disturbed habitats (Mucina et al. 2016; Rendeková and Mičeta 2017, 2018).

In the SM class, 68 species exhibited changes in their presence. The retreat of species such as *Datura stramonium*, *Malva neglecta*, *Malva pusilla*, and *Senecio viscosus* was observed. However, the increase in species cover of *Convolvulus arvensis*, *Geranium pusillum*, *Medicago sativa*, *Trifolium arvense*, and *Tripleurospermum inodorum* indicates a change in this class. Changes in the species spectrum and cover of the SM class are common due to adaptation to regular or irregular disturbance of the vegetation and substrate (Chytrý 2009). The average nectar-producing and pollen-producing potential increased by 50% and 76.2%. This can be attributed to an increase in the frequency of occurrence of native species, such as *Echium vulgare*, *Carduus acanthoides*, *Tanacetum vulgare*, *Cirsium arvense*, *Cichorium intybus*, *Trifolium pratense*, *Convolvulus arvensis*, and *Taraxacum* sect. *Taraxacum*.

Studies on the melliferous potential of ruderal vegetation are rare. A similar study in Romania (Ion et al. 2018) assessed nectar collection directly from flowers using capillaries. Although the methods differ, both studies indicate that perennial ruderal herbaceous species contribute positively to the honey-bearing potential of vegetation. Ion et al. (2018) discussed that the higher melliferous potential of ruderal vegetation could be linked to their root systems, which may support greater nectar production or plant vigor in perennials. In line with this, our study found an increase specifically in perennial ruderal species, suggesting that these plants may play a key role in enhancing the melliferous potential of urban vegetation. Mačukanović-Jocić and Jarić (2016) investigated the ruderal vegetation of Vojvodina (Serbia) using an established scale for melliferous potential. Like our study, they classified the melliferous potential of the PP and SM classes as “poor.” Similarly, invasive species such as *Helianthus tuberosus* were present in Vojvodina, contributing to an increase in the honey-bearing potential of the vegetation.

Several invasive plant species have been documented to produce substantial quantities of nectar, thereby enhancing foraging opportunities for pollinators. Notable examples include *Impatiens glandulifera* (Bartomeus et al. 2010), *Symphoricarpon lanceolatum* (Horsburgh et al. 2011), *Solidago canadensis* and *Solidago gigantea* (Jachula et al. 2020), *Reynoutria japonica* (Cucu et al. 2021), and *Helianthus tuberosus* (Denisow et al. 2019), all of which are characterized by high nectar production. These species attract a diverse array of pollinators, including bees and butterflies. Moreover, their extended flowering periods provide a consistent nectar supply in late autumn, when native plant species have already ceased flowering. The melliferous potential of invasive plants is one of the few ecological benefits associated with

biological invasions (Jachula et al. 2020; Cucu et al. 2021). Pollinators generally exhibit no preference between nectar and pollen sources derived from native versus non-native plant species (Bartomeus et al. 2010; Davis et al. 2018). However, the spreading of certain invasive plants may result in a decline in floral diversity (Carboni et al. 2021), which could restrict the range of nutrients available to pollinators (Filipiak 2024). In our study, this effect was not observed, likely due to the regulation of urban greenery, where extensive monocultures of clonal invasive species are less prevalent compared to rural landscapes, where such impacts may be more pronounced (Štajerová et al. 2017).

Urban vegetation across multiple European cities is undergoing significant changes. A key aspect of this change is the increasing presence of alien plant species and the changing balance between native and non-native species (Chocholoušková and Pyšek 2003; Pyšek et al. 2004; Knapp et al. 2010; Gregor et al. 2012; Lososová et al. 2012; Salinitro et al. 2019; Alizadeh and Hitchmough 2020). Our findings show that the cover of melliferous plant species in the study area increases with mean air temperature and precipitation. A higher proportion of these plants in urban vegetation enhances their capacity to provide food for pollinators. Additionally, rising temperature and precipitation directly boost nectar secretion (Pétanidou and Smets 1996; Schweitzer et al. 2013).

In urban areas with park-like plantings of flowering trees and shrubs, gardens rich in floral resources, and adjacent agricultural fields with melliferous species such as *Brassica napus* and *Helianthus annuus*, ruderal vegetation primarily serves as a supplementary food source for pollinators. However, during late summer and autumn, it becomes the primary source of nectar and pollen. Therefore, assessing the nectar-producing potential of species commonly regarded as weeds is of ecological significance (Wrzesień and Denisow 2007). Our findings indicate that the richness of flowering species in late summer and autumn has remained consistent compared to historical records. While the scaled assessment does not allow for precise quantification of changes in nectar and pollen production within these plant communities, our results suggest that their melliferous potential remains substantial.

Conclusion

Our study in Bratislava provides insights into species composition shifts of ruderal vegetation in an urban ecosystem and their consequences for melliferous plant species. Although biological invasions, warming, and land use changes have likely altered species composition, overall plant species richness has remained stable. The most significant changes have occurred in the *Artemisieta vulgaris* and

Galio-Urticetea classes, where invasive species are increasingly asserting themselves, which may have implications for pollinator resources. Although the number of invasive species also increased in the class *Stellarietea mediae*, the observed rise in melliferous potential was driven by native species rather than by the invasive ones. In contrast, the *Polygono arenastri-Poetea annuae* class showed relative stability. However, these shifts have not led to a qualitative change in the melliferous potential of ruderal plant communities, which has consistently remained at a “poor” level. The spread of melliferous invasive species has contributed to a slight increase in total nectar and pollen production, especially in the *Galio-Urticetea* class. However, although invasive species provide food for pollinators, their increasing presence across plant communities could ultimately reduce the floristic diversity of native plant species, which could negatively impact the pollinators. Our findings highlight the importance of long-term monitoring of ruderal vegetation, as it plays a key role in sustaining pollinator populations, especially in late summer and autumn. To mitigate potential negative effects, future research should focus on integrating long-term ecological monitoring with urban planning frameworks, aiming to enhance pollinator conservation while managing invasive species effectively.

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Data availability Data is available upon request.

Declarations

Conflict of interest The authors declare no competing interests.

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