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RESEARCH

Urban flower-power for wild bee and hoverfly conservation

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Abstract

Wild bees and hoverflies are some of the most important pollinator groups across the globe, including in urban areas. Urban areas are increasingly recognized as potential pollinator refugia, mostly due to the lower pressure from agrochemicals in comparison to rural areas and often high floral diversity in human-maintained landscapes. Because many factors influence the suitability of urban green spaces for pollinators local studies considering different taxa are needed to best inform the pollinator-friendly management. We studied bee and hoverfly communities across urban green spaces of Zagreb, a city in an understudied region of Europe. We tested how temperature, urbanization, and availability of floral resources impact pollinator species richness. We report 123 species of wild bees and 50 species of hoverflies for Zagreb, including 7 species of conservation interest at the European level. Increased average site temperature, due to urban heat island effect, negatively impacts hoverfly species richness, but not that of the bees. Sites with higher floral abundance had higher species richness of both pollinator groups. Our results show that a simple intervention such as reducing the intense mowing regime in urban green areas to increase abundance of floral resources, can have significant positive impact on urban pollinator diversity and contribute to conservation of threatened species.

Keywords Syrphidae · Anthophila · Urban heat island · Pollinators

Introduction

The decline of insect diversity and abundance is documented across the globe (Hallmann et al. 2017; Forister et al. 2019; Wagner 2020), caused by habitat loss, pesticide use, climate change, and urbanization (Sánchez-Bayo and Wyckhuys 2019). Among the declining insect taxa, pollinators have received special attention (Biesmeijer et al. 2006; Potts et al. 2010; IPBES 2016), because of their popularity in comparison with most other insect taxa (Hall and Martins 2020), and because of the ecosystem services they provide (IPBES 2016). Globally, animal pollination ensures the reproduction of about 85% of flowering plant species (Ollerton et al. 2011) and 75% of the most important crops (Klein et al. 2007).

Overall impact of urbanization on pollinator richness and abundance is negative, especially for Lepidoptera, soil nesting bees, and spring flyers (Liang et al. 2023). However, growing number of pollinator studies show that urban areas can play a role in pollinator conservation (Baldock et al. 2015, 2019; Theodorou et al. 2020; Grossmann et al. 2023). A recent review of urban pollinators diversity across the globe reports 3148 species, including birds, mammals, and 2691 species of insects (Silva et al. 2023). For pollinators, cities can provide continuous and diverse floral resources for nutrition (Grossmann et al. 2023), nesting sites for some groups (particularly cavity-nesting bees, which easily nest in human infrastructure), and reduced pesticide exposure compared to agricultural areas (Theodorou et al. 2020). Some studies report higher pollinator diversity in cities than

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in surrounding rural areas, and in rare cases even higher than in surrounding nature reserves (Baldock et al. 2015; Hall et al. 2017).

Bees (clade Anthophila) and hoverflies (family Syrphidae) are considered some of the most significant pollinator taxa globally, but especially in temperate regions (Rader et al. 2020). Studies investigating the urban ecology of wild bees are becoming common, as most urban pollinator studies worldwide focus on bees (Silva et al. 2023). However, similar studies of hoverflies are less common (Lequerica Tamara et al. 2023; McCune et al. 2023) as well as studies including both taxa (Baldock et al. 2015; Persson et al. 2020; Gathof et al. 2022; Grossmann et al. 2023). Various factors impact the capacity of cities to provide habitats for wild bees and hoverflies. Importance of individual factors vary between the studies and regions (Liang et al. 2023), so conducting local investigations is useful for informing pollinator-friendly management and for planning conservation actions.

Previous studies identify the availability of floral resources and the degree of urbanization, as some of the most important predictors of pollinator richness and abundance (Gathof et al. 2022; Grossmann et al. 2023; Liang et al. 2023). Another important variable is temperature – urban studies provide the opportunity to test the impact of increased average temperatures on pollinators (Hamblin et al. 2017; McCune et al. 2023), thanks to urban heat island effect, i.e., significantly higher night temperatures and smaller difference between night and day temperature in city centers due to a high percentage of impermeable surfaces and lack of vegetation (Oke 1973; Hart and Sailor 2009). Higher temperatures impact insect development and immune system (Fründ et al. 2013; Noel et al. 2022), increase bee sensitivity to pesticides (Albacete et al. 2023), and induce phenological changes in pollinator foraging leading to desynchronization with plant flowering time (Bartomeus et al. 2011; Kühsel and Blüthgen 2015).

Bees and hoverflies have different life history traits, habitat requirements, and global distribution patterns (Keil et al. 2008; Rotheray and Gilbert 2011; Orr et al. 2021). Overall, bees tolerate higher temperatures and xeric environments better than hoverflies and are more successful in colonizing urban habitats (Rotheray and Gilbert 2011; Hall et al. 2017; Orr et al. 2021; Liang et al. 2023). Previous studies showed no impact of the urban heat island effect on species richness of bees and hoverflies, but a decrease in bee abundance (Hamblin et al. 2018), and a decrease in hoverfly richness for some functional groups (McCune et al. 2023). Testing how ecological characteristics of urban habitats impact both bee and hoverfly communities is important to inform conservation planning that takes ecological diversity of pollinators into account. Diversity of pollinating communities is important for maintaining diverse populations of plants (Wei et al. 2021) and providing high agricultural yields (Garibaldi et al. 2013; Grab et al. 2019).

In this study, we look at wild bee and hoverfly communities in capital of Croatia, Zagreb, a city from understudied region of Europe with significant knowledge gap on pollinator diversity (Potts et al. 2020; Reverté et al. 2023). We ask if Zagreb can support rich pollinator communities and contribute to bee and hoverfly conservation, as was shown for other cities. Our aim was to explore how urbanization, floral richness and abundance, commonly shown as important for pollinators, impact pollinator richness. Additionally, we use a temperature gradient created by the urban heat island effect to test the impact of increased average temperature on bee and hoverfly richness. We discuss our findings in the context of urban green area management, providing recommendations for city of Zagreb, relevant for similar cities with temperate continental climate.

Methods and materials

Study sites

We studied wild bee and hoverfly communities of the Croatian capital, the city of Zagreb (45.80°N 15.99°E, elevation 145 m). Zagreb is situated in south-eastern Europe, one of the most understudied regions of Europe for both bees and hoverflies (Reverté et al. 2023). Zagreb has 767,131 inhabitants (Croatian Bureau of Statistics 2022), population density of 1,196.33 inhabitants per km^2 and a continental climate with warm summers (Zaninović et al. 2008). Average monthly temperature is 22 °C in warmest month (July) and 0.6 °C in coldest (January), based on the measurements from 1861 to 2023 (Croatian Meteorological and Hydrological Service 2024). To represent a temperature gradient across urban green spaces we chose our sampling sites using the Landsat-8 map thermal map (Fig. 1), based on average summer land surface temperatures 2013–2020. We chose 8 green spaces for our study: four sites in the city center, within the influence of urban heat island (hereafter urban sites), and four sites outside of city center (hereafter peri-urban sites) (Sites 1–8 in Fig. 1, Table 1). We expected that our urban sites will be significantly warmer and have higher percentage of impervious surface, than our peri-urban sites. In addition to temperature, we chose our sites to represent a gradient of sizes, floral resources, percent of impervious surfaces, and management intensity. Two of the urban sites were botanical gardens (PMF and PHAR, Site 2 and 4 in Fig. 1), with high floral richness and abundance, and low mowing intensity (1–4 times per year, depending on the area). The other two urban sites (ROKO and RIB, Sites 1

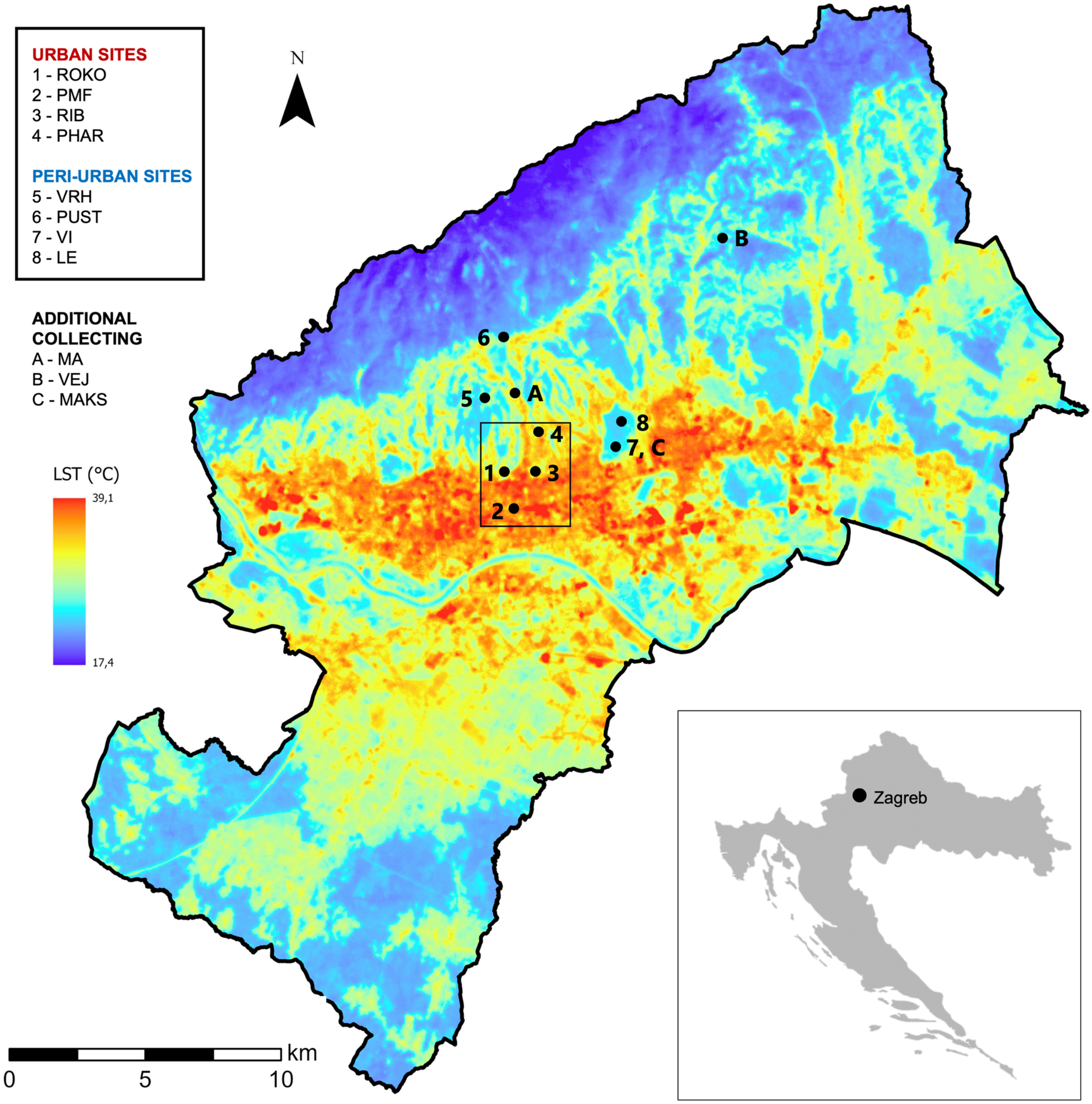

Fig. 1 Zagreb Land Surface Temperature (LST) map with main (1–8) and additional sampling sites (**A**-**C**). Position of Zagreb within Croatia is indicated on a smaller map

and 3) were typical city parks, with trees, bushes, and intensively managed open grassy areas (bi-weekly to monthly mowing). Peri-urban site Vrhovac (VRH, Site 5) was an urban meadow, mowed at least 3 times per year, and site 6 (PUST) was an old levee covered with grass, with intensive mowing regime. Sites 7 and 8 (VI and LE) were situated in a larger city park, Maksimir park. Both were open areas with some trees or bushes, differing in mowing intensity: site 7 (VI) had mowing regime like urban parks while site 8 (LE) had lower mowing regime (once per year). Minimum distance between the sites was 0.75 km.

We also sampled pollinators at three additional sites (Sites A-C in Fig. 1. and Table 1), which we report for full species list, but which were excluded from our main analyses due to lack of temperature data, drastic landscaping changes (topsoil removed after first collecting at one of the

Table 1 Sampling locality names, coordinates in decimal degrees (WGS 84), and size

Site		*N*	E	Area (ha)
1	ROKO - Rokov perivoj	45.814716	15.967685	0.8
2	PMF - PMF Botanical Garden	45.804640	15.973035	3.6
3	RIB - Ribnjak park	45.815150	15.981050	3.7
4	PHAR - Pharmacy Botanical Garden	45.828589	15.983297	2.4
5	VRH - Vrhovac	45.832902	15.948376	0.7
6	PUST - Pustodol	45.861021	15.966870	0.5
7	VI - Vidikovac, Maksimir	45.824759	16.022651	0.7
8	LE - Livada Leptira, Maksimir	45.831435	16.023869	0.3
A	MA - Mallinov park	45.840782	15.972999	1.1
B	VEJ - Vejalnica	45.919096	16.078520	2.6
C	MAKS - Lipovo sjedište, Maksimir	45.822785	16.020776	0.2

sites), and logistics. These additional sampling sites were an urban park (A), a peri-urban managed grassland (B), and another site in Maksimir Park (C), similar and very close to site 7 (Fig. 1).

Pollinator sampling

We hand-collected wild bees and hoverflies with entomological net using variable transect walk (Westphal et al. 2008) for a standardized period of 30 min per site and per collecting event, in optimal conditions for pollinator activity - between 8:00 and 17:00, no rain or wind, temperature above 17 °C if cloudy, and above 15 °C if sunny. Each variable transect walk consisted of slowly walking across the site, aiming to cover as much of the area as possible, and hand collecting at any potential floral resources, including planted floral patches, bushes, trees, and lawn areas. All collected wild bees and hoverflies were preserved in vial with 70% ethanol or stored in empty vials and frozen at −20 C°, then pinned for identification under stereomicroscope.

We sampled our main sites, sites 1–8 (Fig. 1), once pre month in April (13. −14.4.), May (18.−19.5.), June (19.−21.6.), and August (1.−3.8.) of 2022 (a total of 32 collecting events or 16 h of hand collecting). The 2022 data is used for our ecological analyses, as we have the full temperature data for that year and those sites. We also sampled some of the main sites (PMF, PHAR, RIB, ROKO, LE) and three additional sites (A, B, and C in Fig. 1) in June, July, and September of 2021. We report these additional sampling events because Croatia is one of the most understudied regions of Europe for both bees and hoverflies (Potts et al. 2020; Reverté et al. 2023). Additional data provides a more comprehensive species list of Zagreb pollinators, needed to support conservation planning and encourage further local studies.

Ecological data

We measured air temperature at the start of each sampling event with a handheld thermometer (Taylor 9482 NSF), and average temperature of sites by installing two data loggers (EasyLog USB-1, Lascar Electronics) per site, placing them on the ground on the top of the fallen dried vegetation, in the shade of a hedge bush. Temperature loggers were programmed to measure the temperature every 20 min from 15th April to 13th September 2022. We averaged the measurements from two data loggers for 6 out of 8 sites. At remaining two sites (ROKO and PHARM) one of the loggers failed, so data for those sites came from a single logger. We chose the temperatures measured every day from 19:00 to 21:00 to calculate average site temperature. Temperatures in that period best show the effect of the urban heat island without the interference of direct solar radiation and enable comparison of localities according to their relative warming better than average daily temperatures (Meineke et al. 2016; Hamblin et al. 2018). To measure floral richness, we recorded the number of entomophilous plant species in flower at the time of collecting, which in our sites mostly included herbaceous plants, but also flowering trees and bushes. To measure the availability of floral resource for pollinators per site we visually estimated percentage of the entire site covered by flowers (Szigeti et al. 2016), and converted these estimates into abundance categories, with category 1 indicating 0–10% of coverage with flowers, category 2 indicating 11–20% coveage, and so on. We measured the size of each site in QGS (QGIS.org 2024) and included it in our analyses, to account for potential size effects of green areas. We also used QGIS to calculate the percentage of the impervious surface within a 500-meter radius of our sites, using Impervious Built-up map based on Sentinel-2 satellite images (10-meter resolution), available at European Environmental Agency website (data citation identifier: DAT-14-en). The 500-meter radius encompasses the foraging radius of majority of bee species (Steffan-Dewenter et al. 2002; Gathmann and Tscharntke 2002; Zurbuchen et al. 2010) and is also informative for hoverflies (Wratten et al. 2003; Grossmann et al. 2023).

Sample identification

We identified all collected bees and hoverflies using a stereoscopic microscope (ZEISS Stemi 305 trino) and taxonomic keys for bees (Scheuchl 1996; Amiet et al. 2007; Bogusch and Straka 2012; Smit 2018; Michez et al. 2019) and hoverflies (van Veen 2010; Nedeljković 2011; Speight and Sarthou 2017; Speight et al. 2020). Our hoverfly identifications were confirmed or identified by experts from University of Novi Sad: Ante Vujić for *Merodon* and

Cheilosia, Ana Grković for *Eumerus*, and Tamara Tot for all other hoverfly genera. Species identifications for bees were validated at Linz Biological Center bee collection, with help from Martin Schwartz and Esther Ockermüller. Taxonomically challenging groups were further confirmed or identified by: Simoni Flaminio and Andreas Ebmer for Halictidae, Thomas Wood for *Andrena*, Achik Dorchin for *Eucera*, Guillaume Ghisbain for *Bombus*, and Romain Le Divellec for *Hylaeus*.

Data analyses

We ran all analyses and created plots in R programming language, version 4.4.2 (R Core Team 2024). We used the number of sampled species per site and per sampling for analyses of species richness, rather than pooled or averaged numbers across the sites, to keep the granularity of important urban variables, such as floral abundance, which vary depending on the management regime. To test the effect of average temperature, floral resources, and impervious surface cover on the bee and hoverfly species richness we used generalized mixed models with Poisson family distribution. We chose GLMM model selection for our study because it performs well with ecological count data, enables including the site identity as a categorical random variable to account for repeated sampling, and because it provides flexible and realistic inference for exploratory ecological study such as ours, without clear binary hypothesis (Burnham and Anderson 2002; Bolker et al. 2009; Harrison et al. 2018). To account for seasonal variation, we included the month of sampling as a categorical variable (Table 2). Further, we sampled all sites in the same 2–3 days of each sampling month, to minimize seasonal effects within the sampling round. We analyzed the data using the function and package glmmTMB (Brooks et al. 2017), and a package MuMIn (Barton 2019). We constructed separate models for bees and hoverflies, because of their different biology (Persson et al. 2020). Some of our variables were moderately to strongly correlated: floral richness and abundance (Pearson correlation coefficient, $r = 0.64$, $p < 0.001$), as well as average temperature and the impervious surface ($r = 0.84$, $p < 0.001$). We tested effect of correlated variables on species richness using separate models, to avoid collinearity and to be able to disentangle their individual effects. We ran a model comparison based on AIC values to select optimal models (Burnham and Anderson 2002). We checked for overdispersion of each model using diagnostics in DHARMa package (Hartig 2020), and changed the distribution if overdispersion was detected (for 3 out of 30 tested models we changed the distribution to negative binomial, Table S2). To calculate the significance level of individual categorical variables, for which we report GLMM statistics, we used likelihood ratio test, comparing the full and reduced model. Data set and R code used for all analyses are available at a personal github page (https://github.com/anajesovnik/zagreb-buzz*)*.

Table 2 Modeled variables

Predictor variables	
Floral abundance	categorical
Floral richness	numeric
Average site temperature	numeric
Impervious surface area	numeric
Covariates	
Sampling temperature	numeric
Site size	numeric
Month of sampling	categorical
Site identity	categorical, random

Results

Pollinator diversity in urban green areas

In two years and across 11 sites we collected 123 species of bees (721 specimens) and 50 species of hoverflies (190 specimens) in city of Zagreb (Table S1), representing 17% and 18% of the national bee and hoverfly fauna of Croatia, respectively (Reverté et al. 2023). Total bee species richness of site varied from 22 to 46 (average 7.75 ± 4.6 standard deviation, per collecting event) and for hoverflies from 3 to 22 (2.56 ± 2.42). Botanical garden in the city center (Site 2, PMF) had the highest total number of bee species (46 species), while hoverfly richness was highest in a peri-urban site (22 species), Site 5, Vrhovac.

We recorded species of conservation concern in Europe, assessed by most recent European Red List for bees (Nieto et al. 2014) and hoverflies (Vujić et al. 2022). These included three bee species with near threatened (NT) conservation status: *Andrena hattorfiana* (Fabricius, 1775), *Lasioglossum majus* (Nylander, 1852), and *Nomada armata* Herrich-Schäffer, 1839; as well as four hoverfly species: endangered (EN) *Paragus finitimus* Goeldlin, 1971 and *Eumerus sinuatus* Loew, 1855, vulnerable (VU) *Microdon mutabilis/myrmicae*, and near threatened (NT) *Microdon devius* (Linnaeus, 1761). Three most abundant bee species in our study were *Bombus pascuorum* (Scopoli, 1763), *Lasioglossum marginatum* (Brullé, 1832), and *Anthophora plumipes* (Pallas, 1772). Species *Episyrphus balteatus* (De Geer, 1776), *Sphaerophoria scripta* (Linnaeus, 1758), and *Eristalis arbustorum* (Linnaeus, 1758) were the most common hoverflies. All six species are widely distributed generalists (Michez et al. 2019; Speight 2020) and some of the most common urban pollinator species globally (Silva et al. 2023).

We report five new records for Croatian bee and hoverfly fauna (Reverté et al. 2023): four hoverfly species (*Fagisyrphus cinctus* (Fallén, 1817), *Lapposyrphus lapponicus* (Zetterstedt, 1838), *Paragus finitimus* Goeldlin, 1971, and *Philhelius stackelbergi* (Violovitsh, 1975), as well as one bee species (*Anthidium septemspinosum* Lepeletier, 1841), bringing the national species numbers to 666 for bees and 293 for hoverflies in Croatia. In one of our urban sites, the botanical garden in city center (Site 4, PHAR), we recorded a non-native giant resin bee, *Megachile sculpturalis* Smith, 1853, which was introduced from Asia to Europe in 2008. This potentially invasive species is present in Croatia since 2018 (Bila Dubaić et al. 2022). Giant resin bee was the only non-native species we recorded.

Environmental predictors of species richness

Average evening temperature of sites, measured by our data loggers, varied from 17.9 °C (Site 6, PUST) to 20.9 °C (Site 1, ROKO). The percent of impervious surface in a 500-meter radius ranged from 0.7% (Site 8, LE) to 66.5% (Site 3, RIB). Urban sites had statistically significantly warmer evenings than peri-urban sites (Kruskal Wallis $\chi^2=23.6$, df=1, $p<0.01$), 1.53 °C on average, and they had significantly higher percent of impervious surfaces (Kruskal Wallis $\chi^2=23.6$, df=1, $p<0.01$); 59% on average, in comparison to 7% on average for peri-urban sites.

Average site temperature had different effect on bees and hoverflies. For hoverflies, it was a negative predictor (Fig. 2), as urban green areas with higher average temperature had lower hoverfly species richness (β = − 0.3, SE=0.1, $p=0.005$). In addition to average site temperature, optimal model for predicting hoverfly species richness included sampling temperature and floral abundance (Fig. 2; Table 3 , Table S2). Temperature at the time of sampling also had negative effect on hoverfly species richness (β = − 0.06, SE=0.02, $p=0.008$), but floral abundance was a positive predictor (Likelihood ratio test, LRT: $\chi^2=13.7$, df=4, $p=0.008$), although this effect was driven by highest category of abundance, category 6 (β=1.28, SE=0.37, $p=0.006$).

For bees, the three optimal models included floral abundance, temperature at the time of sampling, and month (Table 3). Floral abundance had a strong positive effect on bee species richness (Fig. 3, LRT: $\chi^2=30.9$, df=4, $p<0.01$), as sites with higher abundance of entomophilous flowers had more bee species. Floral abundance was a significant predictor in all three optimal models (Table 2). The two highest abundance categories had largest effect: category 5 (β=1.06, SE=0.17, $p<0.01$) and category 6 (β=1.04, SE=0.30, $p<0.01$).

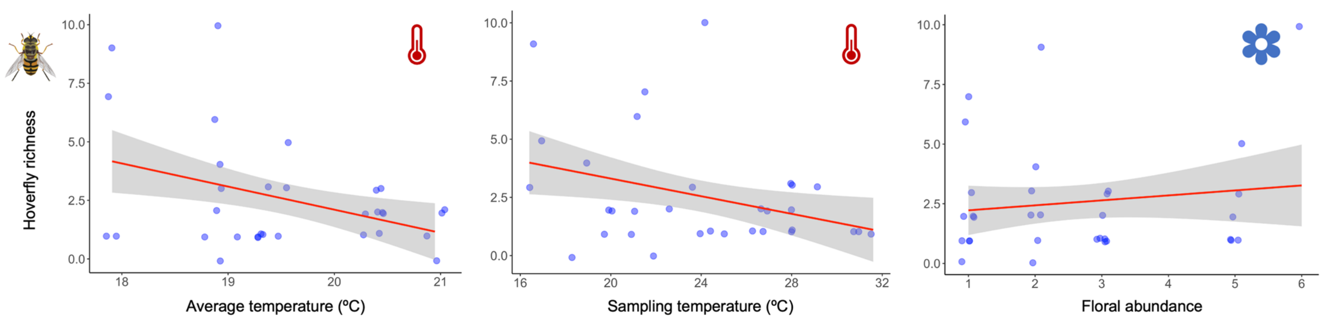

Fig. 2 Environmental predictors of hoverfly species richness: average site temperature, temperature at the time of sampling, and floral abundance category

Table 3 Optimal models of hoverfly (RICHSyrph) and bee (RICHBee) species richness. Model terms include: TEMPAver – average site temperature, TEMPColl- air temperature at the start of collecting event, FLORALAbundCat - category of floral abundance (1–10), with 1 indicating 0–10% of coverage with flowers, month – the month of sampling. For each model degrees of freedom (Df), AIC values, ΔAIC, and Akaike weights (wi) are listed, as well as marginal and conditional R^2. Significant predictors are indicated in italic

Model terms	Df	AIC	AIC differences	Akaike Weights	R2 marginal	R2 cond
Hoverflies						
RICHSyrph ~ *TEMPAver* + *TEMPColl* + *FLORALAbundCat* + (1|LOCATION)	8	123.673	0	0.766	0.43	0.43
Bees						
RICHBee ~ *FLORALAbundCat* + *month* + (1|LOCATION)	9	157.564	0.518	0.298	0.63	0.63
RICHBee ~ *FLORALAbundCat* + month + TEMPColl + (1|LOCATION)	10	158.742	1.695	0.165	0.63	0.63
RICHBee ~ *FLORALAbundCat* + *TEMPColl* + (1|LOCATION)	7	157.046	0	0.386	0.61	0.61

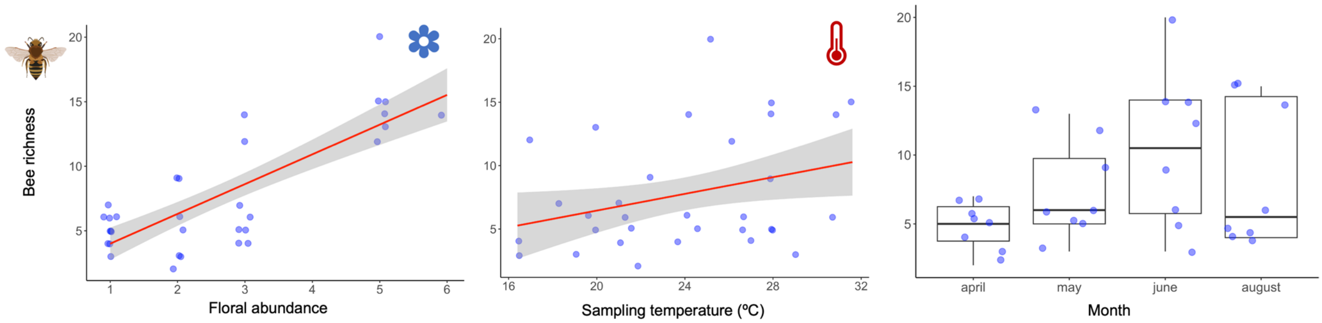

Fig. 3 Environmental predictors of bee species richness: floral abundance, temperature at the time of sampling, and month of sampling

Similar to hoverflies, sampling temperature was a significant predictor of bee richness in one of the optimal models (Table 3), but its effect was positive rather than negative ($\beta = 0.03$, SE = 0.01, $p = 0.03$). Month of sampling was also a significant predictor in one of the two optimal models (LRT: $\chi^2 = 7.8$, df = 3, $p < 0.05$). Across the season, we collected highest number of bee species in June ($\beta = 0.62$, SE = 0.19, $p < 0.01$), with numbers dropping both towards spring and autumn (Fig. 3). In contrast to hoverflies, average site temperature was not included in any of the optimal models (Table 3, Table S2).

Discussion

We confirm results of many previous studies showing the importance of urban areas for pollinator diversity and conservation (Hall et al. 2017; Silva et al. 2023). We report high species richness of bees and hoverflies, including the species of conservation concern in Europe. We tested the impact of urban heat island effect and habitat characteristics of urban green spaces on bee and hoverfly communities of Zagreb. Warmer parks had less species of hoverflies, but urban heat island effect did not impact bee species richness. Floral abundance, but not floral richness, was important predictor for both groups, as sites with higher availability of floral resources had higher species richness of bees and hoverflies.

Zagreb has diverse bee and hoverfly communities, including threatened species

Pollinator species richness of Zagreb (123 bees, 50 hoverflies) is comparable to some other European cities, such as Paris (118 bees, 37 hoverflies), Rome (96 bees), and Birmingham (58 bees, 50 hoverflies) (Bates et al. 2011; Zaninotto and Dajoz 2022; Geppert et al. 2023). Further studies using additional sampling methods across more localities and habitats will likely reveal further species. In addition to common and widespread generalist species we also found specialists (Table S1), e.g. bee *Chelostoma rapunculi*, a specialist on genus *Campanula*, and seven species of conservation concern. Hoverfly species of conservation concern were all collected at peri-urban sites. Two out of three bee species of conservation concern were collected in Zagreb city center, *Andrena hattorfiana* and its cuckoo bee *Nomada armata*. *Andrena hattorfiana* is pollen specialist on *Knautia* and *Scabiosa*, which are grown in studied botanical gardens and occur naturally in some of our peri-urban sites. *Nomada armata* is kleptoparasite that lays eggs into the nest of *Andrena hattorfiana* and is rarer than its host. The presence of *Nomada armata* in Zagreb city center implies a healthy population of its host, showing that even highly urbanized areas can support complex pollinator communities, if the right plant communities are available.

We report five new species for Croatia, which is not unexpected, as Croatia has one of the most understudied bee and hoverfly fauna in Europe (Reverté et al. 2023). The surprising new record is endangered hoverfly species *Paragus finitimus*, which is rare in the southern Europe (Speight 2020). We collected this species in one of the additional peri-urban locations (Site B, VEJ), a small Natura 2000 site, characterized by remnants of dry grassland habitat (habitat type 6210).

Negative impact of urban heat on hoverflies

Site temperature was a negative predictor of hoverfly richness in urban green spaces, in contrast with, to our knowledge, the only other work that tested the impact of urban heat island effect on hoverflies, which did not find any impact on overall hoverfly richness (McCune et al. 2023). However, they conducted a study in a cooler climate (Montreal, Canada) and used urban heat island maps, based on a combination of surface temperature, NDVI (Normalized Difference Vegetation Index), imperviousness, and land use data, rather than measuring temperature in the field with the data loggers. These climatic and methodological differences make our studies not ideal for direct comparison. Negative impact of site temperature on hoverfly species richness was previously found in natural habitats (Corcos et al. 2018). Increase in temperature can impact hoverfly fitness directly, e.g., by decreasing survival rate of larvae, as was found for *Episyrphus balteatus* (Noel et al. 2022). Also, warming can trigger phenological shifts in hoverflies and result in temporal mismatches with plants (Hassall et al. 2017; Olsen et al. 2020). Hoverflies have relatively uniform species richness across most of temperate Europe (Keil et al. 2008; Reverté et al. 2023), without a decrease in diversity along increasing latitude (i.e., northern faunas are not species poor in comparison to south). Diversity of some hoverfly groups is associated with cooler climates (Rotheray and Gilbert 2011) and wet habitats (Keil et al. 2008), mostly due to ecological requirements of their larvae (Rotheray and Gilbert 2011), although some taxa have Mediterranean radiations (Vujić et al. 2012). Increased urban temperatures also contribute to urban habitats being on average dryer that their rural counterparts. As larvae of some hoverfly species depend on wet habitats for development, and majority of hoverfly larvae cannot tolerate completely dry conditions (Keil et al. 2008), this could be another mechanism through which urban heat negatively impacts hoverflies. Further studies, which measure the air humidity, in addition to temperature, would likely improve our understanding of ecological requirements of urban hoverfly communities.

In our study, average temperature was highly correlated with impervious surface cover. Out of those two variables, our results show that for hoverfly communities of Zagreb average site temperature is a better predictor than impervious surface cover, suggesting that the impact of impervious surface cover can be largely explained by its higher temperature. Impervious surface cover is often used as an urbanization proxy and it is tightly linked to urban heat island, i.e., areas with higher percentage of impervious surfaces are usually also warmer. Impervious surface cover also broadly correlates with the amount of natural vegetation, habitat heterogeneity, and air quality. Other research found that impervious surface cover has negative impact on hoverflies (Bates et al. 2011; Gathof et al. 2022), although some studies also found no effect (Rocha et al. 2018). Although impervious surface cover is a relevant metric in urban studies, our results indicate importance of measuring the site temperature, to enable disentangling different effects of urbanization.

Impact of temperature and seasonality on bees

In contrast to hoverflies, urban heat island effect did not affect bee species richness in Zagreb. Previous research on urban warming and bees showed temperature impacts bee species abundance and community composition, but similarly to our result it did not drive changes in species richness (Hamblin et al. 2017, 2018; Geppert et al. 2023). One common explanation of high bee species richness in temperate-climate cities, which are usually dryer and warmer than the surrounding areas, is a strong affinity of bees for warm and xeric Mediterranean climates, resulting in a rare, bimodal global distribution pattern (Orr et al. 2021; Reverté et al. 2023). Our results show that increased urban temperature in Zagreb does not yet impact bee species richness. However, as there is ample evidence suggesting that bees are and will be impacted by global warming and other consequences of climate change, such as increased frequency of extreme weather events (Polce et al. 2014; Hamblin et al. 2017, 2018; Sirois-Delisle and Kerr 2018; Wyver et al. 2023; Albacete et al. 2023), we expect that bee communities of Zagreb will face higher pressure from urban heat island effect in the near future. This is especially true for bumblebees (genus *Bombus)*, expected to be more sensitive to global warming that other bee taxa, because of their evolutionary adaptations to cold climates (Sirois-Delisle and Kerr 2018).

While average site temperature did not influence bee species richness, sampling temperature and month of sampling were significant predictors. We included both as covariates due to their known effects on the bee activity and richness (Oertli et al. 2005; Orr et al. 2021). Although complementary, these factors impact species richness through different mechanisms: higher sampling temperature directly increases bee activity and thus the number of species captured (Corbert et al. 1993; Willmer and Stone 2004; Mahon and Hodge 2022), while seasonal effects reflect changes in species composition and temperature changes over time. The peak richness in June in Zagreb likely resulted from the overlap of spring and early summer bee species (Oertli et al. 2005; Schmack and Egerer 2023; Brasil et al. 2023). Although not the primary focus of our study, the seasonal turnover of species has important implications for conservation, as the availability of floral resources needs to be continuous throughout the foraging season to support diverse bee communities.

Floral abundance increases wild pollinator richness of City parks

Floral abundance was an important predictor of species richness for both bees and hoverflies, although the effect was stronger for bees (Fig. 3). This is in contrast with previous research (Potts et al. 2003; Lowenstein et al. 2014; Neumann et al. 2024), including a recent meta-analysis (Liang et al. 2023), that shows that floral richness, rather than abundance, is the most important factor for bee, as well as for hoverfly species richness (Neumann et al. 2024). However, some studies also show that floral abundance can be better predictor for bees (Hamblin et al. 2018), and that both are significant for hoverflies (Meyer et al. 2009; Lequerica Tamara et al. 2023). These two variables are often corelated, as they were in our data set. In general, greater floral abundance increases nectar and pollen availability, providing food for larger pollinator populations (Hyjazie and Sargent 2022), while higher floral richness offers a broader range of nutrients, phenological variability, and sustains more pollen specialists (Ebeling et al. 2008; Klaus et al. 2021; Hyjazie and Sargent 2022; Lorenzato et al. 2024). This is especially important for bees, which depend on floral resources in all their life stages, and which are central place foragers (Michener 2007), while hoverflies depend on nectar and pollen only as adults, and are not as spatially restricted as bees (Rotheray and Gilbert 2011). Although our results show that floral abundance is best predictor for pollinator richness in Zagreb, floral richness should also be considered in management actions because of its phenological and nutritional benefits. Further, because hoverflies have diverse larval requirements, in some cases tied to a certain plant for larval development, not necessarily the same plant that they feed on as adults (Rotheray and Gilbert 2011), measuring total plant richness, rather than only of entomophilous flowers, could be an important variable to consider for future studies.

Urban management implications

To support populations of threatened bee and hoverfly species in Zagreb, the protection and restoration of semi-natural grassland is critical, especially those with populations of host plants of threatened species. Larger and well-connected habitat patches can also support species in adapting to various impacts of climate change (Mawdsley 2011; Oliver et al. 2013). Protecting the existing urban trees and planting new, native trees are important to mitigate the warming in the urban center. Protection of old trees will also support hoverflies with saproxylic larvae (Rotheray and Gilbert 2011) and provide nesting habitats for some bee species.

Simple management intervention, such as lowering the intensive mowing regime or introducing mosaic mowing, can increase the abundance of floral resources available for pollinators in public green spaces. Reduction in intensive mowing regime also has general biodiversity benefits, economic benefits, and reduces greenhouse gas emission (Unterweger et al. 2018; Watson et al. 2020). Implementing such affordable biodiversity-friendly solutions can enhance pollinator richness in urban areas and contribute to pollinator conservation.

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Data availability Data set and R code used for all analyses are available at a personal github page (https://github.com/anajesovnik/zagreb-buzz).

Declarations

Competing interests The authors declare no competing interests.

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