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Original article

Spatial and habitat determinants of small-mammal biodiversity in urban green areas: Lessons for nature-based solutions

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ABSTRACT

In an increasingly anthropogenic world, urban green areas are critical for human well-being because of the ecosystem services they offer. However, the management of these areas often prioritizes economic, architectural, and esthetic needs over ecological functionality, undermining the benefits they ought to provide. Actions to restore the functional ecological processes of urban green areas have thus become increasingly urgent. This study investigated the impact of urban green area characteristics on the community composition of an indicator animal group to inform Nature-Based Solutions (NBSs) for urban biodiversity and sustainability enhancement. We analyzed data on small mammal community composition from three Italian metropolitan cities (Milan, Florence, and Rome), focusing on the distribution pattern of synanthropic and non-synanthropic species. Small mammal surveys were carried out using hair tubes in sampled areas located along a gradient of green area size and fragmentation. Multiple Linear Mixed Models assessed the influence of spatial and habitat green area characteristics on species richness. Synanthropic species richness was positively associated with manicured urban parks, while non-synanthropic species richness was higher in woodland green areas characterized by high shrub cover. Through a Linear Mixed Model and NODF-based Nestedness analyses, we found that competitive exclusion and selective extinction/colonization processes did not significantly influence community composition. These insights emphasize the major influence of habitat composition in supporting functional communities of urban small mammals. To move toward resilient urban ecosystems, NBSs must primarily be implemented at a local scale by creating green patches with high habitat quality, and secondarily, they should be embedded in an interconnected and functional network at a city scale.

1. Introduction

In an increasingly impervious world, urban green areas are pivotal for human well-being due to the ecosystem services they provide (e.g., biodiversity provisioning, cooling effect, air quality improvement, nutrient cycling, health benefits, etc.) (Manzini et al., 2023; Cena and Labra, 2024). Nonetheless, green areas in large cities have been widely implemented and managed based on human-oriented rather than nature-oriented criteria (Xie and Bulkeley, 2020; Aznarez et al., 2022), often undermining key ecological processes (e.g., soil regenerations, pollinations, plant/animal dispersal, heat absorption, carbon stock, etc.). Actions to restore functional ecological processes in urban green areas have thus become increasingly urgent for the long-term maintenance of habitable and sustainable cities (Lookingbill et al., 2022).

In the last decade, governance interest on interventions for improving urban nature and ecological services has emerged within the broader concept of Nature-Based Solutions (NBSs), (European Commission, 2016; Cohen-Shacham et al., 2016). The International Union

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for Conservation of Nature (IUCN) coined the first global definition of NBSs as “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits” (Cohen-Shacham et al., 2019). Today, a broad spectrum of policy makers views NBSs as a vital mechanism for achieving sustainable development and attaining the key objectives of the Green Deal and EU Biodiversity Strategy 2030 (IUCN, 2020; Xie and Bulkeley, 2020).

Despite a range of pilot projects explored pathways to make urban ecosystems functionally and ecologically resilient throughout NBSs (Aznarez et al., 2022; Kabisch et al., 2022), few empirical studies have been carried out to understand how and where to implement these actions (IUCN, 2020; Kabisch et al., 2022). A particularly unexplored field regards data-driven analysis on the effect of urban green areas characteristics on species biodiversity (Xie and Bulkeley, 2020; Marselle et al., 2021; Kabisch et al., 2022). This information is pivotal for guiding an effective design, creation, and management of NBSs (Van Helden et al., 2020; Cena and Labra, 2024). Xie and Bulkeley (Xie and Bulkeley, 2020), for instance, emphasized that “future urban NBS interventions may be able to enhance their contribution towards global biodiversity goals by including a greater focus on the species”. The few studies focused on animal biodiversity in urban green areas have been almost exclusively carried out throughout expert-based and citizen science approaches (e.g., (Aznarez et al., 2022); (Turner et al., 2022), two methods affected by subjectivity issues (Di Febbraro et al., 2018) and inherent spatial bias (Di Febbraro et al., 2023), respectively. Additionally, most of the studies focused on the implementation and management of biodiversity-friendly green areas, have been carried out in single cities (e.g., (Solano et al., 2021); (Aznarez et al., 2022; Pantaloni et al., 2022), making the results not broadly generalizable. Additionally, the rare empirical studies based on systematic field data collection often used overall “species richness” as a proxy for “biodiversity” (e.g., (Mahan and O’Connell, 2005) but ignored ecological differences between species, which have been demonstrated to be key drivers of community responses to habitat characteristics (Gomes et al., 2011; Dondina et al., 2017; Grade et al., 2022).

The aim of this research was to advance empirical investigation of the effects of green areas attributes on animal biodiversity, providing evidence-based insights for implementation of urban NBSs. To achieve this aim, we explored the effect of urban green area characteristics on the composition of small mammal assemblages by comparing the response of two ecologically distinct groups of species, i.e., synanthropic and non-synanthropic species. The distribution and abundance of small mammals are influenced by available resources (food and nesting sites), evolutionary history, species specialization degree, interspecific interactions, and both microhabitat and macrohabitat structure and composition (Gomes et al., 2011). Small mammals are ideal model organisms compared to rare (e.g., secondary cavity nester birds; (Dondina et al., 2015) or large-sized species (e.g., (Barrett and Peles, 1999), which are rarely abundant and diversified in highly urbanized areas. Due to their adaptability, small size, and limited home range, small mammals often thrive in urban green spaces, parks, and even residential gardens (Gomes et al., 2011; Klimant et al., 2017). Small mammals, such as mice, voles, and shrews, act as essential sentinels for gauging environmental quality (Bertolino et al., 2015). Similarly, a decrease in overall small mammal diversity may indicate a reduction in ecological connectivity or habitat loss (Johnson and Karels, 2016). Unlike large-sized mammals with longer lifespans, which may tolerate gradual environmental degradation, small mammal populations fluctuate rapidly in response to shifts in resource availability and quality, and landscape connectivity (Pardini et al., 2005; Rowe and Terry, 2014). This responsiveness makes them ideal indicators of ecosystem health (Avenant, 2011). More generally, small mammals are both influenced by habitat quality and provide important ecosystem services themselves (e.g., seed dispersal, contribution to soil structure and composition, pest control, coverage of key roles in the food chain, (Pearce, 2017), thus serving as valuable indicators of habitat quality while simultaneously influencing successional ecosystem dynamics (Gomes et al., 2011). Therefore, studying small mammal assemblages serves as a crucial early warning system, allowing for timely intervention and protection of our precious ecosystems.

In this study, we analyzed the effects of green area landscape (distance from city center, size, spatial configuration) and local (green area type and habitat structure) characteristics on small mammal community composition based on data collected in three Italian metropolitan cities. Following previous studies (Gomes et al., 2011; Aznarez et al., 2022; Grade et al., 2022) we hypothesized that urbanization would lead to species homogenization, with synanthropic generalists persisting in more urbanized areas, while non-synanthropic specialists would be confined to few high-quality peripheral patches. We also investigated how three widely studied mechanisms (Nielsen et al., 2014) influenced small mammal responses to green areas characteristics: (i) interspecific competition, (ii) selective extinction/colonization dynamics, (iii) habitat selection. The final goal of this study was to provide scientific-based insights into where and how NBSs should be implemented and managed to move toward ecologically functional and resilient urban ecosystems.

2. Methods

2.1. Study areas and sampling design

The study was carried out in the urban and peri-urban area of three major metropolitan Italian cities (Art. 1, Paragraph 5, Law No. 56/2014) distributed along a latitudinal north-south gradient, namely Milan, Florence, and Rome. The metropolitan areas of Milan (northern Italy), Florence (north-central Italy), and Rome (central Italy) cover an area of about 1575 km^2, 3515 km^2, and 5360 km^2 with about 3.3 million, 1.1 million, and 4.4 million inhabitants, respectively.

We adopted a standardized sampling design to select sample sites along a green area size-fragmentation gradient. A 1 × 1 km^2 grid was overlaid on each city (https://www.eea.europa.eu/data-and-maps/data/eea-reference-grids-2 - Italy shapefile; WGS 84-UTM 32 N system for Milan and Florence, and WGS 84-UTM 33 N system for Rome). Green area size and fragmentation degree within each cell were measured in FRAGSTATS (McGarigal, 1995) using *Land Cover* and *Land Use* layers of the ISPRA 2021 National Maps (https://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/copertura-del-suolo/carta-di-copertura-del-suolo). The size of green areas was calculated as the cumulative area covered by each green area intersected by the 1 × 1 km^2 cell. Each cell was classified into a size class (A: 0–0.02 km^2, B: 0.02–0.24 km^2, C: 0.24–0.1 km^2, D: > 1 km^2). The fragmentation degree was quantified calculating the Aggregation Index (AI) of green areas within a circular buffer centered around the cell centroid (buffer radius 1.5 km). Each cell was classified into a fragmentation degree class (1: AI < 67, 2: $67 < AI < 73$, 3: $73 < AI < 81$, 4: AI > 81) (1: maximally fragmented, 4: minimally fragmented) (Fig. 1). By cross-referencing all size and fragmentation classes, all the cells of the investigated cities were classified according to one of the resulting 16 classes (Fig. 1). In each city, sampling cells were selected to maximizing the representativeness across all the classes of the size-fragmentation gradient (see Supplementary Material for details on the Sampling Design Protocol).

The final sampling pool was composed of 11 cells in Milan, 18 in Florence, and 12 in Rome. Data are available in Mendeley Data: DOI: 10.17632/9cg2mjtmyh.1 (Viviano et al., 2024).

2.2. Data collection

2.2.1. Biological sample collection

Two sampling plots were randomly selected in natural or semi-natural green areas within each 1 × 1 km^2 sample cell. In each plot we placed four PVC hair-tubes (length: 40 cm, diameter: 5 cm) covered

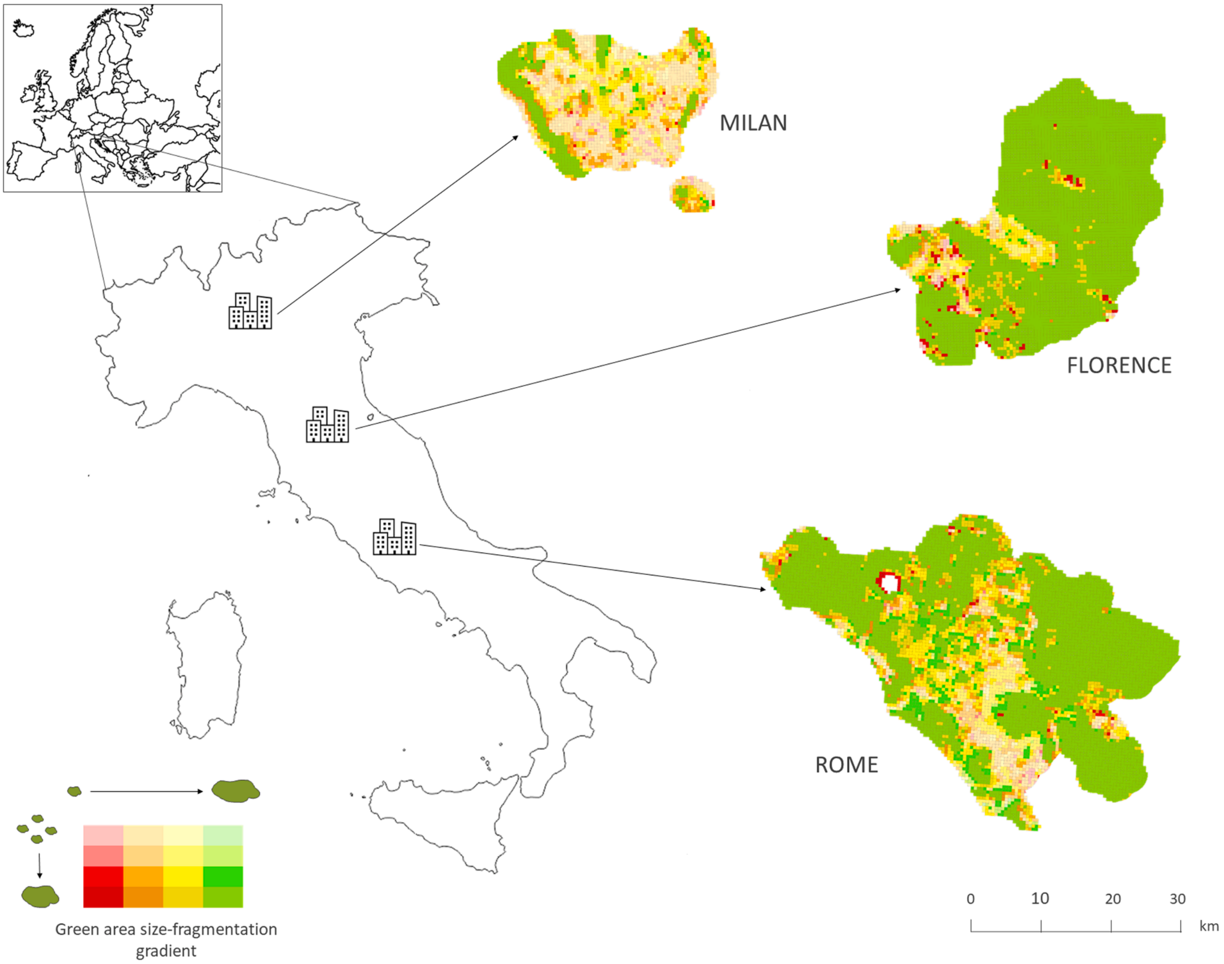

Fig. 1. Sampling areas and sampling design.

with double-sided tape around the entire internal circumference of both sides of the tube for 8 cm thickness (Zozzoli et al., 2018). Two hair-tubes were located on the ground near the roots collar and two on tree branches, at about 1.5–2 m height to sample both ground-dwelling and arboreal small mammals. Hair-tubes were baited with peanut butter and checked once a month from June to November 2023. Peanut butter was chosen for its attractive qualities for multiple small mammal species (Dürger et al., 2024). At each control, the double-sided tape was replaced, and the tube was baited again.

2.2.2. *Species identification*

Each double-sided tape collected was examined under a stereomicroscope to investigate the possible presence of hairs. To remove hairs from double-sided tapes a drop of vegetable oil was laid on it for one minute, the hair was then soaked in ethanol (one minute) and in water (one minute). Only GH1 and GH2 hairs (Teerink, 1991) were considered for species identification following the dichotomous keys proposed by Paolucci and Bon (2022). Hair length was measured using a stereomicroscope and a graph paper. The cuticula pattern was identified using an optical microscope from a cast of the hair surface made on a thin film of transparent nail polish on a microscope slide (De Marinis and Agnelli, 1993). Medulla structure was observed directly on the hair dipped in a drop of cedar oil. The hair was then glued between two strips of scotch tape, and two 2mm-wide strips were cut at the shield level (proximal and distal) (De Marinis and Agnelli, 1993) using a scalpel blade. The 2 mm strip was placed perpendicularly on a microscope slide, and the cross section of the hair was observed and classified.

2.3. *Data analyses*

2.3.1. *Effect of green area characteristics on small mammal community*

We separately analyzed the effect of green area characteristics on the species richness of synanthropic (human commensal in (Paolucci and Bon, 2022) and non-synanthropic (non-human commensal in Paolucci and Bon (2022) species. For each assemblage, species richness was obtained by aggregating at the 1 × 1 km^2 cell level the number of species detected during all surveys in the two spatial plots. Multiple Linear Mixed Models (LMMs) were run to estimate the effect of green area characteristics on both synanthropic and non-synanthropic species richness. Within the LMMs, green area characteristics were considered as the fixed factors, while sampling cities as the random factor. We built Linear Mixed Models instead of Generalized Linear Mixed Models with a Poisson error distribution, generally recommended for count data, following the guidelines of McDonald and White (2010) who suggest assuming a normal error distribution in cases of count data with mean value lower than two. We validated the choice of the error distribution by comparing the AIC values (Burnham and Anderson, 2002) of the two models (LMM *vs* GLMM) for both synanthropic and non-synanthropic species.

The following green area characteristics were calculated at the cell level: distance from city center (mean of the distance of the two sampling plots from city center); size (categorical variable with three levels: B, C, D); aggregation index (categorical variable with four levels: 1, 2, 3, 4); green area type (categorical variable with two levels: woodland, urban park); shrub cover measured at two spatial scales: 10 m and 100 m circular buffer (maximum of the shrub cover measured around the two plots of the same cell classified in a categorical variable with four levels: <10 %,10–40 %,40–60 %,>60 %). Shrub cover was used as habitat quality proxy based on the focal species approach (Lambeck, 1997; Dondina et al., 2020). Specifically, the species most sensitive to urbanization and habitat composition was identified among the species sampled in this study (i.e., the hazel dormouse *Muscardinus avellanarius*, (Bani et al., 2017; Bani et al., 2018) and the habitat characteristic that most affects this species (i.e., shrub cover, (Dondina et al., 2016) was selected. To identify the most important variables influencing the species richness of both synanthropic and non-synanthropic species, we used an AIC-based variable selection procedure (*stepcAIC* in the R package cAIC4; (Säfken et al., 2018). The p-value of the estimated regression coefficients and the Marginal-R^2 of the best models were calculated using the *sjPlot* R package (Lüdecke, 2024). All the analyses were performed in R v 4.3.2 (R Core Team, 2023).

2.3.2. *Other ecological processes possibly driving small mammal response to green area characteristics*

To assess that the influence of green area characteristics on small mammal community was driven by habitat preferences and not mediated by other ecological processes, the possible effect of competitive exclusion and selective extinction/colonization processes was tested.

The competitive exclusion effect of synanthropic species at the expense of non-synanthropic species was evaluated by a LMM considering non-synanthropic species richness as the dependent variable, synanthropic species richness as the fixed factor and the sampling cities as the random factor. The p-value of regression coefficients' estimates and the Marginal-R^2 of the model were calculated using the *sjPlot* R package.

To test for a possible effect of selective extinction/colonization processes, typically driven by habitat loss/isolation phenomena in fragmented landscapes (Cheptou et al., 2017; Dondina et al., 2022), we carried out a nestedness analysis. An occurrence matrix was built by associating to each 1×1 km^2 cell (rows) the presence (1) or absence (0) of each species (columns). The occurrence matrix was used to test for nestedness pattern in small mammal communities in each city separately. The degree of nestedness was quantified through the NODF metric (nestedness metric based on Overlap and Decreasing Fill) (Almeida-Neto et al., 2008), largely considered the most robust nestedness index (Matthews et al., 2015). To determine whether the observed NODF score for each city was significantly higher (i.e., nested) than those expected by chance (null hypothesis), the NODF score of the maximally packed matrix was compared with the NODF scores of 1000 highly constrained random community matrices using the *tswap* permutation method (preserving both row and column totals) (Miklós and Podani, 2004). Nestedness was estimated for both the whole occurrence matrix and independently for species (NODF among rows, NODFr) and cells (NODF among columns, NODFc). The nestedness analyses were run using the *oecosimu* function with nestednodf method in the Vegan R package (Oksanen et al., 2013).

3. Results

3.1. *Surveyed species*

Across the sampled cells, we detected a total of 14 species: four synanthropic and 10 non-synanthropic (Table 1). Five species were found in all the investigated cities, five in two cities, and four in one city only (Table 1). The mean number of species detected within each cell was 3.488 (SE=0.240). The mean number of synanthropic and non-synanthropic species was 1.756 (SE= 0.143) and 1.732 (SE= 0.207), respectively. All the species, except for the gray squirrel (*Sciurus carolinensis*), were native to Italy. Data are available in Mendeley Data: DOI: 10.17632/9cg2mjtmyh.1.

Table 1

Synanthropic and non-synanthropic species detected in each investigated city during the study period (June-November 2023). "x": presence, "-": absence.

Species	Ecological group	MILAN	FLORENCE	ROME
Rattus norvegicus	Synanthropic	x	x	x
Rattus rattus	Synanthropic	x	x	x
Mus domesticus	Synanthropic	x	x	x
Apodemus spp.	Non-synanthropic Synanthropic	x	x	x
Arvicola italicus	Non-synanthropic	x	x	-
Clethrionomys glareolus	Non-synanthropic	-	-	x
Muscardinus avellanarius	Non-synanthropic	x	x	x
Glis glis	Non-synanthropic	x	-	-
Sciurus vulgaris	Non-synanthropic	-	x	x
Sciurus carolinensis	Synanthropic	x	-	-
Crocidura spp.	Non-synanthropic	-	x	x
Sorex spp.	Non-synanthropic	x	-	-
Suncus etruscus	Non-synanthropic	-	x	x
Erinaceus europaeus	Non-synanthropic	x	-	x

3.2. *Effect of green area characteristics on small mammal community*

The best LMM run on synanthropic species richness was the full model with a Marginal-R^2 of 0.311. The model showed a significant positive effect of green area type: urban park (Table 2).

The best LMM run on non-synanthropic species richness was the full model with a Marginal-R^2 of 0.384. The model showed a significant positive effect of the percentage of shrub cover measured at the 100 m scale higher than 60 % and a significant negative effect of green area type: urban park (Table 3).

3.3. *Other ecological processes possibly driving small mammal response to green area characteristics*

3.3.1. *Competitive exclusion*

The LMM run to evaluate a possible competitive exclusion by synanthropic species on non-synanthropic species showed that synanthropic species richness did not significantly impact non-synanthropic species richness (Estimate= −0.220, SE= 0.228, t = -0.967, Pr(>|t|)= 0.340, Marginal R^2= 0.022) (Fig. 2).

3.3.2. *Selective extinction/colonization*

Overall, small mammal communities were no significantly nested in any sampled city (Milan: NODF = 57.015, p = 0.491; Florence: NODF = 55.157, p = 0.457; Rome: NODF = 50.789, p = 0.437). Moreover, neither significantly species (Milan: NODFr = 57.735, p = 0.424;

Table 2

Best LMM developed to identify the effect of green area characteristics on synanthropic species richness, selected via AIC. SE: standard error of estimates. t: t statistic for testing the null hypothesis. Pr(>|t|): probability that the null hypothesis is true.

Fixed effects	Estimate	SE	t	Pr(>|t|)
(Intercept)	0.841	0.559	1.505	0.145
Distance from city center	0.085	0.180	0.471	0.641
Size C	−0.012	0.343	−0.034	0.973
Size D	−0.079	0.441	−0.180	0.859
Aggregation index 2	−0.021	0.463	−0.045	0.965
Aggregation index 3	0.730	0.485	1.505	0.145
Aggregation index 4	0.711	0.496	1.432	0.165
Green area type: Urban park	0.825	0.366	2.254	0.003
Shrub cover (10 m): 10–40 %	0.477	0.555	0.859	0.398
Shrub cover (10 m): 40–60 %	0.739	0.654	1.130	0.269
Shrub cover (10 m) > 60 %	1.345	0.732	1.836	0.078
Shrub cover (100 m): 10–40 %	−0.518	0.616	−0.841	0.408
Shrub cover (100 m): 40–60 %	−1.105	0.665	−1.660	0.109
Shrub cover (100 m) > 60 %	−0.930	0.939	−0.990	0.331

Table 3
Best LMM developed to identify the effect of green area characteristics on non-synanthropic species richness, selected via AIC. SE: standard error of estimates. t: t statistic for testing the null hypothesis. Pr(>|t|): probability that the null hypothesis is true.

Fixed effects	Estimate	SE	t	Pr(>|t|)
(Intercept)	1.382	0.764	1.809	0.082
Distance from city center	0.123	0.232	0.529	0.601
Size C	0.185	0.443	0.417	0.680
Size D	0.411	0.576	0.714	0.482
Aggregation index 2	−0.289	0.598	−0.483	0.633
Aggregation index 3	0.005	0.626	0.008	0.994
Aggregation index 4	0.178	0.648	0.275	0.785
Green area type: Urban park	−1.000	0.473	−2.116	0.044
Shrub cover (10 m): 10–40 %	−0.231	0.729	−0.317	0.754
Shrub cover (10 m): 40–60 %	−1.057	0.885	−1.194	0.244
Shrub cover (10 m) > 60 %	−1.154	0.969	−1.191	0.245
Shrub cover (100 m): 10–40 %	1.720	0.844	2.039	0.052
Shrub cover (100 m): 40–60 %	1.872	0.942	1.988	0.058
Shrub cover (100 m) > 60 %	3.153	1.253	2.517	0.019

Florence: $NODFr = 56.645$, $p = 0.517$; Rome: $NODFr = 50.000$, $p = 0.558$) nor cell (Milan: $NODFc = 56.389$, $p = 0.676$; Florence: $NODFc = 48.835$, $p = 0.407$; Rome: $NODFc = 56.000$, $p = 0.423$) nestedness was detected (Fig. 3).

4. Discussion

Nature-Based Solutions have gained recognition as effective strategies for addressing urban sustainability challenges (Cohen-Shacham et al., 2016). By enhancing urban biodiversity and providing ecosystem services, NBSs can contribute meaningfully to the broader objective of urban ecological transformation (Aznarez et al., 2022; Kabisch et al., 2022) as encouraged by the EU Green Deal, the EU Biodiversity Strategy 2030 and the recent Nature Restoration Law. Our study aligns with these objectives, focusing on investigating the ecological processes that shape the ability of urban green areas to support animal biodiversity, in order to provide recommendations for the successful implementation and management of NBSs. We found that specific attributes of urban green areas significantly affect the community composition of a biodiversity indicator group in multiple cities. Through the investigation of the processes driving this response, we identified key factors for an effective integration of biodiversity-focused NBSs in urban planning.

4.1. Ecological drivers of the effect of green area characteristics on small mammal community

Overall, the local habitat characteristics of green areas play a significantly more important role in shaping small mammal communities than the spatial variables measured at the landscape level. To take

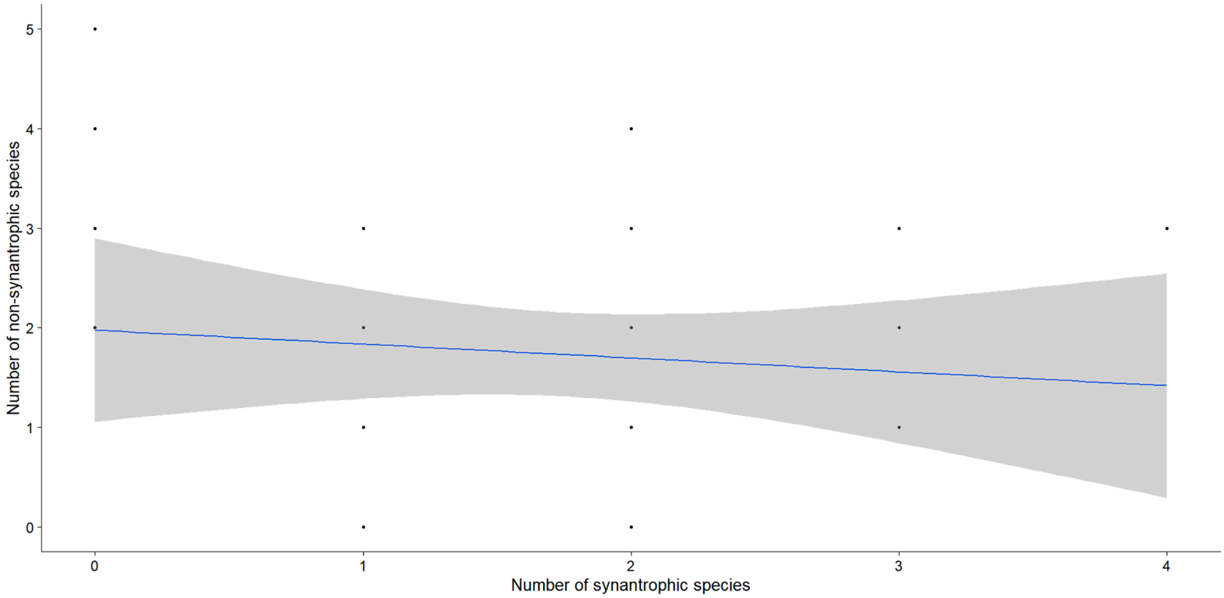

Fig. 2. Relationship between synanthropic species richness and non-synanthropic species richness.

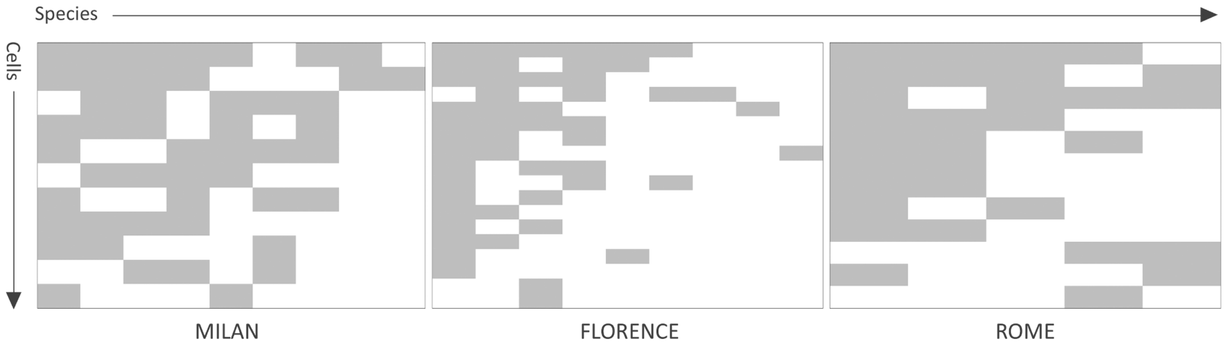

Fig. 3. Incidence plots obtained from nestedness analyses performed on small mammal communities in Milan, Florence, and Rome (Italy). The nested metric employed was NODF using the maximally packed matrix. X-axis: species. Y-axis: cells. Gray bars indicate that a given species was sampled in a given cell, whilst a blank bar indicates that the species was not found in the cell.

a step forward in the research of the ecological drivers that underline this general pattern, we explored why synanthropic species prevail in urban parks, typically characterized by manicured vegetation management and anthropogenic food resources availability (Mahan and O'Connell, 2005), while more wild species are confined to woodland patches with high shrub cover. Specifically, we evaluated whether this evidence was directly attributable to species ecological preferences or if additional concurrent processes influenced the composition of small mammal community in the investigated urban areas.

Our analyses showed that the number of non-synanthropic species was not significantly influenced by the number of synanthropic species, leading us to disregard the hypothesis of competitive exclusion of non-synanthropic species in urban parks. Moreover, no significantly nested patterns were detected in any sampled city, suggesting that habitat characteristics directly influence species composition, rather than being mediated by selective extinction or colonization processes. This means that urban parks did not feature higher richness of non-synanthropic species in the past, in contrast to current assemblages dominated by synanthropic generalist species (or in any case, this phenomenon is no longer occurring), nor that suitable areas for non-synanthropic species occur in unreachable areas due to ecological connectivity issues. In other words, neither a progressively reduction in patch size/quality, nor loss of ecological connectivity is the main driver of the current distribution of synanthropic and non-synanthropic species in the sampled cities. Our study suggests that the most plausible hypothesis is that shrubbed woodland patches are preferred by non-synanthropic species, compared to managed urban park, because these are the only areas hosting suitable habitat characteristics (Van Helden et al., 2020) profitable to maintain local sub-populations of more sensitive non-synanthropic species in urban areas (Grade et al., 2022). Several environmental characteristics crucial for supporting non-synanthropic small mammals are typically found in shrubbed woodland patches but are absent in manicured urban parks. To cite a few examples: hard and soft mast plants that provide food resources throughout the year; low growing trees in the shrub layer that ensure well-structured green patches; climbing plants (e.g., *Hedera helix* L.) and bramble (*Rubus* sp.) that can provide safe movement paths and nesting material (Pearce, 2017); dead wood on the ground that can provide shelter and trophic resources (e.g., invertebrates), etc.

We hypothesized that the common pattern of spatial segregation between synanthropic and non-synanthropic species observed not only in our research, but also in other studies, is due to non-synanthropic species requirement for specific suitable habitat characteristics. This finding is consistent with previous studies demonstrating the primary importance of habitat structure and composition in sustaining functional small mammal communities both in natural (Casula et al., 2017; Paniccia et al., 2022) and urban environments (Harper, 2005). Furthermore, this hypothesis is reinforced by the absence of a consistent relationship between species richness and green area size, nor a consistent pattern of community composition along a periphery-to-center spatial gradient across various studies. Our study did not find a significant influence of either the size of green areas or their distance from the city center. Other studies have instead found a significant increase of small mammal species richness in peripheral areas ascribing this relationship to the occurrence of larger parks in the peri-urban sectors of the sampled city (Hernández Romero et al., 2024). Moreover, a general lack of consistency among studies focusing on the relationship between species richness and ecological connectivity in urban areas was already evidenced in the past (Alberti et al., 2020; Lookingbill et al., 2022). These discrepancies suggest that green area size and connectivity are not the primary factor influencing small mammal distribution patterns in metropolitan cities (see also (Nielsen et al., 2014), in contrast to the predictions of island biogeography theory (Dondina et al., 2017). This is likely because urban parks, often characterized by a lack of suitable environmental features, tend to be larger in size compared to woodland patches located in urban centers (Nielsen et al., 2014), making the area effect negligible in shaping small mammal biodiversity. The absence of clear evidence regarding the impact of connectivity loss on the distribution patterns of small mammals, on the other hands, indicates a need for specific studies based on advanced connectivity modeling approaches to investigate this relationship further.

The lack of incorporation of results from advanced connectivity models in the analyses developed in this study is one of the major limitations of our research. This, in turn, is due to another limitation of the study, i.e., the moderately small sample size, which hindered the chance to develop complex models to investigate the effects of urban green space characteristics on small mammal biodiversity. Along with the impact of connectivity, also the influence of many potentially important local-scale factors was overlooked, such as the fine-scale structure and composition of vegetation layers, the occurrence of water bodies and natural/anthropogenic food resources, the potential presence of rodenticide traps, as well as traffic intensity, and noise and light pollution. As explained in Section 4.2, it will be important for future studies to focus on addressing these gaps. Nevertheless, we are confident that these limitations do not undermine the reliability of the results obtained, which highlighted the effect of general spatial configuration and composition of green areas on small mammal diversity in multiple cities.

4.2. NBSs management implications

The final results of this research highlight both an ecological and management relevance of small mammals in urban studies. Our evidence suggested that to shift from highly impervious cities poor in biodiversity to functional urban ecosystems it is necessary to focus on the implementation and management of NBSs in the form of green areas characterized by high habitat quality (e.g., shrub cover). The exercise we conducted using small mammals as model species indicates that such green spaces do not necessarily need to be large but can also be small patches that, collectively, support viable meta-populations of non-synanthropic species over the long term, according to the archipelago effect (Dondina et al., 2017, 2022). The importance of small green areas in urban biodiversity conservation efforts has often been neglected, even though they represent a substantial portion of the total green areas in urban landscapes (Goddard et al., 2010) and can provide refuge and food resources even to more sensitive non-synanthropic species (Van Helden et al., 2020).

We argued that, before focusing on ecologically connecting green areas in urban environments, as suggested by many authors (e.g., (Alberti et al., 2020; App et al., 2022;Lookingbill et al., 2022; McCluskey et al., 2024), suitable habitat characteristics should be created/restored at a fine spatial scale. Undoubtedly, when implementing NBSs as high-quality small patches, it is essential to consider how they integrate into the existing urban ecological network. In this context, predictive modeling tools comparing the connectivity gain associated with alternative scenarios of NBSs implementation (e.g., (García-Feced et al., 2011) will play a crucial role in deciding where to locate these high-quality patches to maximize the strength and resilience of the urban ecological network.

From a practical perspective, such high-quality small patches could be implemented in abandoned areas (e.g., former railroad yards), private gardens, school gardens, tree-lined avenues etc. Moreover, it is essential that small high-quality patches would be also created or restored within urban parks to make these key green areas accessible to non-synanthropic species and to reinforce the urban ecological network. Planning for NBSs thus needs to originate at a local spatial scale and progressively develop into landscape-scale green network restoration projects (Kabisch et al., 2022) merging private and public contributions under specific governance approaches (Dewaelheyns et al., 2016).

From this perspective, future studies should focus on (i) the identification of structural and compositional habitat characteristics that make green areas suitable for non-synanthropic specialist species at the local-scale (e.g., cover, height, and floristic composition of herbaceous, shrub and tree layer), and (ii) the identification of effective strategies to link local-scale interventions within a comprehensive city-scale ecological network. This information will be pivotal to provide accurate qualitative and quantitative guidance to the governance and to the managing entities responsible for the implementation of NBSs.

5. Conclusions

Our study highlights the importance of understanding the ecological dynamics within urban green areas to effectively implement NBSs for biodiversity conservation. We found that specific attributes of urban green spaces dramatically influence the community composition of an indicator animal group across urban landscapes. Contrary to competitive exclusion or selective colonization/extinction dynamics, our results suggested that non-synanthropic species are mostly excluded from urban recreational parks due to the absence of suitable habitat conditions. This underscores the critical role of high-quality small patches, such as passively restored abandoned areas or actively reforested plots, in supporting viable populations of sensitive species. Moving forward, our findings advocate for prioritizing habitat quality over size when planning NBSs in urban environments. By strategically enhancing habitat quality in small, interconnected green spaces, cities could host resilient ecosystems that accommodate high biodiversity levels and contribute to urban ecological sustainability goals.

Declaration of AI-Assisted Technologies in the Paper Writing Process

During the preparation of this work the authors used ChatGPT in order to improve the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

CRediT authorship contribution statement

Leonardo Ancillotto: Writing – review & editing, Supervision, Investigation, Conceptualization. **Pietro Tirozzi:** Writing – review & editing, Investigation. **Andrea Viviano:** Writing – review & editing, Investigation, Data curation. **Maria Chiara Pastore:** Methodology. **Luciano Bani:** Writing – review & editing, Project administration. **Olivia Dondina:** Writing – original draft, Methodology, Formal analysis, Conceptualization. **Nicola Tommasi:** Methodology, Data curation. **Emliano Mori:** Writing – review & editing, Project administration, Data curation, Conceptualization. **Valerio Orioli:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Enrico Caprio:** Methodology. **Corinna Patetta:** Methodology. **Alessandro Tanzi:** Investigation. **Lisa Bazzoli:** Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

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