Breeding birds in the largest historical urban park of Rome (Villa Doria Pamphilj): community structure and spatial patterns of species richness and occurrence

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Abstract - This study presents preliminary data obtained through intensive sampling using a spatial survey approach (breeding bird atlas) carried out in Rome's largest historic urban park: Villa Doria Pamphilj (184 hectares). A total of 44 breeding bird species were recorded across 88 survey units, each measuring 160×160 meters (Chao2 species richness estimator: 45.19±1.82 species). *Psittacula krameri*, *Corvus cornix*, *Cyanistes caeruleus*, *Sylvia atricapilla*, *Turdus merula*, and *Apus apus* were the most widely distributed species, occurring in more than 50% of the sampling units. The forest and synanthropic species guilds were both the most species-rich and the most spatially widespread. Differences in frequencies of occurrences among ecological guilds were clearly illustrated in the Whittaker plots. High habitat heterogeneity at the landscape scale appears to provide a wide range of ecological niches and resources, promoting overall species diversity. Species richness was positively associated with the extent of forest cover and proximity to watersheds, with localized hotspots observed near small lakes surrounded by mature trees and riparian vegetation. Despite the abundance of open areas (e.g., meadows), species typically associated with these habitats were absent, likely due to intense anthropogenic disturbance (e.g., high human and dog presence, frequent mowing). At the finer scale of the survey units, habitat heterogeneity did not explain variation in species richness: no significant correlation was found between fine-scale habitat diversity and species richness. This suggests that the resolution of the atlas grid may not align with the ecological grain perceived by bird species. Local atlases conducted in large urban parks can serve as valuable tools for the long-term monitoring of spatial patterns in bird species and guilds, supporting both geographical and temporal comparisons.

Key words: fine-grained atlas, guilds, Whittaker plots, land use, habitat diversity, Italy.

Riassunto - Uccelli nidificanti nel più grande parco storico urbano di Roma (Villa Doria Pamphilj): struttura di comunità e modelli spaziali di presenza e ricchezza di specie.

Questo studio presenta dati preliminari raccolti attraverso un campionamento intensivo basato su un approccio spaziale di indagine (atlante degli uccelli nidificanti) condotto nel più grande parco urbano storico di Roma (Villa Doria Pamphilj, 184 ettari). Abbiamo registrato 44 specie di uccelli nidificanti nelle 88 unità di rilevamento di 160×160 m (stima della ricchezza di Chao2: 45,19 specie ±1,82). *Psittacula krameri, Corvus cornix, Cyanistes caeruleus, Sylvia atricapilla, Turdus merula* e *Apus apus* sono state le specie più ampiamente distribuite, con una frequenza percentuale di occorrenza superiore al 50%. Sia le gilde di specie forestali che quelle sinantropiche sono risultate sia le più ricche in numero di specie, sia le più diffuse in termini di copertura territoriale (le differenze tra le frequenze delle specie nelle gilde ecologiche sono chiaramente visibili nel modello riportato nei grafici Whittaker). L'elevata diversità di habitat a scala di paesaggio fornisce un gran numero di nicchie e risorse diverse per differenti specie. La ricchezza di specie aumenta con l'aumento delle dimensioni dell'estensione forestale e dei bacini idrici: il pattern di ricchezza di specie ha mostrato un hot-spot localizzato in prossimità di un piccolo lago circondato da alberi maturi e vegetazione ripariale. Nonostante la presenza di considerevoli spazi aperti (prati), le specie associate a questi ambienti sono assenti a causa dei numerosi disturbi antropici (elevata frequenza di cittadini e cani, sfalcio periodico per la manutenzione delle aree aperte). La diversità di habitat a grana fine (alla scala dell'unità di rilevamento) non sembra essere un fattore in grado di spiegare l'aumento della ricchezza di specie (diversità di habitat e ricchezza di specie non sono risultati correlati tra di loro): nel nostro caso, la grana fine di definizione della griglia dell'atlante potrebbe non corrispondere alla grana ecologica percepita dalle specie. Gli atlanti locali condotti su grandi parchi urbani possono rappresentare un utile strumento per il monitoraggio a lungo termine dei modelli di distribuzione spaziale di specie e gilde, utili per confronti geografici e temporali.

Parole chiave: atlante a grana fine, categorie ecologiche, diagrammi di Whittaker, uso del suolo, diversità di habitat, Italia.

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INTRODUCTION

Urbanization has a profound impact on bird communities (Beissinger & Osborne, 1982; Chace & Walsh, 2006; Clergeau *et al.*, 2006; Seress & Liker, 2015; Hahs *et al.*, 2023; for Italy, see Fraissinet & Fulgione, 2008). Within urbanized areas, historic parks are often regarded as important ecosystems embedded in highly anthropogenic landscapes, and as such, they tend to host distinctive and often specialized bird assemblages (Fernández-Juricic, 2000; Fernández-Juricic & Jokimäki, 2001; Kelcey & Rheinwald, 2005; Chace & Walsh, 2006; Clergeau *et al.*, 2006; Ramalho & Hobbs, 2012). Moreover, these green spaces may support a variety of ecological assemblages (i.e., guilds), including generalist synanthropic species—both native (e.g., crows and doves) and non-native (e.g., parakeets; Mori *et al.*, 2013)—as well as more specialized groups such as forest-dependent species (e.g., woodpeckers, tits, and treecreepers) associated with mature ornamental trees or remnant woodland patches and water-related species linked to lakes and other water basins (ducks and rails; Sorace & Gustin, 2008; Di Santo *et al.,* 2015).

The presence of diverse habitat types within these parks (fine-grained heterogeneity), often lacking in the surrounding urban matrix, can make them local hotspots of species richness (Nielsen *et al.*, 2014). In some cases, species abundance may also increase locally due to a 'crowding effect', where individuals concentrate in the few remaining green areas within an otherwise unsuitable landscape, a phenomenon comparable to that observed in insular habitats (Debinski & Holt, 2000).

Bird communities in urban parks are subject to dynamic changes over time, driven by processes such as colonization by new species or local extinctions (Battisti & Dodaro, 2016). These shifts may result from both local factors (e.g., urban expansion, fine-grained changes in vegetation structure and settlement densities) and broader-scale environmental changes (change in surrounding rural landscapes and decline of species at a regional/continental level) (Murgui, 2014; Korňan, 2023).

Urban-park bird communities have been extensively studied worldwide (Kelcey & Rheinwald, 2005; McCaffrey & Mannan, 2012), employing a wide range of survey methodologies—including mapping methods (e.g., Suhonen & Jokimäki, 1988; Battisti & Dodaro, 2016; Battisti, 2023), line transects (Haas *et al.*, 2020; Yang *et al.*, 2020), and point counts (van Heezik & Seddon, 2016). More recently, the adoption of atlas-based approaches using spatial grids to record presence/absence data (i.e., species occurrences) has provided new insights into spatial distribution patterns, as well as the relationships between different species or ecological guilds (Verner, 1984; Fauth *et al.*, 2006) and various land-use types. These methods are particularly useful for identifying associations with specific habitat features, including potential keystone habitats (Tews *et al.*, 2004; see, for Italy, Taffon *et al.*, 2008).

In many of Italy's historic cities, large historic parks—originally established as early as the 17th century, with some elements dating back to the Middle Ages—were developed and later expanded in subsequent centuries, reflecting a range of landscape and architectural styles (Cignini, 2015). These parks provide important ecosystem services (Silli *et al.*, 2015; Gratani *et al.*, 2016; Battisti & Zocchi, 2018). Owing to their diverse structural elements (including mature ornamental trees, monumental buildings, archaeological sites, hedgerows, tree-lined avenues, meadows, and water basins), they are capable of supporting diverse bird communities. In some cases, these communities may be richer or differently structured than those found in nearby semi-natural areas (Haas *et al.*, 2020).

Rome hosts numerous historic parks (Bruno *et al.*, 2006), several of which have been the focus of ornithological studies. Among the largest, Villa Doria Pamphilj has been studied in detail (Battisti, 1986; Angelici *et al.,* 1988; Battisti & Dodaro, 2016), as have Villa Ada (Ianniello, 1987) and Villa Borghese (Salvati, 1992, 1995; see review in Zapparoli & Cignini, 2005). However, few studies have surveyed the entire surface area of these urban parks using an atlas grid approach, which would allow for a detailed analysis of spatial patterns in species richness and occurrence (see, for example, the atlas of the Appia Antica regional park; Taffon *et al.*, 2008).

This study presents preliminary data collected through intensive sampling based on a survey unit (UR) approach—a "local atlas" focused on breeding bird species (Sutherland, 2006; see also Taffon & Battisti, 2003; Taffon *et al.*, 2008; Battisti & Guidi, 2010; Marini *et al.*, 2014; Battisti *et al.*, 2020; Battisti *et al.*, 2022)—conducted in Rome's largest historic urban park, Villa Doria Pamphilj. To minimize potential bias due to the "observer effect" (e.g., Donald & Fuller, 1998), which may result from variation in surveyor effort or skill across units, we applied a standardized methodology: the same number of surveyors was assigned to each unit, and consistent spatial and temporal protocols were followed across all equally sized grid cells.

To our knowledge, excluding Taffon *et al.* (2008), this represents the first atlas employing a fine-scale grid system that fully covers a large historic urban park, at least within the Mediterranean region.

MATERIALS AND METHODS

Study area

The study area corresponds to the Villa Doria Pamphilj (also referred to as 'Pamphili'; Rome, central Italy), the largest historic urban park in Rome (central Italy). This green area is situated in the western sector of the metropolitan extent (184 hectares, approximately 50 m a.s.l.) and is designated as a Special Protection Area sensu EU Habitats Directive 92/43/EEC (site code IT6003052; coordinates: 41°53' N, 12°27' E).

The park originated in 1630, when Pamphilio Pamphilj acquired an initial portion of rural land within the Roman countryside ('Campagna Romana'). From 1640 onward, Prince Camillo Pamphilj progressively purchased adjacent agricultural plots, transforming them into Italian-style gardens enriched with ornamental vegetation and water basins (fountains, ponds, canals), embedded in an agroforestry mosaic of high historical and ecological value. This landscape type is now increasingly rare, as it has become enveloped by the expanding urban settlements of Rome (Celesti-Grapow & Fanelli, 1993). Since the 1960s, Villa Doria Pamphilj has been progressively opened to the public (Cignini, 2015).

Villa Doria Pamphilj is considered one of the sites with the highest levels of plant species richness in the city (Ricotta *et al.*, 2001). Within the park, a heterogeneous agroforestry landscape persists, including remnants of native oak woodland patches (*Quercus ilex*, *Q. pubescens*, *Q. petraea*), along with secondary species such as *Ulmus campestris*, *Laurus nobilis*, and *Cercis siliquastrum*. Scattered ornamental trees are also present, including *Pinus pinea*, *Cedrus libani*, *Aesculus hippocastanum*, *Robinia pseudoacacia*, *Cupressus* spp., and *Ailanthus altissima*, interspersed with frequently mown and heavily disturbed grasslands dominated by species from the families Gramineae, Malvaceae, and Compositae (for further details on vegetation structure and plant distribution, see Celesti-Grapow, 1995; Cignini, 2015; Fig. 1).

Protocol

In this study area, we conducted a local-scale breeding bird atlas focused on mapping the distribution pattern of breeding species. To obtain standardized percentage coverage of occurrence for each species, intensive field sampling was carried out across the entire surface of the urban park. A square-grid mesh was overlaid on the study area (including immediately adjacent zones), resulting in a total of 88 URs, each measuring 160×160 meters. The grid was defined using high-resolution aerial photogrammetric data (Fig. 1).

Starting from a 1:10,000 base map, we generated a 160-meter resolution fishnet grid, which served as the basic sampling unit. Each unit was assigned a unique alphanumeric identifier (consistent with field data collection codes), which was used as the primary key to link field observations with spatial data in a geographic database (.gpkg format; Fig. 1). This geodatabase was subsequently used to produce species-specific presence/absence maps, as well as a composite species richness map (see *Appendix 1*). For this purpose, a field was created containing the total number of species present for each UR. The same information was used to develop a heatmap of species. This map was elaborated through a kernel density tool (algorithm "kernel density estimation" - Kernel shape "Epanechnikov"). This technique allows biodiversity hotspots to be identified within the study area. All spatial operations were performed in a GIS environment (QGIS, version 3.34). URs that were not sampled were excluded from the spatial analyses.

During the spring of 2024 (March-June), each 160×160 m UR was intensively and randomly surveyed using a non-linear transect walk lasting 10 minutes, with the objective of covering the entire UR as comprehensively as possible. Each UR was visited twice: once during early spring (March-April) and once during late spring (May-June). In total, 1760 minutes of standardized field sampling were carried out. During each sampling, all direct (visual sightings) and indirect (songs, active nests, and tracks) contacts with presumably breeding bird species were recorded, resulting in a presence (occurrence) value for each UR (Bibby *et al.*, 2000). Species recorded during this study but that were domestic (e.g., *Cygnus olor*, domestic ducks); wintering but still present in early spring (e.g., *Ardea cinerea*, *Phalacrocorax carbo sinensis*, *Chroicocephalus ridibundus*, *Egretta garzetta*, *Turdus philomelos, Anthus pratensis, Phylloscopus collybita, Phoenicurus ochruros*); vagrant/nesting outside the study area but in surrounding natural habitats (e.g., *Larus michahellis*, *Milvus migrans*, *Merops apiaster*); or probably escaped from captivity and not naturalized (*Thec-*

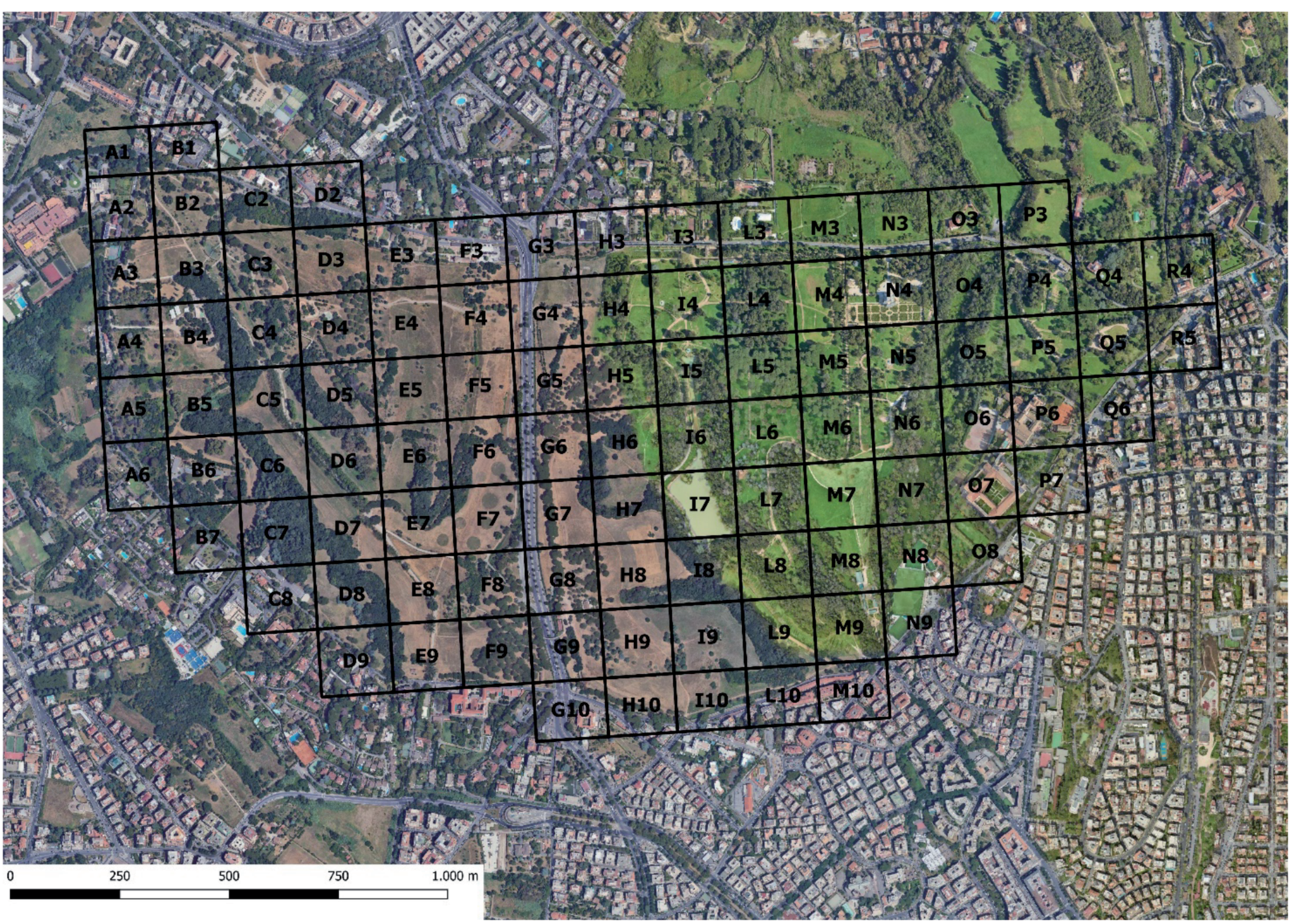

Fig. 1 − The study area (Villa Doria Pamphjli historic urban park, Rome, central Italy), with the atlas grid (and alpha numerical codes of survey units). / Area di studio (parco urbano storico di Villa Doria Pamphilj; Roma, Italia centrale) con griglia quadrettata (e codici alfa-numerici in unità di rilevamento).

tocercus acuticaudatus) were excluded from the dataset. Data regarding aerial foragers (*Apus apus, Hirundo rustica, Delichon urbicum*) refers to trophic areas of occurrence. Field sampling adhered, as possible, to established data-reliability criteria (Battisti *et al.*, 2014).

For the atlas and its graphical representation, a species was considered "present" in a given UR if at least one direct or indirect contact was recorded during either of the two survey sessions. No data on species abundance was collected. The methodology did not permit a reliable assessment of crepuscular or nocturnal species, which are therefore likely to be underrepresented in the dataset. All observations were made using professional-grade Leica 8×42 binoculars.

Presence/absence data (i.e., species occurrence) were recorded in binary format (1 = presence; 0 = probable absence) and entered into a matrix using Microsoft Excel software. Based on this matrix, a local-scale distribution map was generated for each species, along with a composite species richness map showing the total number of species per UR.

For each species, we calculated the number of occupied URs (N_{UR}) and the frequency of occurrence (Fr_{UR}), defined as the percentage of URs in which the species was detected out of the total number of units surveyed (n=88). This metric provides insight into the spatial distribution pattern of occurrence and relative frequency of each species at the local scale.

We also calculated the relative frequency of occupied URs (Fr_{occ}), defined as the ratio between the number of URs occupied by a species (n_i) and the total number of species occurrences (N_{occ}) across all units ($Fr=n_i/N_{occ}$). Species with a relative frequency greater than 50% for Fr_{UR} and greater than 0.05 for Fr_{occ} were considered dominant, respectively in terms of the N_{UR} and total occurrences.

At the community level, the following parameters were computed: i) species richness (S), defined as the number of species per UR; ii) Shannon-Wiener diversity index (H'=–Σfr·ln[fr]; Shannon & Weaver, 1963); and iii) evenness index (J=H'/H'max, where H'max=lnS; Lloyd & Ghelardi, 1964; Pielou, 1966; see also Magurran, 2004, for further details). Values of H' and J were also calculated separately for each guild. To illustrate species frequency distributions, rank–occurrence plots (Whittaker plots; Magurran, 2004) were generated at the guild level.

To estimate the true species richness in the study area based on the sampling effort, we applied a non-parametric metric, the Chao2 estimator (Magurran, 2004) [Eq. 1]:

$$S_{Chao2} = S + Q_1^2/2Q_2 \qquad \text{[Eq. 1]}$$

where S is the observed species richness, Q_1 is the number of species occurring in only one sampling unit, and Q_2 is the number of species occurring in two sampling units. Additionally, a Mao-Tau rarefaction curve was generated to evaluate sampling completeness (Hammer *et al.*, 2001).

Additionally, an analysis was conducted at the guild level, grouping species into ecologically related assemblages (Verner, 1984; Magurran, 2004). Based on the preferred habitats of each species at regional and national scales (Brunelli *et al.*, 2011; Lardelli *et al.*, 2022), species were classified into four ecological guilds: synanthropic, edge/mosaic, forest, and water-associated species. To assess potential differences in distribution patterns and dominance among guilds, we calculated the total number of occurrences (N_{occ}) and the average N_{UR}, as well as their relative percentages of the total URs.

A land use/cover analysis was performed using the ISPRA land use/cover database (10 m/pixel resolution, updated to 2023; https://groupware.sinanet.isprambiente.it/uso-copertura-e-consumo-di-suolo/library/copertura-del-suolo). From this, the frequency of four pre-selected land cover macro-categories (urban, open habitats, forests, water bodies) was calculated for each UR.

Using these frequency values, a habitat diversity index was computed based on the Shannon-Wiener formula, where, in this case, fr represents the relative frequency of each land cover macro-category within each UR. This index was then used as an independent variable to examine its relationship with the total species richness and guild-specific richness per UR, through ordinary least squares regression analysis (Dytham, 2011).

To compare the median N_{UR} among ecological guilds, the Kruskal-Wallis test for equal medians was applied; to compare relative frequencies, we performed a χ^2 test. All statistical analyses were performed using PAST version 4.01 (Hammer *et al.*, 2001), with the significance level set at α=0.05. Species nomenclature follows Baccetti *et al.* (2021).

RESULTS

During the 2024 sampling period, a total of 995 species occurrences were recorded, corresponding to 44 breeding bird species (Appendix 1). Among these, three allochthonous species (*Psittacula krameri*, *P. eupatria*, *Myiopsitta monachus*) and one domestic form (*Columba livia* domestica) were included.

Psittacula krameri, Corvus cornix, Cyanistes caeruleus, Sylvia atricapilla, Turdus merula, and *Apus apus* were the most widely distributed species, each exhibiting a frequency of spatial occurrence exceeding 50%. Conversely, eighteen species showed a Fr_{UR} below 10%, indicating a locally restricted distribution (Tab. 1). Despite the presence of large open habitats (mowed meadows) within the study area, species typically associated with these environments—such as larks, *Coturnix coturnix*, *Cisticola juncidis*—were totally absent. Species distribution maps are provided in *Appendix 2*.

The species richness map (Fig. 2) reveals a notable pattern, highlighting a hotspot situated near a small lake (Lake of Giglio) surrounded by mature ornamental trees and oak wood patches, better evidenced by the Kernel interpolation (Fig. 3). The number of species per UR ranged from 1 to 26, with a mean species richness of 11.31±4.37. The estimated total species richness, based on the Chao2 estimator, was 45.19±1.82 (sample rarefaction curve shown in Fig. 4). Overall, the occurrence-based Shannon-Wiener diversity index (H') was 3.28, with an evenness index (J) of 0.867.

Species richness per UR showed a positive correlation with the surface area of forested (r=0.32, p=0.002) and water-related habitats (r=0.31, p=0.003), and a negative correlation with the surface area of open environments (r=-0.27, p=0.011).

Ecological guilds differed significantly in species richness (χ^2=18.18, p<0.001) and Fr_{UR} (χ^2=1040.9, p<0.001), as

Tab. 1 − Breeding bird species in the Villa Doria Pamphilj urban park, subdivided for ecological guilds (syn: synantropic; for: forest; edg: edge/mosaic; wat: water-related species). Number (N_{UR}) and frequency (Fr_N) of occupied UR and frequency of occurrence (Fr_{occ}) have been reported. In bold, species occupying >50% of UR (Fr_N; n=88) or >0.05 in Fr_{occ} (n=995). / Specie di uccelli nidificanti nel parco urbano di Villa Doria Pamphilj, suddivise per gilde (categorie ecologiche): syn: sinantropiche; for: forestali; edg: di ambienti marginali e di mosaic; wat: legate all'acqua. Sono stati riportati il numero (N_{UR}) e la frequenza (Fr_N) di UR occupate e la frequenza di occorrenza (Fr_{occ}). In grassetto, le specie occupanti >50% delle UR (Fr_N; n=88) o >0.05 in Fr_{occ} (n=995).

Species	guild	N_{UR}	Fr_N	Fr_{occ}	Species	guild	N_{UR}	Fr_N	Fr_{occ}
Psittacula krameri	syn	81	**0.920**	**0.081**	*Aegithalos caudatus*	for	14	0.159	0.014
Corvus cornix	syn	78	**0.886**	**0.078**	*Motacilla alba*	edg	11	0.125	0.011
Cyanistes caeruleus	for	74	**0.841**	**0.074**	*Falco tinnunculus*	syn	11	0.125	0.011
Sylvia atricapilla	for	67	**0.761**	**0.067**	*Dryobates minor*	for	9	0.102	0.009
Turdus merula	for	58	**0.659**	**0.058**	*Serinus serinus*	edg	8	0.091	0.008
Apus apus	syn	52	**0.591**	**0.052**	*Anas platyrhynchos*	wat	6	0.068	0.006
Columba palumbus	for	49	**0.557**	0.049	*Hippolais polyglotta*	edg	5	0.057	0.005
Sturnus vulgaris	syn	48	**0.545**	0.048	*Streptopelia decaocto*	syn	5	0.057	0.005
Parus major	for	47	**0.534**	0.047	*Luscinia megarhynchos*	edg	5	0.057	0.005
Columba livia dom.	syn	46	**0.523**	0.046	*Delichon urbicum*	syn	4	0.045	0.004
Certhia brachydactyla	for	37	0.420	0.037	*Gallinula chloropus*	wat	4	0.045	0.004
Hirundo rustica	syn	33	0.375	0.033	*Psittacula eupatria*	syn	3	0.034	0.003
Picus viridis	for	31	0.352	0.031	*Falco peregrinus*	syn	3	0.034	0.003
Myiopsitta monachus	syn	28	0.318	0.028	*Oriolus oriolus*	for	3	0.034	0.003
Dendrocopos major	for	27	0.307	0.027	*Curruca melanocephala*	edg	2	0.023	0.002
Troglodytes troglodytes	for	26	0.295	0.026	*Muscicapa striata*	edg	2	0.023	0.002
Passer italiae	syn	20	0.227	0.020	*Jynx torquilla*	for	2	0.023	0.002
Regulus ignicapilla	for	19	0.216	0.019	*Chloris chloris*	edg	2	0.023	0.002
Garrulus glandarius	for	19	0.216	0.019	*Athene noctua*	syn	1	0.011	0.001
Carduelis carduelis	edg	18	0.205	0.018	*Accipiter nisus*	for	1	0.011	0.001
Fringilla coelebs	for	18	0.205	0.018	*Sylvia cantillans*	edg	1	0.011	0.001
Erithacus rubecula	for	16	0.182	0.016	*Corvus monedula*	syn	1	0.011	0.001
						Total	995	1	1

well as in the mean N_{UR} (H=8.169, p=0.042; Kruskal-Wallis test for equal medians; Fig. 5). Both forest-related and synanthropic guilds were the most widespread, accounting for 52% and 41.6% of total occurrences, respectively, and were also the richest in species numbers, representing 40.9% and 34.1% of the total species recorded (Tab. 2). The variation in species frequencies across ecological guilds is clearly illustrated by the rank-occurrence (Whittaker) plots (Fig. 6). Distribution maps for ecological guilds are provided in *Appendix 3*.

As expected, forest species richness was positively correlated with the size of forest habitats (r=0.49; p<0.001) and negatively correlated with the extent of open (r=-0.34; p=0.001) and artificial environments (r=-0.28; p=0.008). Similarly, the richness of water-related species showed a strong positive correlation with the size of water basins (r=0.58; p<0.001) and a negative correlation with the size of open habitats within each UR (r=-0.23; p=0.029). Edge species richness was also positively correlated with the extent of water basins (r=0.22; p=0.043). Contrary to expectations, neither total species richness nor guild-specific richness showed a significant correlation with habitat diversity.

Tab. 2 − Ecological guilds in the Villa Doria Pamphilj urban park (syn: synantropic; for: forest; edg: edge/mosaic; wat: water-related species). N_{occ}: total number of occurrences; $\%N_{occ}$: percentage of occurrence on the total number of occurrences (n=995); S: number of species (guild level) and percentage (%) on the total number of species; H': Shannon-Wiener diversity index (guild level); J: evenness index (guild level). / Gilde (categorie ecologiche) nel parco urbano di Villa Doria Pamphilj: syn: sinantropiche; for: forestali; edg: di ambienti marginali e di mosaico; wat: legate all'acqua. N_{occ}: numero totale di occorrenze; $\%N_{occ}$: percentuale di occorrenze sul totale (n=995); S: numero di specie (livello delle gilde) e percentuale (%) sul totale; H': indice di diversità di Shannon-Wiener (livello delle gilde); J: indice di evenness index (livello delle gilde).

	syn	edg	for	wat
N_{occ}	414	54	517	10
$\%N_{occ}$	0.416	0.054	0.520	0.010
S (%)	15 (34.1)	9 (20.5)	18 (40.9)	2 (4.5)
H'	2.21	1.85	2.59	0.67
J	0.816	0.842	0.896	0.967

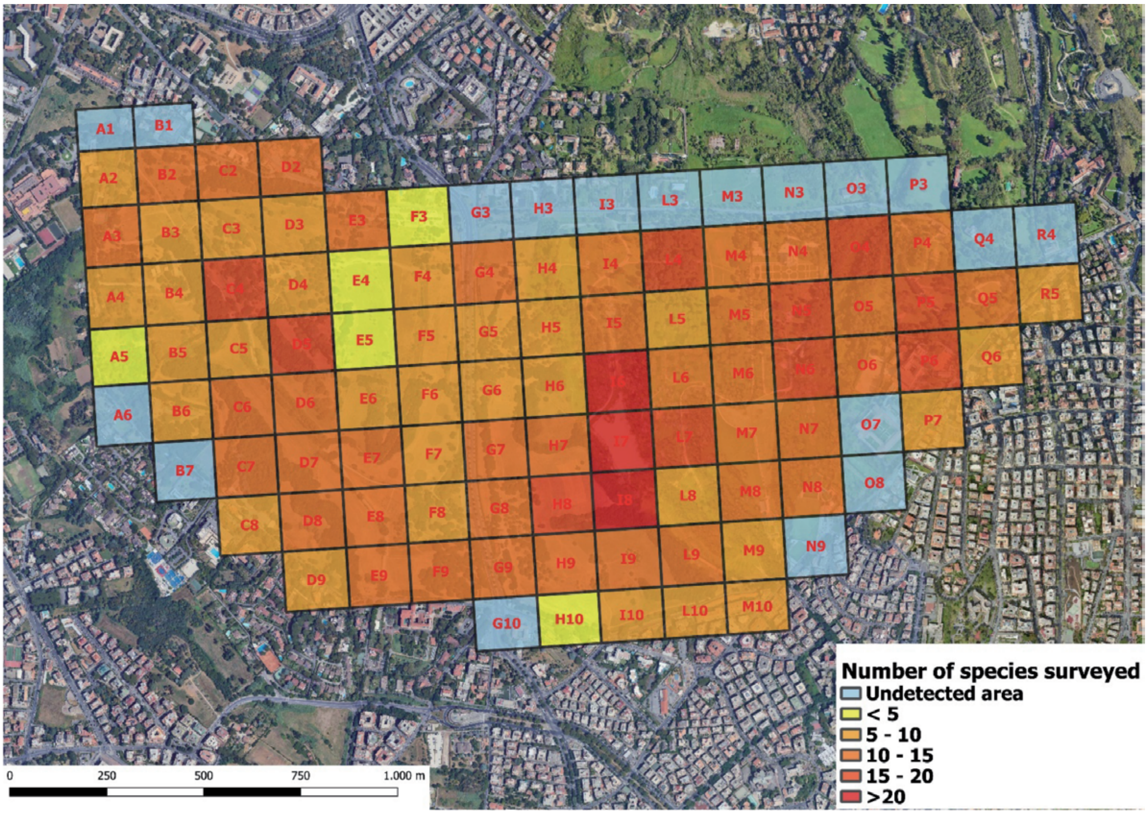

Fig. 2 − Map of the total species richness in the Villa Doria Pamphjli urban park (Rome, central Italy). / Mappa della ricchezza totale di specie nel parco urbano di Villa Doria Pamphilj (Roma, Italia centrale).

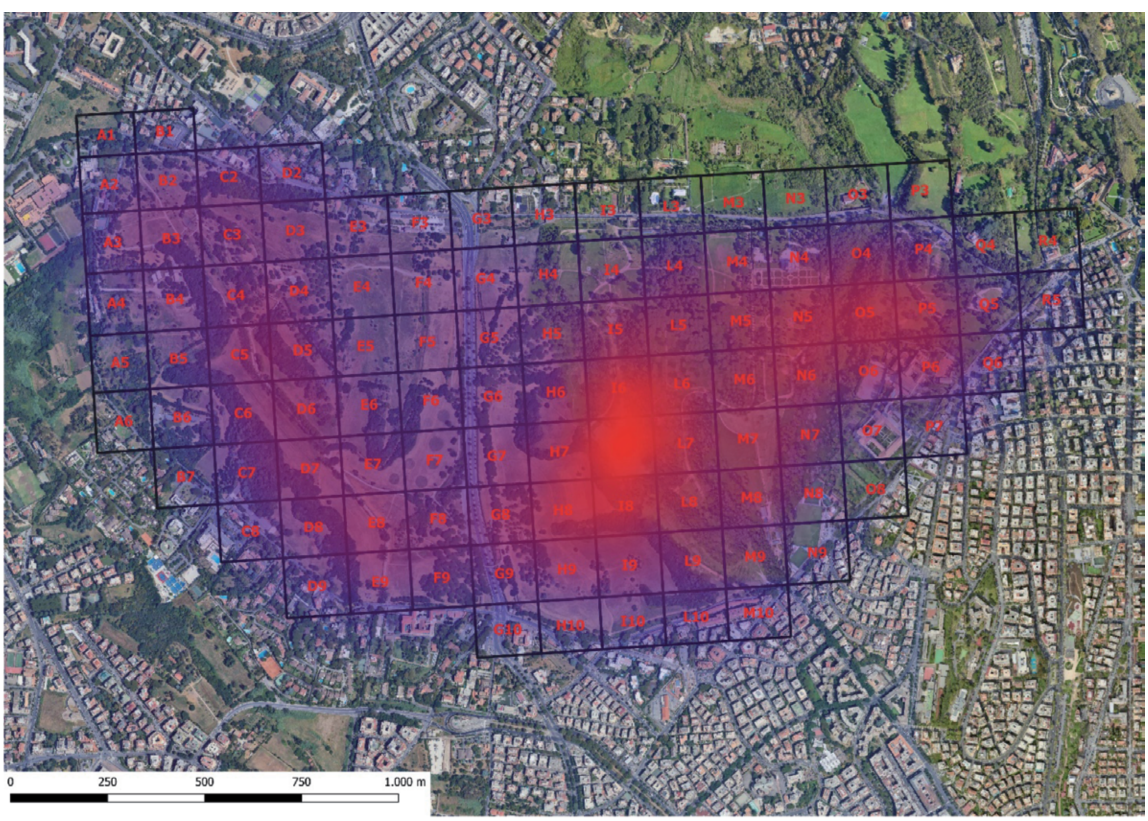

Fig. 3 − Heatmap of total species richness in the Villa Doria Pamphjli (Rome, central Italy) realized using the kernel density tool (algorithm "kernel density estimation" - Kernel shape "Epanechnikov"). / Mappa interpolata di ricchezza di specie totale nel parco urbano di Villa Doria Pamphilj (Roma, Italia centrale) realizzata usando lo strumento di densità di kernel (algoritmo: "stima della densità di kernel" – format kernel "Epanechnikov").

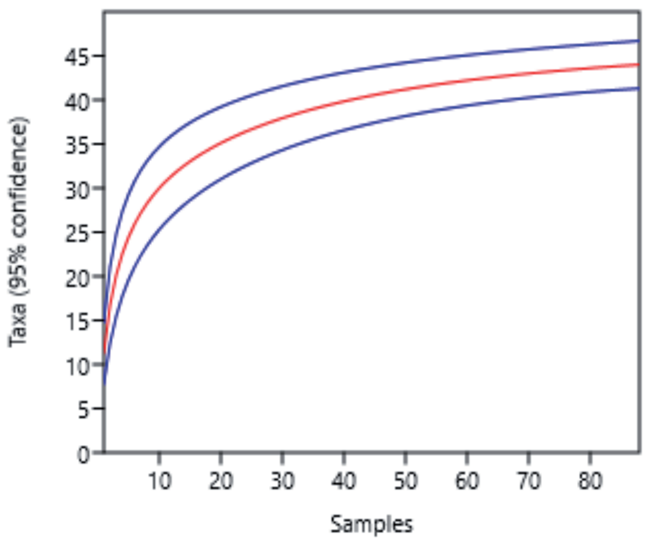

Fig. 4 − Sample rarefaction curve (MauTau, and 95% confidence intervals) for the total species richness. / Curva di rarefazione sui campionamenti di occorrenza (MauTau, e 95% di intervallo di confidenza) per la ricchezza di specie totale.

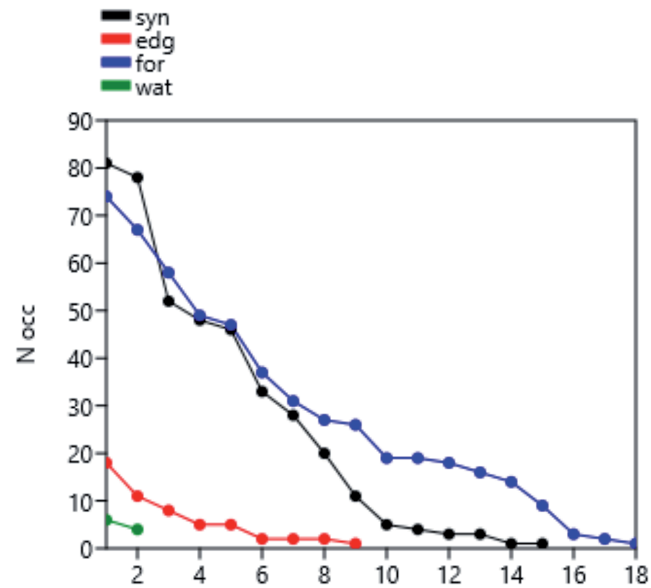

Fig. 6 − Whittaker plot (occurrence-based) for the four ecological guilds (y-axis: number of occurrences, N occ; x-axis: species rank): syn: synantropic; for: forest; edg: edge/mosaic; wat: water-related species. / Diagramma di Whittaker (basato sulle occorrenze) per le quattro gilde (asse y: numero di occorrenze, N occ; asse x: rango delle specie): for: forestali; edg: di ambienti marginali e di mosaico; wat: legate all'acqua.

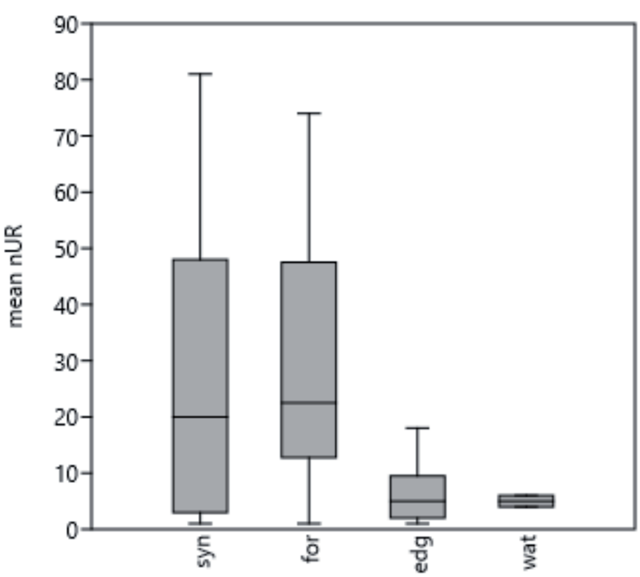

Fig. 5 − Box plots of average number of sampling units (nUR) (y-axis) occupied by different ecological guilds (syn: synantropic; for: forest; edg: edge/mosaic; wat: water-related species). Minimal and maximal values are shown with short horizontal lines ("whiskers"); 25-75 percentiles are drawn using a box; horizontal line shows the median values. / Box plots del numero mediano di Unità di Rilevamento (nUR) occupate dalle specie appartenenti alle differenti gilde (for: forestali; edg: di ambienti marginali e di mosaico; wat: legate all'acqua). Sono riportati i valori minimi e massimi con righe orizzontali ("baffi") e il range del 25-75 percenntile con un rettangolo grigio; la linea orizzontale nel rettangolo indica il valore mediano.

DISCUSSION AND CONCLUSIONS

Villa Doria Pamphilj hosts a diverse community of breeding birds, owing to its agroforestry mosaic within a highly urbanized environment. This area has been extensively studied over recent decades, both at the level of individual species (Zocchi, 1982; Sorace, 1990; Gustin & Sorace, 1993; Zocchi *et al.*, 2009; Battisti, 2013; Dodaro & Battisti, 2014; Giampaoletti & Battisti, 2024) and at the level of guilds and communities (Zocchi & Panella, 1978; Battisti, 1986; Angelici *et al.*, 1988; Battisti & Dodaro, 2016).

As expected, land cover strongly influences bird community composition in urban parks (Ortega-Álvarez & Macgregor-Fors, 2009). The high environmental heterogeneity at the landscape scale—including oak wood patches, pinewoods, historic Italian gardens with ornamental plants, water basins, and historic buildings—provides a wide array of niches and resources for numerous species. Similar patterns have been observed in other urban parks of Rome (Ianniello, 1987; Salvati, 1992, 1995, 1996; Arca *et al.*, 2005, 2012; Fraticelli, 2005; Taffon *et al.*, 2008).

The community is characterized by common species typical of anthropized environments (e.g., *Corvus cornix*, *Streptopelia decaocto, Apus apus*) and non-native species such as parakeets, alongside species associated with forest habitats and tree-lined avenues with mature vegetation (e.g., woodpeckers and other primary and secondary cavity nesters), as well as, to a lesser extent, species linked to water-related habitats (e.g., *Gallinula chloropus*, *Anas platyrhynchos*). Of particular interest is the localized presence of species of conservation concern, such as *Falco peregrinus*, or species that are still relatively uncommon in urban areas of Rome, such as *Accipiter nisus* (Gattabria & Marangoni, 2002; Battisti, 2014; Battisti & Mandolini, 2018) and *Dryobates minor* (Mansi *et al.*, 2022).

Our atlas dataset contributes additional insights into the spatial patterns of species richness and occurrence within this urban park. In this context, several noteworthy aspects emerge.

First, a notably high spatial distribution of two non-native parakeet species is evident, with one of them being the most dominant species in the area. This species began colonizing Rome in the mid-1980s: initial observations date back to Angelici (1984, 1986), and it was confirmed as breeding in the city at the beginning of 2000 (Fraticelli & Molajoli, 2002). The presence of mature trees (>60 cm; Zangari *et al*., 2013) and a diverse array of spatial and trophic resources—such as ornamental plants and fruit trees—creates highly suitable habitats for these parakeets and other historic parks, which may have important implications for the local biodiversity (Strubbe & Matthysen, 2007, 2009a, 2009b; Newson *et al*., 2011; Orchan *et al*., 2013; Battisti & Fanelli, 2022). Analogous results have been obtained for forested areas in urban and periurban mosaics (Canedoli *et al*., 2018). For instance, the population explosion of parakeets could contribute to competition for nesting cavities, potentially impacting native species like *Sturnus vulgaris* (Dodaro & Battisti, 2014) and *Sitta europaea* (occurring presently until a few years ago and now disappeared as a nesting bird; Cignini & Zapparoli, 1996; Giampaoletti and Battisti, pers. obs.). Another species of parakeet (*Psittacula eupatria*), yet recorded for Rome (Angelici & Fiorillo, 2015), has been recorded in Villa Doria Pamphilj and, analogously to the other two species, could show a similar demographic increase in Rome in the next decades.

Second, species richness increases with the availability of forest patches and water basins. Forests, with their complex vertical stratification, and water basins, offering ecotones along their banks, provide a variety of niches and trophic resources that support diverse bird communities with different ecological requirements (Wiens, 1989; Huang *et al*., 2022; see Di Santo *et al*., 2015, for a review of birds in water basins in Rome). When wood patches, mature trees, and water basins co-occur, species richness is particularly high, as highlighted by the main hotspot near a small lake surrounded by mature trees and riparian vegetation on the species richness maps. The other secondary red zones correspond to small wood patches.

Third, despite the presence of extensive open spaces such as meadows, species typically associated with these habitats are notably absent. Common species, linked to meadows and croplands found in nearby suburban areas (Sorace, 2001; Battisti, 2014)—such as *Coturnix coturnix*, *Alauda arvensis*, *Cisticola juncidis*, *Saxicola torquatus* and *Emberiza calandra*—are missing from the park. This absence can likely be attributed to the high frequentation of humans and dogs and to disturbances caused by regular mowing practices used in green area management. It has been previously highlighted that management intensity in urban parks can significantly influence bird communities (Shwartz *et al*., 2008). Frequent mowing affects open-habitat birds both directly and indirectly by reducing the availability of key food resources like arthropods in terms of abundance and diversity (Huang *et al*., 2015; Proske *et al*., 2022). In this regard, some management recommendations to promote bird diversity in this park had already been proposed by Angelici *et al.* (1991). Finally, species linked to agroforest mosaics (as *Pica pica* and *Streptopelia turtur*) have not been recorded in this survey.

Last but not least, habitat diversity measured at the scale of individual URs (160×160 m) does not appear to explain variations in species richness. Although the positive relationship between species richness and habitat diversity is well documented for birds (González-Oreja *et al*., 2012; Chang & Lee, 2016), species' sensitivity to environmental heterogeneity can vary depending on the spatial scale considered (Arlettaz, 2012). In our case, the fine spatial grain of the atlas may not correspond to the ecological scale perceived by the common species, here recorded. Therefore, for future analyses, it may be useful to consider habitat diversity at the landscape level rather than within individual URs. Moreover, in addition to habitat extent, it would also be important to include measures of habitat quality, such as the presence of trees of different ages (as mature plants >60 cm) and structural complexity.

From a methodological standpoint, it is important to note that, due to the need to standardize sampling over a relatively large area, the survey time allocated to each UR was necessarily reduced (20 minutes). This limitation may have resulted in an underestimation of occurrences for rarer or more locally restricted species, such as *Passer montanus* and *Cettia cetti*, here not recorded but occurring in this park (Cignini & Zapparoli, 1996, and pers. obs.). Additionally, the protocol employed was not suitable for detecting nocturnal and crepuscular species known to inhabit the area—for example, *Strix aluco* (Manganaro *et al.*, 1990; Manganaro *et al.*, 1992), *Athene noctua* (recorded only once as an occasional contact) and *Tyto alba,* the last not more detected in recent decades (Buscemi *et al.*, 1995).

In the last decades, there has been a notable turnover in the bird community composition. Whereas in the mid-1980s communities were mainly associated with agroforestry mosaics with a minor synanthropic component (Battisti, 1986), the past twenty years have seen a steady increase in medium-to-large biomass species, both synanthropic and allochtonous (e.g., *Streptopelia decaocto*, *Sturnus vulgaris*, *Psittacula krameri*, *Myiopsitta monachus*), alongside forest species expanding at national, regional, and local scales (e.g., *Columba palumbus*, Amman *et al.*, 2017; *Garrulus glandarius* and woodpeckers). Concurrently, the frequency of species such as *Passer italiae* and *Jynx torquilla* has progressively declined (Battisti & Dodaro, 2016), mirroring trends observed on broader scales (Summer-Smith, 2003; Brichetti *et al.*, 2008; Brambilla, 2019). In this context, fine-grained atlases conducted in large urban parks represent valuable tools for long-term monitoring in anthropized environments: indeed, they provide critical insights into changes in spatial distribution patterns of species in these dynamic habitats, facilitating both geographical and temporal comparisons (Jokimäki & Suhonen, 1993; Jokimäki, 1999).

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SUPPORTING INFORMATION

Appendix 1 – Check-list of breeding bird species recorded in this study (in systematic order, following Baccetti *et al*., 2021). Common names in English and in Italian. / Appendice 1 – Lista delle specie di uccelli nidificanti rilevate in questo studio (in ordine sistematico, da Baccetti *et al.*, 2021). Nomi comuni in Inglese e in Italiano.

Appendix 2 – Maps of breeding bird species (in systematic order, see Appendix 1). / Appendice 2 – Mappe delle specie di uccelli nidificanti (in ordine sistematico, si veda Appendice 1).

Appendix 3 – Maps of ecological guilds. / Appendice 3 – Mappe delle gilde ecologiche.