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Research article

Urbanisation impacts avian biodiversity on stream ecosystems – insights from a large geographical scale

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A R T I C L E I N F O

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A B S T R A C T

Urban blue and green spaces, such as streams and adjacent riparian areas, constitute important biodiversity refuges in highly anthropogenically -modified areas, but this depends on their ecological characteristics, preservation and management. Birds are useful indicators of ecosystem quality due to their relatively high trophic position. They may also disseminate and control pathogenic organisms, being good indicators for human and animal health risks. In our study, we used presence/absence data of avian species, and a wide environmental characterization of 102 urban streams across five European cities with a broad latitudinal range (Portugal, France, Italy, Belgium, and Norway), to evaluate how the impacts of urbanisation on ecosystem health impacted avian biodiversity. Benevento and Oslo differed most strongly from the remaining cities. The most representative bird species were different among the cities, which indicated that there is not a full homogenization of in European riparian zones. Yet, the number of insectivorous bird species was negatively associated with increasing urbanisation, including some of its proxies such as imperviousness, artificial light at night and population density. Streams with higher diversity of vegetation types and habitats tended to favour insectivorous birds like the Eurasian Wren *Troglodytes troglodytes* and the Common Chiffchaff *Phylloscopus collybita*. This is relevant in the context of One Health because this feeding guild may control the abundance of potential disease vector-mosquitoes. Management strategies should focus on preserving and rehabilitating riparian zones with structured vegetation and promoting habitat diversity through the maintenance of hedgerows and patches of natural green areas.

1. Introduction

Most of the human population now lives in urban areas (Johnson and Munshi-South, 2017). This ongoing expansion of cities leads to a loss of natural habitats for wild species and imposes a major toll on biodiversity. Despite some wild species behaviourally adapting to these novel habitats, and being able to exploit human-derived resources, such as food subsidies, they become also exposed to several pressures including direct disturbance (e.g., habitat loss), contamination (e.g., chemical, noise, light), increased competition and exposure to novel pathogens (e.g., such as those commonly found in domestic animals; Isaksson, 2018). Such stressors related to the urban environment may act synergistically and concomitantly with other global pressures, such as climate change, and contribute to physiologically stressed individuals, susceptible to infections and disease, with impaired capacity to reproduce successfully or survive. Given their high trophic position, birds are good indicators of

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environmental risks (Mansfield et al., 2024; Norte et al., 2022). Also, they are relevant for the maintenance and dissemination of microorganisms. Birds can constitute a pool of reservoir hosts of zoonotic pathogens that may be transmitted to humans, domestic animals, and other wild animals (e.g., Salmonellae, West Nile virus, *Borrelia burgdorferi* s.l. (Pejchar et al., 2025). But biodiverse avian communities can also contribute to reduce health risks for humans and domestic animals, by acting as biological controls of important disease vectors such as mosquitoes (Culicidae) and agricultural pests, contributing to maintaining One Health (Garcia et al., 2020; Lourenço et al., 2021; Singh and Lalit Mohan, 2013). Additionally, birds provide regulating (e.g. promote seed dispersal, pollination), supporting (maintenance of food webs, habitat engineering, nutrient cycling), and cultural services (e.g., enhancing human well-being and connection to nature). Therefore, they can be considered indicators for human and animal health risks.

Avian species that usually occur in urban areas include not only cosmopolitan species that are present in cities across the globe (e.g., the House Sparrow *Passer domesticus*, the Feral Pigeon *Columba livia*, the Common Starling *Sturnus vulgaris*, the Barn Swallow *Hirundo rustica* (Aronson et al., 2014), but also others that are representatives of the set of species from each biogeographical region. Generally, these species dwelling in urban habitats share a set of common morphological and life-history traits such as being generalists, having a smaller body size, higher dispersal ability and larger clutch sizes (Neate-Clegg et al., 2023; Peña et al., 2024). Further, these urban communities usually have lower taxonomic richness and functional diversity, and include non-native species (Devictor et al., 2007; Peña et al., 2024). These trends have been observed both at broad spatial scales and in long-term studies that simultaneously monitored habitat and community changes (Devictor et al., 2007; Xu et al., 2018).

Studies taking into account species phylogenetic diversity showed that, at a global scale, bird species richness and the community evolutionary uniqueness (or distinctiveness) were lower in urban areas, suggesting global biotic homogenization (Ibáñez-Álamo et al., 2017). In Europe, this biotic homogenization (phylogenetic relatedness) was found to be driven by the extent of built-up area and other indicators of urbanisation, while the presence of grass, trees, and water (rivers or urban streams) positively affected the phylogenetic diversity of avian communities (Morelli et al., 2021). Noise pollution did not affect any of the avian diversity metrics (Morelli et al., 2021). A decade of urban expansion in Shanghai, China, significantly decreased the avian species richness, with the avian communities of wetlands and open areas being the most affected (Xu et al., 2018). Another study, in continental USA, has revealed the importance of waterbodies for avian biodiversity in urban areas (Callaghan et al., 2021): they found that the proportion of water cover within a city was more important than that of tree cover in explaining the avian species richness.

Waterbodies and associated wetlands provide a sanctuary for many birds, including migratory stopovers, breeding, or wintering grounds. Due to the disproportionate species richness of inland freshwaters, declines in their biodiversity are steeper than those observed in even the most affected terrestrial ecosystems (Sala et al., 2000). Major threats include water contamination, over-exploitation, flow modification, habitat degradation, and species invasion (Dudgeon et al., 2005). Freshwater streams are particularly important because they represent corridors for bird movements, facilitating faunal mixing on a broad scale and functioning as connectors of forests across fragmented landscapes (Knopf and Samson, 1994). The complexity of vegetation structure in riparian areas due to its humidity and nutrient levels leads to greater levels of food resources for wildlife, and also benefits birds due to associated multiple edge-effects (Palmer and Bennett, 2006; and references therein).

Inventories of biodiversity associated with freshwaters are usually incomplete, especially in some regions of the globe, but also in habitats not perceived as of high quality, such as those in urbanised areas (Campos et al., 2024). Yet, these ecosystems represent some of the most important natural areas within cities, as they can safeguard biodiversity and provide important ecosystem services to humans, contributing to their wellbeing (Aronson et al., 2014; Ranta et al., 2021; Sousa et al., 2024). To draw conservation measures for urban freshwater ecosystems, their avian communities need to be characterised and related to potential driving factors. Few previous studies that surveyed avian biodiversity in relation to urbanisation in freshwater ecosystems were limited to a single river basin and/or were mostly performed in North America (Banville et al., 2017; Green and Baker, 2003; Hennings and Edge, 2003; Rottenborn, 1999).

To assess how bird communities are related to the impacts of urbanisation on stream ecosystem health, with potential reflexes in One Health, we evaluated avian biodiversity in 102 urban streams of 5 European cities, and investigated which drivers associated with anthropogenic habitat modifications in urban areas were correlated with the avian community. We expected a high homogenization of urban stream communities across European cities, and that streams characterised by higher levels of urbanisation (e.g., higher population density, larger built-up areas), and poorer water quality, would be associated with communities dominated by omnivorous generalist species and lower abundance of more specialized feeding guild species such as insectivorous birds. Also, we aim to identify which habitat characteristics of urban streams are the main drivers of bird community composition independently of geographic location within Europe. We expect that characteristics related to vegetation structure will be the most important in shaping bird communities. Finally, we aim to identify a sensitive avian bioindicator (bird species or group of species/guild) that can act as an early-warning indicator of urban stream degradation and risks for One Health.

2. Materials and methods

2.1. Study areas

The study was performed in 5 cities, covering a latitudinal and climatic gradient across Europe: Coimbra, Portugal (20 streams); Toulouse, France (22 streams); Benevento, Italy (20 streams); Ghent, Belgium (22 streams) and Oslo, Norway (18 streams); comprising a total of 102 streams (Fig. 1) within the framework of the OneAquaHealth Horizon Europe project. The cities have temperate (Coimbra, Benevento, Toulouse and Ghent) and cold (Oslo) climates, varying from a hot-summer Mediterranean climate in Coimbra and Benevento to a warm-summer humid continental climate in Ghent and Oslo (Rodrigues et al., 2025).

Coimbra has approximately 150,000 inhabitants, and is crossed by the largest river entirely contained in Portuguese territory, the Mondego, to which many streams drain. In the old city, they have been highly modified and covered or channelized; while in the more recent districts, the streams are uncovered, with some riparian vegetation but also with many non-native and invasive plant species (Campos et al., 2024). In the city outskirts, small streams run through a mixture of urbanised, industrialized, and agricultural fields. Toulouse, in the Southwest of France, has ca. 500,000 inhabitants. The river Garonne originates in the Pyrenean mountains and crosses the city center of Toulouse, to which flow many small and often intermittent streams. Agriculture, urbanisation, industrial development, and touristic activities affect the river and streams. Benevento city has 60,000 inhabitants, being in the inland basin within the Campania region (135 m asl), southern Italy. It is surrounded by high hills and mountains and crossed by the rivers Calore and Sabato. Water pollution is a main cause of river degradation, while the riparian vegetation is preserved in some stream and river reaches. Oslo, the capital of Norway, has ca. 700 000 inhabitants. Several rivers and streams discharge into the Oslo Fjord, and since 2000, some have been rehabilitated and improved in terms of water quality, while others have kept dense riparian forests. In Belgium, the study area comprises selected urban and peri-urban regions of

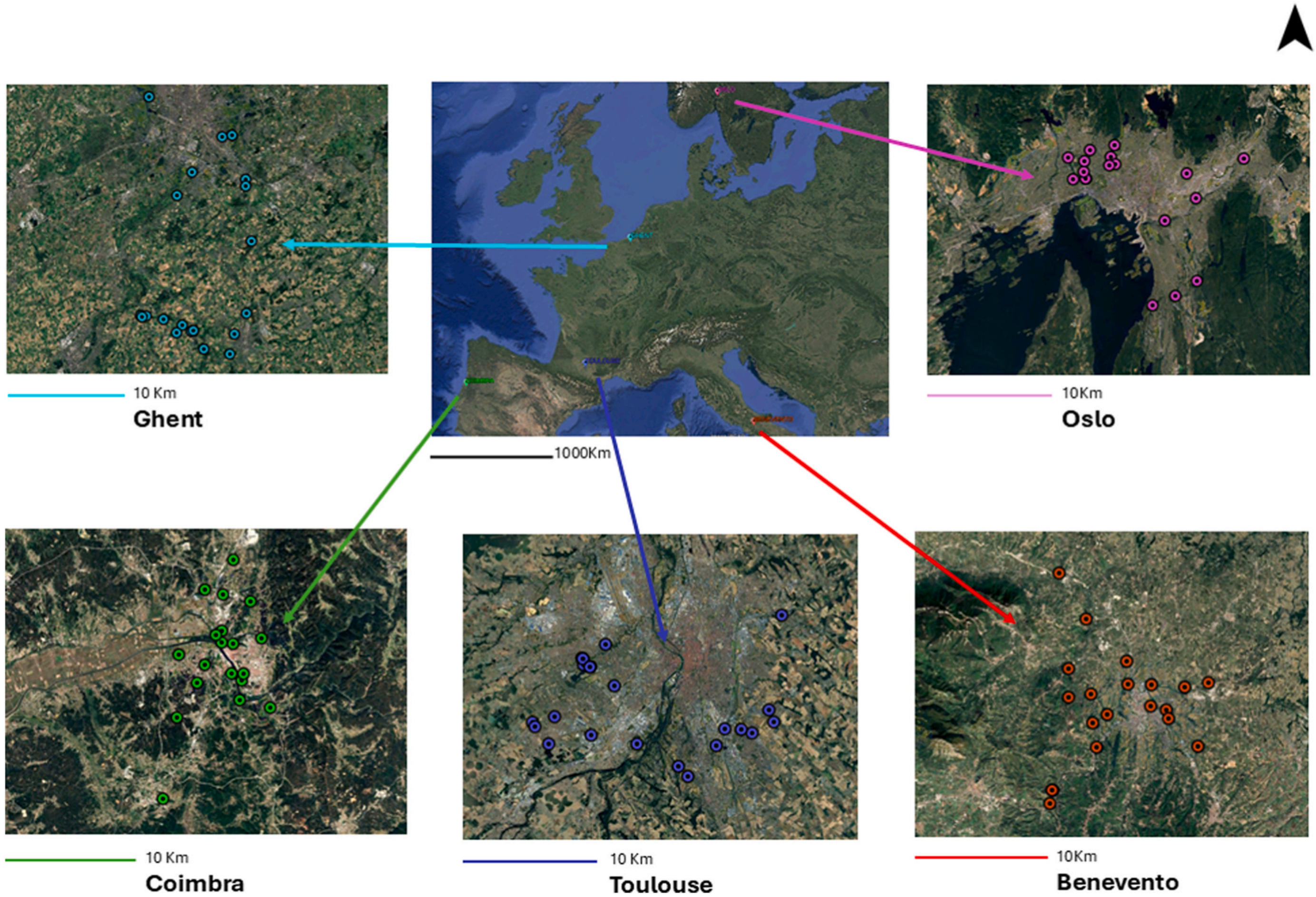

Fig. 1. Map of the sampling points in the five European cities – Benevento, Coimbra, Ghent, Oslo and Toulouse (Google Earth Pro).

eastern Flanders, specifically in and around Ghent, including the municipalities of Merelbeke-Melle, Zottegem, Zwalm, and Oosterzele. The study region is densely populated with a total of about 350,000 inhabitants. The Scheldt river is the main river in the region, to which several rivers and streams drain, including Zwalm, in whose catchment the stream sites were located. Water pollution and artificialization are the main causes of river degradation (Boets et al., 2021; Forio et al., 2020). The cities were chosen for corresponding to a broad latitudinal and climatic gradient, within Europe, from Mediterranean to temperate and cold-climate urban systems. Within each city, the sites were chosen to cover local gradients of urbanisation, including variation in imperviousness, population density, artificial light at night, riparian vegetation, habitat diversity, and water quality (Chen et al., 2026; Rodrigues et al., 2026).

2.2. Birds survey

During the breeding and post breeding season (May – September) of 2024, avian call detection through a free bird identification app (Merlin mobile application; Cornell Lab of Ornithology, Cornell University) was performed at each study site (i.e. each stream with a corresponding reach of 100m), within a 50-m radius centred on the stream channel, encompassing both riparian vegetation and immediately adjacent urban infrastructure (e.g., footpaths, residential edges) if present. Each site was chosen according to being representative of the stream, and was the same that had been previously characterised within the framework of this project, and where all the other samples and parameters (e.g. aquatic invertebrates) were collected. The site was visited for 10 min, and recordings to assess the presence of bird species were performed during early morning hours (0600–1000) to maximize detectability and obtain a representation of the breeding bird community composition (Sutherland, 2006). Obtained data was later verified (ACN and JAR) and Merlin flagged uncommon observations (total n = 7) were checked and confirmed for the respective location/date to exclude identifications that did not match the bird species distributional ranges (Sup. Mat. 1). Avian biodiversity monitoring using the Merlin app is a practical approach, allowing wide scale assessments such as ours, and by a larger number of surveyors. Yet, this approach also has limitations. The detection and recognition of low intensity sounds (e.g. when the bird is far away), and in noisy areas decreases the sensitivity of the method (Goodman et al., 2025). Also, the databases of bird sounds may not be fully complete for all regions. But, with database growth and following validation through dedicated pipelines, it has the potential to contribute to global biodiversity databases (Goodman et al., 2025). Also, in one of the cities (Coimbra), mist-netting data (unpublished) from the same streams showed a strong agreement with Merlin detections.

Identified bird species were classified by diet as insectivorous (invertebrate eaters), granivorous (plant seed eaters), omnivorous, and scavengers/vertebrate eaters, including fish (Cramp and Simmons, 1977; Wilman et al., 2014; Sup. Mat. 2). The classification of bird species into feeding guilds is a common approach in avian community ecology because it reveals the functional organization of the community and constitutes a more sensitive indicator of the impacts of habitat changes and resource availability than species alone (De Silva and Medellín, 2002; Kissling et al., 2012).

2.3. Environmental and physico-chemical characterization of the study sites

Public databases were used to obtain population density (Eurostat, 2023), imperviousness density (EEA, 2020a), tree cover density (EEA, 2020b), and conifer area (EEA, 2020c) across a circular buffer zone of 500 m radius (geodesic distance) around each sampling site. We defined this buffer area as it represents an area of influence on an urban stream encompassing the riparian area and immediate adjacent area, but without overlapping with other nearby streams. Spatial data were projected to ETRS 1989 LAEA (Lambert Azimuthal Equal-Area) to ensure accurate calculations of area and distance. Population density (population/km^2) within each buffer zone was derived as the weighted mean within each buffer, the weighting based on the proportion of the local administrative unit area that intersected the buffer. Imperviousness density, tree cover density, and conifer area were extracted for each buffer as the weighted average of the raster data using the raster cells area as the weight using the exactextractr package (version 0.10.0 (Baston, 2024), in R (version 4.3.2). Small woody features (5m resolution) were based on the spatial pattern of the woody linear and patchy vegetation elements; it provides information on habitat fragmentation and includes herbaceous features like hedgerows, shrubs, and small clusters of trees (Table 1). Artificial Light at Night (ALAN; nW/cm2/sr) was obtained from https://eogdata.mines.edu/nighttime_light/monthly/v10/2024/202409/vcmcfg/for the month when the avian calls were monitored in each city.

Land use in the margins was visually classified within a 10 m distance from the stream bank and 50 m along the stream sampling site according to the presence or absence of the following categories: urban/suburban infrastructures, parks and gardens, scrubs/shrubs, and orchards. For each study site, the number of land use types flanking the stream was summed up as a proxy of habitat diversity surrounding the stream. Stream bank artificialization was characterised visually at each site by scoring the predominance of earth soil (1), laid natural stones without concrete (2), gabion (3), or concrete/artificial impervious materials (4) in its composition. Then, stream bank artificialization was quantified by assigning average scores based on the dominant materials of the bank. This characterization is part of the sampling protocol of OneAquaHealth.

At each stream sampling site, water temperature (°C) was measured *in situ* with the probes WTW™ Multi 3420 SET G (Toulouse and Ghent), HANNA's HI 98199 (Coimbra and Oslo), XS Revio (Benevento). Water samples were collected, preserved in cooling boxes between 5 and 10°C, and later analysed by the Plateforme d'Analyses Physico-Chimiques (PAPC) of the Research Center on Biodiversity and the Environment (CRBE). Total organic carbon (TOC) was determined from the unfiltered water with a ShimadzuTM-TC-L analyser. Nitrates (NO^{3-}), phosphates (PO_4 $^{3-}$), ammonium (NH_4^+) were assessed from filtered water using ThermoScientific ion-chromatographs DionexTM ICS-5000+ and DionexTM DX 120.

2.4. Statistical analyses

We compared avian community composition in the different cities using a non-metric multidimensional scaling (nMDS) ordination based on presence/absence data at the 102 streams from five European cities (Coimbra, Toulouse, Benevento, Ghent and Oslo). Significant differences ($p < 0.05$) in avian communities were tested among cities using permutational multivariate analysis of variance (PERMANOVA: unrestricted permutations of raw data (9999 randomisations) for the fixed factor city, based on a Bray Curtis dissimilarity matrix on presence/absence of species. Pair-wise post hoc tests were performed whenever an overall effect was significant. We also used the presence/absence data in a Similarity Percentage analysis (SIMPER) to assess which species were the most representative of each city. We calculated the total number of unique species in each city and the co-occurrence patterns between

Table 1
Environmental variables used to characterise urban streams.

Variable	Resolution	Description
Imperviousness (%)	10m	Ground impermeable barrier sealing density in the range from 0% to 100% for 2018
ALAN (nW/cm2/sr)	500m	Monthly radiance values obtained from nocturnal satellite imagery (https://eogdata.mines.edu/products/vnl/#monthly) as a proxy of light pollution levels
Population density (population/km2)		Population density within each buffer zone was derived as the weighted mean population density by accounting for the proportion of the area of each local administrative unit intersecting the buffers. This weighted mean represents the population density within the buffer, adjusted for the varying sizes of the intersected local administrative units.
Tree cover density (%)	10m	Level of tree cover density in a range from 0% to 100% for 2018
Conifer area (m^2)	10m	Area (m^2) within each buffer (exactextractr package in R) using the formula: At = $\sum$(Fi ×Ap), where At is the total area occupied by a given tree type within the buffer, Fi is the fractional coverage of pixel i, and Ap is the pixel area (100 m^2). The total area for the tree type was then aggregated for each buffer.
Broadleaf cover (m^2)	10m	Area (m^2) within each buffer (exactextractr package in R) using the formula: At = $\sum$(Fi ×Ap), where At is the total area occupied by a given tree type within the buffer, Fi is the fractional coverage of pixel i, and Ap is the pixel area (100 m^2). The total area for the tree type was then aggregated for each buffer.
Small woody features (m^2)	5m	Area (m^2) of small woody elements such as hedgerows, tree groups, and individual trees. Categorizes them based on their linear or patch-like nature, offering insights into landscape structure and vegetation density.
Number of habitat types	50 m	Number of land use types (orchards, urban and suburban infrastructures, parks and gardens, scrubs and shrubs) in the surrounding area of the stream was summed up as a proxy of habitat diversity surrounding the stream
Bank artificialization score		Average score according to the material composition of the bank (earth soil (1), laid natural stones without concrete (2), gabion (3) or concrete/artificial impervious materials (4) in its composition)
Water temperature (°C)		Stream site water temperature measured *in situ*
Total organic carbon (TOC; mg/ml)		Concentration of TOC from the stream water
Ammonium (mg/L)		Concentration of NH_4^+ from the stream water
Phosphates (mg/L)		Concentration of PO_4^{3-} from the stream water
Nitrates (mg/L)		Concentration of NO_3^- from the stream water
Orchards	50 m	Presence or absence of orchards assessed within a 10 m distance from the stream bank and 50 m along the stream research site
Urban and suburban infrastructures	50 m	Presence or absence of urban and suburban infrastructures assessed within a 10 m distance from the stream bank and 50 m along the stream research site
Parks and gardens	50 m	Presence or absence of parks and gardens assessed within a 10 m distance from the stream bank and 50 m along the stream research site
Scrubs and shrubs	50 m	Presence or absence of scrubs and shrubs assessed within a 10 m distance from the stream bank and 50 m along the stream research site

cities (http://bioinformatics.psb.ugent.be/webtools/Venn/).

To evaluate how bird species were related to the abiotic environmental conditions across the 5 research cities, we applied a Distance-based Linear Model (DistLM) based on a Bray-Curtis dissimilarity matrix derived from species richness data. Environmental variables (n = 15; Table 1) were normalized before analysis, and a Spearman correlation was used to identify highly correlated environmental variables ($r_s \geq 0.8$), which were excluded from further analyses. DistLM was run with stepwise selection based on adjusted R^2 and 9999 permutations to identify the combination of variables that best explained the variation in species richness. In addition, we performed a distance-based redundancy analysis (dbRDA), which provides a constrained ordination representation of the fitted model, showing the relationship between community patterns and environmental gradients. Because the avian communities and urbanisation gradient differed between cities, we also applied DistLM followed by dbRDA to better understand which environmental variables were more relevant to explain each avian community within each city.

Additionally, we performed a Principal Components Analysis (PCA) with 13 environmental variables that characterise the stream sites across the five cities (Tables 1 and 2) in terms of urbanisation to obtain an urbanisation gradient (i.e., a composite urbanisation index). The eigenvalues of the first three PC axes were then used as factors representing combined environmental gradients in further analyses. To understand if there were significant relationships between environmental characteristics of streams and avian feeding guilds, we performed Generalized Linear Models (GLMs) with the five cities PCA scores (PCs 1-3, ie. environmental gradients 1 to 3, and their interactions) as explanatory variables. The number of insectivorous bird species (Poisson distribution), and the number of both granivorous and omnivorous bird species (log x+1 transformed for normal distribution), were used as response variables in three separate GLMs. Scavengers/vertebrate/fish eaters group was modelled as presence/absence data because of the low variability in the number of species when that guild was present. Only significant interactions were maintained.

The PERMANOVA, nMDS, SIMPER, dbRDA and DistLM analyses were performed in PRIMER 6 (Anderson et al., 2008). Remaining analyses were performed in JMP Pro version 18 (SAS Institute).

3. Results

3.1. Bird communities across the different cities

The nMDS ordination based on the avian communities of 102 streams in the five cities showed that Benevento and Oslo differed most strongly from the remaining three cities due to a higher representation of Common Blackbirds (*Turdus merula*) in Oslo and Benevento, and of the Greenfinch (*Chloris chloris*) in Benevento, and a lower representation of insectivorous bird species, such as Eurasian Wrens (*Troglodytes troglodytes*) and Blue Tits (*Cyanistes caeruleus*) in both cities. Benevento and Toulouse were associated granivorous birds such as Wood pigeons *Columba palumbus,* and to omnivorous bird species such as the Eurasian magpie (*Pica pica*; Benevento) (Fig. 2). A PERMANOVA revealed significant differences in avian community composition between cities (Pseudo-F = 7.88, P = 0.0001) and the pairwise tests revealed that all cities differed from each other (all P < 0.001) confirming a lack of homogenization of avian communities across cities. SIMPER analyses showed that: the most representative species (cumulative contribution to the within city similarity up to 70%) were different among the cities, with Benevento showing the highest species diversity. The Eurasian blackcap *Sylvia atricapilla* and *Turdus merula* were among the most representative bird species in three of the cities.(Sup. Mat. 3). The streams of Oslo harboured the avian community with the highest number of unique species (n = 10), while Toulouse (n = 3) and Benevento (n = 0) presented the lowest number of unique species. Only eight bird species were shared by the five cities: *Passer domesticus*, the European Robin *Erithacus rubecula*, *S. atricapilla*, *T. merula*, the Great Tit *Parus major*, *P. pica*, *C. palumbus* and *C. caeruleus* (Sup. Mat. 4).

3.2. Relationship between environmental variables and the avian community across five cities

The DistLM identified eight environmental variables that were significantly associated with avian species' presence across cities: tree cover density (Pseudo-F = 4.45, P = 0.0001), water temperature (Pseudo-F = 3.58, P = 0.0003), small woody features (Pseudo-F = 3.26, P = 0.0004), ALAN (Pseudo-F = 2.93, P = 0.002), imperviousness (Pseudo-F = 3.13, P = 0.001), presence of orchards (Pseudo-F = 2.19, P = 0.02), presence of scrubs and shrubs (Pseudo-F = 2.18, P = 0.02) and population density (Pseudo-F = 1.93, P = 0.04; Sup. Mat. 5). When illustrating this in a dbRDA (Fig. 3) we can see how some of these variables are correlated with certain bird species shaping the avian communities of the 5 cities. Oslo's avian community showed the greatest compositional divergence among the five cities, mainly influenced by the higher ALAN, and tree cover density, which were positively correlated with a higher frequency of thrush species (*Turdus* sp., Fig. 3). A higher frequency of some generalist bird species such as the *P. pica* was associated with higher water temperature and low tree cover density, and lower presence of shrubs and scrubs which characterised some of

Table 2
Eigenvectors of environmental variables in the PCA used to obtain an urbanisation index (PC1) and other environmental gradients (PC2 and PC3) based on stream characteristics in the five European cities. For description of environmental variables see Table 1. In bold are the most important variables for each principal component (PC).

	PC1	PC2	PC3
	20.3%	16.6%	15.1%
ALAN	**0.497**	0.113	0.082
Population density	**0.429**	0.205	−0.148
Imperviousness	**0.425**	0.371	−0.101
Conifer_area	0.305	−0.387	0.267
Nr of habitat types	0.246	−0.154	0.068
Nitrates	0.175	0.139	**−0.397**
Tree cover density	0.088	**−0.419**	0.335
TOC	0.077	0.287	**0.454**
Phosphates	−0.068	0.313	**0.398**
Small woody features	−0.071	0.213	−0.040
Ammonium	−0.100	0.367	**0.466**
Bank artificialization	−0.148	−0.114	0.093
Water T	−0.385	0.257	−0.149

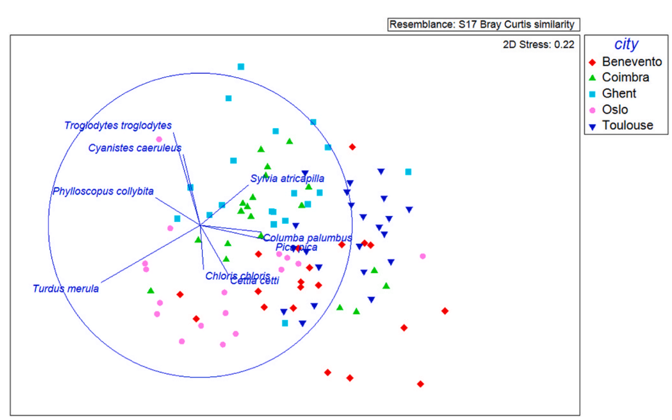

Fig. 2. Non-metric Multidimensional scaling (nMDS) ordination based on the riparian avian communities of 102 sites from 5 European cities (Coimbra, Toulouse, Benevento, Ghent and Oslo) based on presence/absence data (Bray-Curtis dissimilarity). Avian species represented by the vectors correspond to a Pearson correlation >0.3 with the ordination space.

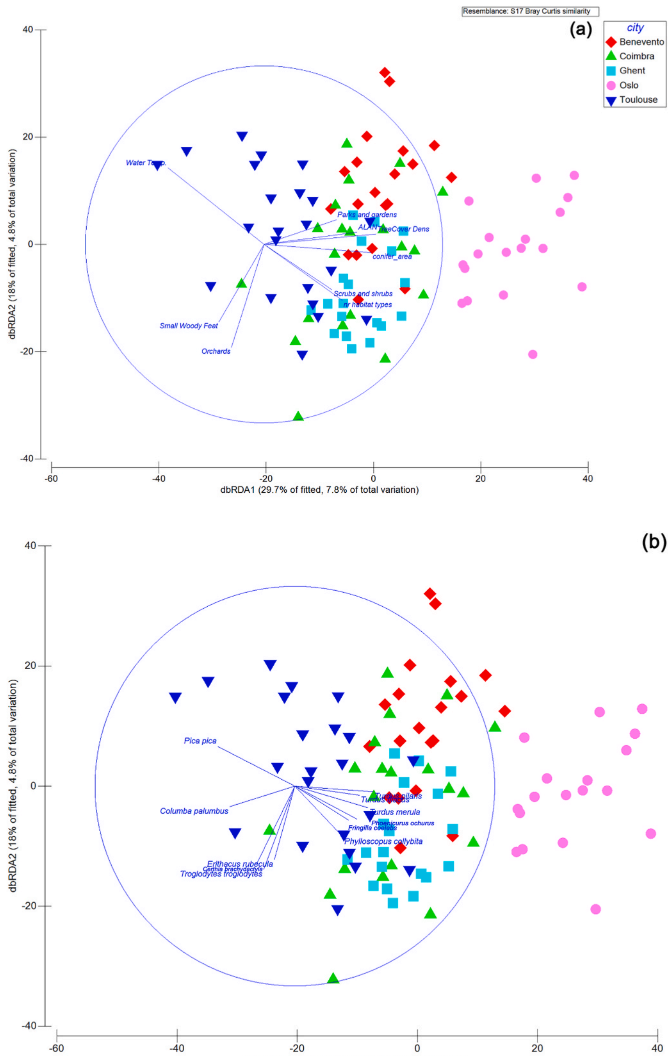

Fig. 3. Distance-based Redundancy Analysis (dbRDA) indicating as vectors the environmental variables correlated with the avian community distribution patterns of the stream sites across the five European cities (a) and the species that were most correlated with the communities' compositional patterns (b); vectors with Pearson$|r|>0.30$).

Toulouse sampling sites (Fig. 3). Small woody features and orchards, present at relatively high frequency in some of Ghent, Toulouse and Coimbra sites were associated with the presence of some species of insectivorous birds such as *T. troglodytes* and the Short-Toed Tree creeper *Certhia brachydactyla*. When relating the environmental variables with avian communities within each city through DistLMs and dbRDA, we observed that the insectivorous *P. major* was absent from the most urbanised streams (closer to areas with higher imperviousness) in Toulouse, and in Oslo (when there were more urban and suburban infrastructures (Fig. 4, Sup. Mat. 6). In Ghent, in areas with higher population density and water temperature, the insectivorous *C. caeruleus* was also absent. In Coimbra, the ubiquitous *E. rubecula*, that mainly feeds on insects but also other food items, was absent from the areas with more urban and suburban infrastructures, in contrast with the granivorous *P. domesticus* (Fig. 4, Sup. Mat. 6) which was widespread, including in these areas with urban and suburban infrastructures. Other non-insectivorous but also specialized-diet bird species like the Common Kingfisher (*Alcedo atthis*) were absent from the most impacted streams of Benevento (with higher population density), but present in those with higher tree cover density (Fig. 4, Sup. Mat. 6).

The PCA based on the environmental variables of the streams in the five cities resulted in three factors (environmental gradients) that explained a cumulative percentage of variation of 47.4% (Table 2). PC1 represented mostly variables associated with urbanisation, being positively correlated with population density, imperviousness, and ALAN and was used as a composite urbanisation index. PC2 was negatively associated with total tree cover density. PC3 reflected chemical and physical properties of stream water, being positively associated with ammonia, phosphates, TOC, and negatively correlated with nitrates. There was a significant negative effect of PC1 scores on the number of insectivorous bird species (estimate $= -0.13 \pm 0.05$; $\chi2 = 7.65$, $P = 0.006$). Neither the number of granivorous nor that of omnivorous bird species was affected by the urbanisation index (all $P > 0.05$). There was a significant interaction between PC1 and PC2 affecting the probability of scavenger/vertebrate/fish eaters presence (estimate PC1*PC2 $= -0.43 \pm 0.19$; $\chi2 = 6.79$, $P = 0.009$), with the probability being the highest for simultaneously high values of PC1 and low values of PC2. This means that this group of birds was most likely to be present when ALAN, imperviousness and population density were high, and the tree cover was simultaneously high. These relationships confirm some of the trends suggested by the DistLM when relating environmental variables with bird species. Namely, the negative association of the insectivorous great tits and blue tits with high imperviousness and population density in Ghent and Toulouse, respectively, and the positive association of tree cover with the specialized fish-eater Common Kingfisher in Benevento.

4. Discussion

We evaluated avian communities' composition in stream ecosystems differing in their degree of urbanisation in five European cities. Our study was the first to focus on urban stream ecosystems over such a large spatial scale and latitudinal gradient. The species composition of the avian communities differed between the five study cities, which is to be expected given their large geographical distance, and we also showed that there was not a full homogenization of bird species in European riparian zone, because the most representative species were different among the cities. But a common trend of more urbanised streams showing an overall reduced number of insectivorous bird species, suggesting lower availability of insect prey, was found. As a result, the loss of insectivorous birds in highly impervious, densely populated areas may diminish natural control of mosquito disease vectors, such as invasive *Aedes* species now expanding across Europe, potentially increasing public health risks.

There was an overall decrease in the number of insectivorous avian species with increased urbanisation around urban streams (i.e., integrated in a composite index (PC) associated with imperviousness, ALAN, and population density), and when the tree cover density decreased. Urbanisation has been consistently shown to reduce avian biodiversity in riparian habitats (Green and Baker, 2003; Banville et al., 2017). In North America, the avian species richness of permanent resident, winter resident, and neotropical guilds in streams in metropolitan Phoenix (Arizona) was negatively related to housing density, road density, and volume of exotic woody species (Green and Baker, 2003). These same avian guilds were positively correlated with the size of the riparian area, stream channel density, and total volume of woody species (Green and Baker, 2003). This is because heavily urbanised areas alter vegetation structure, introduce artificial features, and modify habitat quality, food availability, predation pressures, and disease dynamics (Bernat-Ponce et al., 2018; Marzluff, 2001). Studies from North America reinforce these trends. Rottenborn (1999) surveyed bird communities in riparian woodlands along a gradient of urbanisation in California, USA, and found that both the bird species richness and density decreased as the number of bridges (i.e., artificial structures) increased near that location, and as the volume of native vegetation decreased. When the distance to the nearest building and the width of the riparian habitat increased, the avian species richness also increased. This is in accordance with the results we obtained in relation to imperviousness being

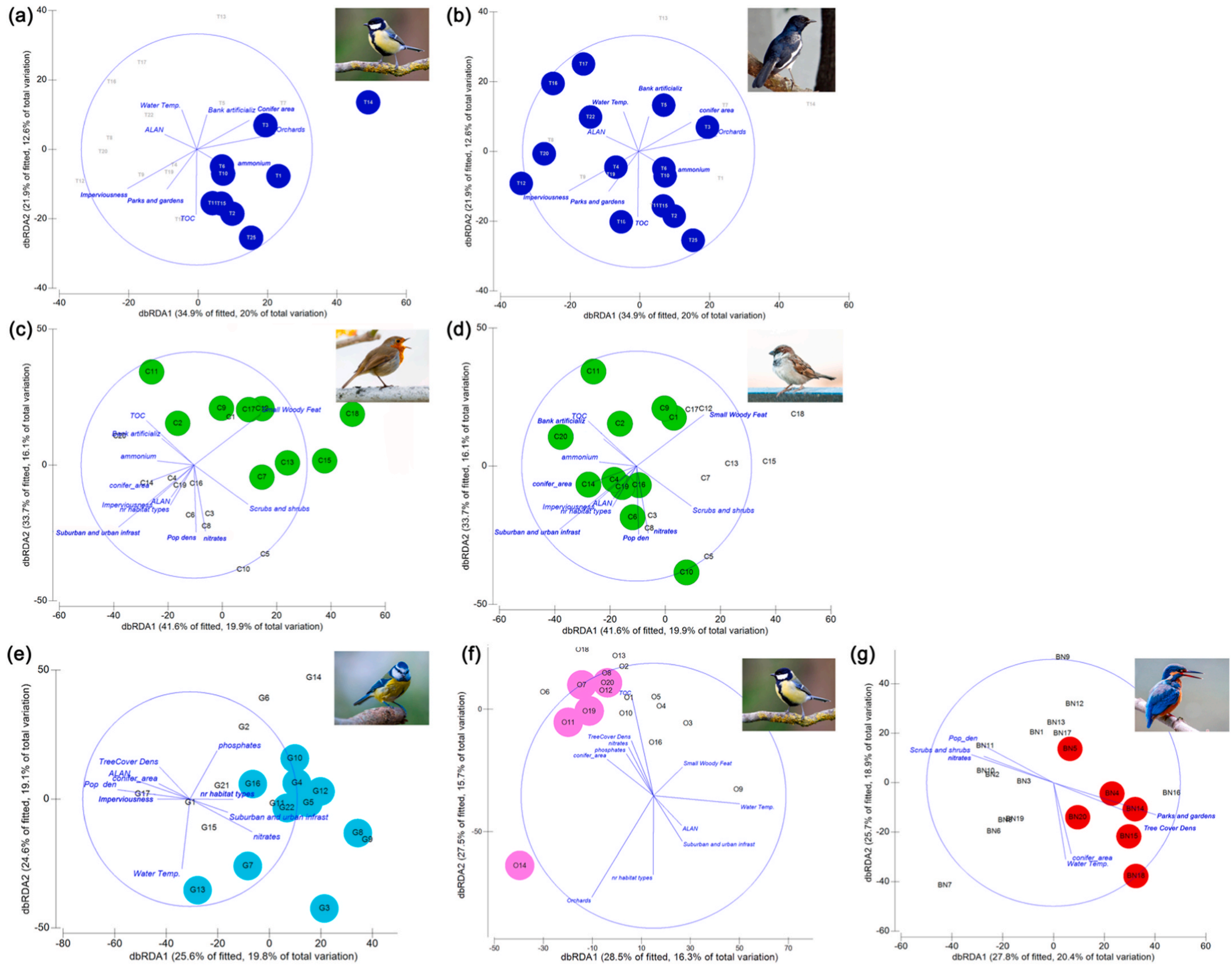

Fig. 4. Distance-based Redundancy Analysis (dbRDA) on how environmental variables of streams in each of the five European cities were related with their avian communities, in particular the presence of insectivorous bird species like: (a) the Great Tit *Parus major* in Toulouse and Oslo (f), the Blue Tit *Cyanistes caeruleus* in Ghent (e); the European Robin (*Erithacus rubecula*) in Coimbra (c); the specialist Common Kingfisher *Alcedo atthis* in Benevento (g), and the generalists Eurasian Magpie *Pica pica* in Toulouse (b) and House Sparrow *Passer domesticus* in Coimbra (d). Stream sampling sites per city where these species were detected are represented with colored circles. Environmental variables significantly correlated with the presence of avian species in each city are represented by underlined eigenvectors. Only vectors with $|r|>0.30$ are shown. Photos from Pixabay (Pixabay.com).

an important variable affecting the avian communities in our study. Long-term studies also show persistent declines in avian biodiversity with increasing urbanisation: over 12 years, in Phoenix (Banville et al., 2017), even common species decreased, and in Shanghai, loss of water bodies was a key driver of biodiversity loss (Xu et al., 2018). However, some evidence suggests that large, heterogeneous cities can support a high avian species richness up to an urbanisation threshold. Bryce et al. (2002) showed that avian communities' richness around streams declined at highly disturbed sites, but increased at moderately disturbed sites, being comparatively lower in dense and close canopy forests which is, consistent with the Intermediate Disturbance Hypothesis (Wilkinson, 1999).

Our findings indicate that artificial light at night alters avian community composition by disproportionately reducing the presence of specialized, and presumably more sensitive, guilds like insectivorous bird species. Artificial light in cities provides an extended photoperiod, which is probably advantageous to some urban dwellers, especially during days with fewer hours of light (Ciach and Fröhlich, 2017). However, while *T. merula*, a typical European urban dweller, in artificially lit areas began their breeding season earlier, initiated laying sooner, and showed shifts in reproductive timing compared to those in darker environments, no improved reproductive success was observed, and it may even inhibit reproductive activity (Dominoni et al., 2013). These authors demonstrated that artificial light at night disrupts natural breeding cycles in *T. merula*, which highlights ALAN as a significant ecological pressure capable of modifying avian life-history traits.

As discussed above, there is a relatively consistent trend found across studies that urbanisation is negatively correlated with avian species richness (Callaghan et al., 2021). However, there may be positive effects of urbanisation on the overall abundance of birds, but driven by only a few bird species. In these cases, even if bird communities in urban areas are of greater biomass, they tend to show decreased evenness, being dominated by a few, very abundant, and often non-native species (Marzluff, 2001). In our study we found no evidence of a full homogenization of bird species in European riparian zones as the species that composed most of the avian communities within each city differed across them. Keten et al. (2020) found a higher abundance of birds in more urbanised areas in an urban riparian corridor in Düzce, Turkey.

However, in their study, the most commonly found species near the city center was *P. domesticus* - a generalist species, highly adapted to human-impacted landscapes. In contrast, native bird species, especially woodland birds, were adversely affected by the deterioration of riparian quality due to lack of vegetation, structured channelling, and high human population density in the most urbanised areas. Therefore, in urban areas, generalist species are expected to increase, while specialist species will show reduced occurrences (Banville et al., 2017; Devictor et al., 2007). Generalist bird species may benefit from predictable anthropogenic food subsidies in urban areas (PAFS; Oro et al., 2013), while specialist species are negatively affected. We also observed that higher water temperature and a lower presence of scrubs and shrubs were related to a higher frequency of generalist species like *Pica pica*. Generally, in our study, the presence of orchards, scrubs and shrubs and the area of small woody features promoted the presence of insectivorous, more specialist birds (like *T. troglodytes*, and the Common Chiffchaff *Phylloscopus collybita*). Likewise, in Oslo, the higher the frequency of occurrence of suburban and urban infrastructures and ALAN, the lower the presence of insectivorous *P. major*. The same trend was found in Toulouse, as a higher imperviousness was related to a lower frequency of this species in the streams. In Ghent, a higher water temperature was negatively related to the presence of the insectivorous *C. caeruleus*. This is in agreement with what (Neves et al., 2025) reported for North Portuguese rivers, as the abundances of insectivorous and tree foragers' were predicted to decrease with gradients reflecting anthropogenic land use such as farmlands, and increase with natural land use (e.g., deciduous riparian forests, pine and oakwood), in contrast with the abundances of farmland, ground-feeding and granivores birds (Neves et al., 2025). Bird surveys in Central Eastern Europe cities (Hungary and Romania), and in China, have also found that insectivorous birds declined in urban parks comparatively with peri-urban reference sites (Lakatos et al., 2025), and in more fragmented patches within a city (Wu et al., 2024).

Insectivores were suggested to be more affected by variation in local-scale variables, than shrubland species which were shown to be more sensitive to the landscape context (Oneal and Rotenberry, 2009). This is consistent with our findings that small woody features (hedgerows and patches of bushes and trees) benefited the presence of insectivorous birds like *C. brachydactyla* and *T. troglodytes*. Hedgerows have been reported to provide important ecosystem services and to be key for maintaining biodiversity in several habitats, mostly agricultural, but also urban (Castro-Caro et al., 2015; Montgomery et al., 2020). This is because hedgerows and other boundaries constitute a connectivity network in the landscape and provide a major habitat resource for birds (Hinsley and Bellamy, 2019).

Because the changes in community composition with urbanisation observed in our study were mainly due to a decrease in the number of insectivorous bird species, this suggests that more urbanised areas probably have a lower number of prey, in particular insects. Overall, insectivorous birds have been reported to be decreasing in Europe, particularly due to a decrease in insect populations due to agricultural intensification and loss of grassland habitat (Bowler et al., 2019). This is the first such report for urban streams, at such a large geographical scale, and with such a thorough environmental characterization. In urban streams, while a lower diversity of insects often results from more degraded aquatic environments, usually the total abundance of this group is compensated by a higher abundance of tolerant taxa such as those of the Diptera order (Serra et al., 2017, 2019). Recently, a study showed the presence of a high number of Diptera disease vectors in the riparian zones of the urban streams of the same European cities studied here (Feio et al. submitted). The ecological function of biological control of potential disease vectors of insectivorous birds, such as that of mosquitoes (Poulin et al., 2010), seems to be prevented in the most impervious areas and with higher population density, potentially putting a higher number of people at risk from infection by Diptera-transmitted diseases. Indeed, mosquitoes of the family Culicidae, including invasive species such as those of the genus *Aedes,* which are vectors of diseases such as Dengue and Chikungunya, are expanding their distribution throughout Europe (Pabst et al., 2025). The Dengue mosquito *Aedes aegypti* was recently detected near Coimbra (https://cm-condeixa.pt/noticia/3746/, accessed 24/10/2025), while *Aedes albopictus,* the Asian tiger mosquito, was detected by our team in the riparian zones of urban streams in Toulouse and Benevento (https://www.ecdc.europa.eu/accessed 24/10/2025; Feio et al. submitted; Roques et al., 2023).

Our findings highlighted that the maintenance of stream ecosystem quality within cities, including habitat diversity and a good riparian vegetation, is important to increase avian biodiversity and the presence of insectivorous birds and to promote One Health. For that, cities' landscape planning should focus on maintaining permeable soils around streams and prevent the construction of grey infrastructure in the riparian zones. In addition, it is important to promote diversified riparian vegetation that provides habitats to bird species from different trophic groups, and especially insectivorous ones. Maintaining native plant species was also indicated by other authors as relevant for bird foraging and breeding (e.g., Dale, 2018; Narango et al., 2017, 2018; Wu et al., 2024). Furthermore, ecological corridors between these important patches should be guaranteed to ensure habitat connectivity.

In future studies, the study of species interactions (e.g., pollination, seed dispersal, parasitism) using an ecological network approach along gradients of urbanisation would be important to further understand ecosystem functioning and resilience (Cruz et al., 2013; Rigacci et al., 2021) in urban areas, and contribute to defining more adequate management approaches (Memmott, 2009). The use of a bioindicator avian species dependent on streams, with a large distributional range and relatively abundant, and the evaluation of their exposure to contaminants and other stressors (Maznikova et al., 2024), paired with their physiological health, would also help to understand urban stream quality and biological integrity.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Ana C. Norte reports financial support was provided by European Union. Maria Joao Feio reports financial support was provided by European Union. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix ASupplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2026.130415.

Data availability

Data is available as Suplementary Material.

References

Anderson, M., Gorley, R.N., Clarke, K., 2008. PERMANOVA+ for Primer: Guide to Software and Statistical Methods. PRIMER-E, Plymouth.
Aronson, M.F.J., La Sorte, F.A., Nilon, C.H., Katti, M., Goddard, M.A., Lepczyk, C.A., Warren, P.S., Williams, N.S.G., Cilliers, S., Clarkson, B., Dobbs, C., Dolan, R., Hedblom, M., Klotz, S., Kooijmans, J.L., Kühn, I., MacGregor-Fors, I., McDonnell, M., Mörtberg, U., Pyšek, P., Siebert, S., Sushinsky, J., Werner, P., Winter, M., 2014. A global analysis of the impacts of urbanization on bird and plant diversity reveals key anthropogenic drivers. Proc. Royal Soc. B. 281, 20133330.
Banville, M.J., Bateman, H.L., Earl, S.R., Warren, P.S., 2017. Decadal declines in bird abundance and diversity in urban riparian zones. Landsc. Urban Plann. 159, 48–61.
Baston, D., 2024. Exactextractr: fast extraction from raster datasets using polygons. R package version 0.10.0.
Bernat-Ponce, E., Gil-Delgado, J.A., Guijarro, D., 2018. Factors affecting the abundance of house sparrows *Passer domesticus* in urban areas of southeast of Spain. Bird Study 65, 404–416.
Boets, P., Dillen, A., Mertens, J., Vervaeke, B., Van Thuyne, G., Breine, J., Goethals, P., Poelman, E., 2021. Do investments in water quality and habitat restoration programs pay off? An analysis of the chemical and biological water quality of a lowland stream in the zwalm river basin (Belgium). Environ. Sci. Policy 124, 115–124.
Bowler, D.E., Heldbjerg, H., Fox, A.D., de Jong, M., Bohning-Gaese, K., 2019. Long-term declines of European insectivorous bird populations and potential causes., 2019. Conserv. Biol. 33, 1120–1130. https://doi.org/10.1111/cobi.13307.
Bryce, S.A., Hughes, R.M., Kaufmann, P.R., 2002. Development of a bird integrity index: using bird assemblages as indicators of riparian condition. Environ. Managem. 30, 294–310.
Callaghan, C.T., Poore, A.G.B., Major, R.E., Cornwell, W.K., Wilshire, J.H., Lyons, M.B., 2021. How to build a biodiverse city: environmental determinants of bird diversity within and among 1581 cities. Biodivers. Conserv. 30, 217–234.
Campos, C.O., Almeida, S.F.P., Serra, S.R.Q., Calapez, A.R., Silveira, P., Feio, M.J., 2024. The overlooked margins: how cities impact diversity of plants and terrestrial invertebrates along urban streams. Urban Ecosyst. 27, 1751–1766.
Castro-Caro, J.C., Barrio, I.C., Tortosa, F.S., 2015. Effects of hedges and herbaceous cover on passerine communities in Mediterranean olive groves. Acta Ornithol 50, 180–192, 113.
Chen, A., Feio, M., Schmitt, R., Martins, M., Rodrigues, F., Calapez, A., Durães, L., Pereira, A., Silva, L., Freitas, A., Almeida, S., 2026. Effects of pharmaceuticals and other contaminants on the structure and health of diatom communities of urban streams. J Environm Sci. https://doi.org/10.1016/j.jes.2026.01.065.
Ciach, M., Fröhlich, A., 2017. Habitat type, food resources, noise and light pollution explain the species composition, abundance and stability of a winter bird assemblage in an urban environment. Urban Ecosyst. 20, 547–559.
Cramp, S., Simmons, K.E.L., 1977. The Birds of the Western Palearctic. Oxford University Press, Oxford.
Cruz, J.C., Ramos, J.A., da Silva, L.P., Tenreiro, P.Q., Heleno, R.H., 2013. Seed dispersal networks in an urban novel ecosystem. Euro. J. For. Res. 132, 887–897.
Dale, S., 2018. Urban bird community composition influenced by size of urban green spaces, presence of native forest, and urbanization. Urban Ecosyst. 21, 1–14. https://doi.org/10.1007/s11252-017-0706-x.
De Silva, H.G., Medellín, R.A., 2002. Are land bird assemblages functionally saturated? An empirical test in Mexico. Oikos 96, 169–181.
Devictor, V., Julliard, R., Denis, C., Lee, A., Jiguet, F., 2007. Functional homogenization effect of urbanization on bird communities. Cons. Biol. 21, 741–751.
Dominoni, D.M., Goymann, W., Helm, B., Partecke, J., 2013. Urban-like night illumination reduces melatonin release in European blackbirds (*turdus Merula*): implications of city life for biological time-keeping of songbirds. Front. Zool. 10, 60.
Dudgeon, D., Arthington, A.H., Gessner, M.O., Kawabata, Z.-I., Knowler, D.J., Lévêque, C., Naiman, R.J., Prieur-Richard, A.-H., Soto, D., Stiassny, M.L.J., Sullivan, C.A., 2005. Freshwater biodiversity: importance, threats, status and conservation challenges. Biol. Rev. 81, 163–182.
EEA, 2020a. Imperviousness Density 2018. European Environmental Agency.
EEA, 2020b. Tree Cover Density 2018. European Environmental Agency.
Eea, c., 2020c. Dominant Leaf Type Change 2015-2018.
Eurostat, 2023. Population statistics. Statistical office of the european union. https://ec.europa.eu/eurostat/web/gisco/geodata/statistical-units/local-administrative-units.
Forio, M.A., De Troyer, N., Lock, K., Witing, F., Baert, L., Saeyer, N.D., Rîşnoveanu, G., Popescu, C., Burdon, F.J., Kupilas, B., Friberg, N., Boets, P., Volk, M., McKie, B.G., Goethals, P., 2020. Small patches of riparian woody vegetation enhance biodiversity of invertebrates. Water 12, 3070.
Garcia, K., Olimpi, E.M., Karp, D.S., Gonthier, D.J., 2020. The good, the bad, and the risky: can birds be incorporated as biological control agents into integrated Pest management programs? J. Integr. Pest Managem. 11, 11.
Goodman, B., Lima, K., Benz, S., Fisichelli, N., Kitzes, J., 2025. Humans outperform merlin sound ID in field-based point-count surveys. Ornithol. Appl. 127. https://doi.org/10.1093/ornithapp/duaf049.
Green, D.M., Baker, M.G., 2003. Urbanization impacts on habitat and bird communities in a sonoran desert ecosystem. Landsc. Urban Plann. 63, 225–239.
Hennings, L.A., Edge, W.D., 2003. Riparian bird community structure in Portland, Oregon: Habitat, urbanization, and spatial scale patterns. Condor 105, 288–302.
Hinsley, S.A., Bellamy, P.E., 2019. Birds of hedgerows and other field boundaries. In: Dover, J.W. (Ed.), The Ecology of Hedgerows and Field Margins. Routledge, London.
Ibáñez-Álamo, J.D., Rubio, E., Benedetti, Y., Morelli, F., 2017. Global loss of Avian evolutionary uniqueness in urban areas. Glob. Chang. Biol. 23, 2990–2998.
Isaksson, C., 2018. Impact of urbanization on birds. Bird species 235, 257.
Johnson, M.T.J., Munshi-South, J., 2017. Evolution of life in urban environments. Science 358, e8327.
Keten, A., Eroglu, E., Kaya, S., Anderson, J.T., 2020. Bird diversity along a riparian corridor in a moderate urban landscape. Ecol. Indic. 118, 106751.
Kissling, W.D., Sekercioglu, C.H., Jetz, W., 2012. Bird dietary guild richness across latitudes, environments and biogeographic regions. Global Ecol. Biogeogr. 21, 328–340.
Knopf, F.L., Samson, F.B., 1994. Scale perspectives on Avian diversity in Western riparian ecosystems. Conserv. Biol. 8, 669–676.
Lakatos, T., Báldi, A., Gallé, R., Korányi, D., Kovács, I., László, Z., Papp, E., Purger, J.J., Sándor, K., Seress, G., Szitár, K., Török, E., Urák, I., Batáry, P., 2025. Functional trait filtering and decline in species richness in urban parks hinder ground-breeding and insectivorous birds. Urban For. Urban Green. 112, 128988. https://doi.org/10.1016/j.ufug.2025.128988.
Lourenço, R., Pereira, P.F., Oliveira, A., Ribeiro-Silva, J., Figueiredo, D., Rabaça, J.E., Mira, A., Marques, J.T., 2021. Effect of vineyard characteristics on the functional diversity of insectivorous birds as indicator of potential biocontrol services. Ecol. Indic. 122, 107251.
Mansfield, I., Reynolds, S.J., Lynch, I., Matthews, T.J., Sadler, J.P., 2024. Birds as bioindicators of plastic pollution in terrestrial and freshwater environments: a 30-year review. Environm. Pol. 348, 123790.
Marzluff, J.M., 2001. Worldwide urbanization and its effects on birds. In: Marzluff, J.M., Bowman, R., Donnelly, R. (Eds.), Avian Ecology and Conservation in an Urbanizing World. Springer, US, Boston, MA, pp. 19–47.
Maznikova, V.N., Ormerod, S.J., Gómez-Serrano, M.Á., 2024. Birds as bioindicators of river pollution and beyond: specific and general lessons from an apex predator. Ecol. Indic. 158, 111366.
Memmott, J., 2009. Food webs: a ladder for picking strawberries or a practical tool for practical problems? Phil. Trans. Roy. Soc. Lond. B 364, 1693–1699.
Montgomery, I., Caruso, T., Reid, N., 2020. Hedgerows as ecosystems: service delivery, management, and restoration. Annu. Rev. Ecol. Evol. Syst. 51, 81–102.
Morelli, F., Benedetti, Y., Ibáñez-Álamo, J.D., Tryjanowski, P., Jokimäki, J., Kaisanlahti-Jokimäki, M.-L., Suhonen, J., Díaz, M., Møller, A.P., Moravec, D., Prosek, J., Bussière, R., Mägi, M., Kominos, T., Galanaki, A., Bukas, N., Marko, G., Pruscini, F., Tonelli, M., Jerzak, L., Ciebiera, O., Reif, J., 2021. Effects of urbanization on taxonomic, functional and phylogenetic avian diversity in Europe. Sci. Total Environ. 795, 148874.
Narango, D., Tallamy, D., Marra, P., 2017. Native plants improve breeding and foraging habitat for an insectivorous bird. Biol. Conserv. 213. https://doi.org/10.1016/j.biocon.2017.06.029.
Narango, D., Tallamy, D., Marra, P., 2018. Nonnative plants reduce population growth of an insectivorous bird. Proc Nat Acad Sci 115, 201809259. https://doi.org/10.1073/pnas.1809259115.
Neate-Clegg, M.H.C., Tonelli, B.A., Youngflesh, C., Wu, J.X., Montgomery, G.A., Şekercioğlu, Ç.H., Tingley, M.W., 2023. Traits shaping urban tolerance in birds differ around the world. Cur. Biol. 33, 1677–1688.e1676.
Neves, J., Reino, L., Faria, J., Santana, J., 2025. Seasonal and spatial patterns of bird communities in a highly disturbed Atlantic riparian corridor. Forests 16, 641.
Norte, A.C., Araújo, P.M., Costantini, D., 2022. A physiological toolbox to explore the relationships between seabirds and their changing environments. In: Ramos, J.A., Pereira, L. (Eds.), Seabird Biodiversity and Human Activities. CRC Press, Boca Raton.
Oneal, A.S., Rotenberry, J.T., 2009. Scale-dependent habitat relations of birds in riparian corridors in an urbanizing landscape. Landsc. Urban Plann. 92, 264–275.
Oro, D., Genovart, M., Tavecchia, G., Fowler, M.S., Martínez-Abraín, A., 2013. Ecological and evolutionary implications of food subsidies from humans. Ecol. Let. 16, 1501–1514.
Pabst, R., Sousa, C.A., Essl, F., García-Rodríguez, A., Liu, D., Lenzner, B., Schertler, A., Zêzere, J.L., Capinha, C., 2025. Global invasion patterns and dynamics of disease vector mosquitoes. Nat. Com 16, 9127.
Palmer, G.C., Bennett, A.F., 2006. Riparian zones provide for distinct bird assemblages in forest mosaics of south-east Australia. Biol. Conserv. 130, 447–457.

Peña, E.d.l., Muriel, J., Gil, D., Pérez-Rodríguez, L., 2024. Parasite shedding is highly influenced by age, time of day, and sampling date in spotless starling *Sturnus unicolor* nestlings. ARDEOLA 71, 307–320, 314.
Pejchar, L., Rega-Brodsky, C.C., Vázquez, L.-B., MacGregor-Fors, I., 2025. Bird-mediated ecosystem services and disservices in cities and towns. Front. Ecol. Environ. 23, e2835.
Poulin, B., Lefebvre, G., Paz, L., 2010. Red flag for green spray: adverse trophic effects of bti on breeding birds. J. Appl. Ecol. 47, 884–889.
Ranta, E., Vidal-Abarca, M.R., Calapez, A.R., Feio, M.J., 2021. Urban stream assessment system (UsAs): an integrative tool to assess biodiversity, ecosystem functions and services. Ecol. Indic. 121, 106980.
Rigacci, E.D.B., Paes, N.D., Félix, G.M., Silva, W.R., 2021. The resilient frugivorous fauna of an urban forest fragment and its potential role in vegetation enrichment. Urban Ecosyst. 24, 943–958.
Rodrigues, F., Calapez, A., Pereira, A., Silva, L., Freitas, A., Bouchali, R., DeCock, A., Forio, M., Goethals, P., Henni, S., Loyau, A., Moen, A., Piscopo, N., Schmeller, D., da Silva, J., Durães, L., Simões, N., Feio, M., 2025. Patterns of pharmaceutical contamination in streams of European cities across urbanisation gradients: potential impacts on one health. J. Hazard. Mater. 499, 139946.
Roques, L., Boivin, T., Papaïx, J., Soubeyrand, S., Bonnefon, O., 2023. Dynamics of *Aedes albopictus* invasion insights from a spatio-temporal model. Biol. Invasions 25, 2679–2695.
Rottenborn, S.C., 1999. Predicting the impacts of urbanization on riparian bird communities. Biol. Conserv. 88, 289–299.
Sala, O.E., Stuart Chapin, F., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M.n., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science 287, 1770–1774.
Serra, S., Graça, M., Dolédec, S., Feio, M., 2017. Discriminating permanent from temporary Rivers with traits of chironomid genera. Annales de Limnologie - Int. J. Limnol. 53, 161–174.
Serra, S.R.Q., Calapez, A.R., Simões, N.E., Sá Marques, J.A.A., Laranjo, M., Feio, M.J., 2019. Effects of variations in water quantity and quality in the structure and functions of invertebrates' community of a mediterranean urban stream. Urban Ecosyst. 22, 1173–1186.
Singh, S., Lalit Mohan, L.M., 2013. Biological control of mosquitoes by insectivorous flycatcher birds. J. Entomol. Res. 37, 359–364.
Sousa, M.C., Martins, R., Simões, N.E., Feio, M.J., 2024. Ecosystem services of urban Rivers: a systematic review. Aquat. Sci. 87, 10.
Sutherland, W.J., 2006. Ecological Census Techniques: a Handbook. Cambridge University press.
Wilkinson, D.M., 1999. The disturbing history of intermediate disturbance. Oikos 84 (1), 145–147. https://doi.org/10.2307/3546874.
Wilman, H., Belmaker, J., Simpson, J., de la Rosa, C., Rivadeneira, M.M., Jetz, W., 2014. EltonTraits 1.0: species-level foraging attributes of the world's birds and mammals. Ecology 95, 2027, 2027.
Wu, R., Zhang, Q., Hao, Z., Li, L., Gao, B., Li, J., Liu, X., Liao, C., Pei, N., 2024. Insectivorous birds are more sensitive to urban greenspace changes in Guangzhou city, China. Urban For. Urban Green. 94, 128243. https://doi.org/10.1016/j.ufug.2024.128243.
Xu, X., Xie, Y., Qi, K., Luo, Z., Wang, X., 2018. Detecting the response of bird communities and biodiversity to habitat loss and fragmentation due to urbanization. Sci. Total Environ. 624, 1561–1576.