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Top ten birds indicators of high environmental quality in European cities

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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 and suburban areas are among the fastest-growing land-use types globally, reducing and fragmenting natural habitats for many animal species and making human-wildlife interactions more common. However, cities also create habitat for several species considered urban tolerant or urban exploiter species. Additionally, the environmental characteristics of urban areas can strongly affect the life quality of citizens. This study aimed to assess the effectiveness of common bird species as indicators of urban areas with high environmental quality within cities. Our study recorded 128 bird species in 1441 point counts distributed in fifteen different European cities. We classified urban areas as "high environmental quality" – HEQ when they were simultaneously characterized by a high vegetation cover and heterogeneity, low level of light pollution, and avian communities with high potential resilience to face ecological stress. Species indicators of HEQ urban areas were identified using the species-level indicator value (IndVal) analysis. Such species can be used as ecological indicators of HEQ in different European cities. The list of top ten birds indicators of HEQ in European cities is led by the Eurasian blackcap, selected as an indicator in more than half of the survey cities. Other birds indicators of HEQ in multiple cities are Blackbird (47%), Great tit (40%), Blue tit, Tree sparrow and Magpie (all 33%). The mean specificity of the top-ranked bird indicator of HEQ urban areas (Eurasian blackcap) was 0.778. Most of the HEQ-indicators are resident or resident/short migratory species characterized by territorial behaviour. Our findings support using multiple species as bioindicators of urban changes by using specific groups with few common species as surrogates of HEQ urban areas. The approach proposed in this study can be applied in different European cities to monitor biodiversity status periodically, even involving citizen science initiatives.

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1. Introduction

Cities constitute a special laboratory for ecologists to understand the effects of fast changes at different levels of biodiversity (Alberti, 2015; Morelli et al., 2021; Wilson et al., 2016). Cities and surrounding areas are among the fastest-growing land-use types across the globe (McDonald, 2008), increasing habitat fragmentation and reduction for several species of wildlife (Fernández-Juricic and Jokimäki, 2001; Schmiegelow and Mönkkönen, 2002). However, urban areas also attract some animal species, often defined as urban tolerant or urban exploiters (Kark et al., 2007; Palacio, 2020; Šálek et al., 2020; Tryjanowski et al., 2021), and this attraction is increasing in recent times (Møller and Díaz, 2017). Different characteristics of urban development have been identified as responsible for the presence of diverse animal and plant communities within cities (Morelli et al., 2020b; Secretariat of the Convention on Biological Diversity, 2012). Some characteristics are also coincident with traits associated with human well-being, such as greenspaces or low levels of environmental pollution (Klemm et al., 2015; Van Den Berg et al., 2015). The coincidence of traits associated with both wildlife diversity and human well-being implies that elements of this diversity, such as the presence or abundance of specific species, can be used as indicators of environmental quality (Díaz et al., 2020).

The coverage and arrangement of green areas at all levels within the cities (e.g., soil level as grass and structure level as bushes and trees) significantly increases taxonomic and phylogenetic diversity of avian communities (Ibáñez-Álamo et al., 2019; Morelli et al., 2021). Urban forests and trees can also help develop strategies for more resilient anthropized landscapes facing climate change effects (Manning et al., 2009). The same characteristics offer many ecosystem services, increasing human residents well-being (Roeland et al., 2019). On the other hand, the level of pollution (light, noise, etc.) is another critical factor driving both urban biodiversity and also human life quality (Ciach and Fröhlich, 2017; Francis et al., 2012, 2009; Hopkins et al., 2018; Ortega, 2012; Van Geffen et al., 2015). In the recent past, light pollution increased significantly to represent a severe biodiversity threat (Dominoni et al., 2016; Hölker et al., 2010; Owens et al., 2020). Research on different taxa (e.g., insects, birds, reptiles, and other wildlife species) shows that artificial light at night, also known as ALAN, can alter behaviours, foraging areas, and breeding cycles, mainly in the most densely populated urban areas (De Molenaar et al., 2006; Gaynor et al., 2018; Kempenaers et al., 2010; Klem, 2007; Longcore and Rich, 2004; Van Geffen et al., 2015). Light pollution is one of the main factors potentially affecting the bird species living in urban areas (Dominoni, 2017). Furthermore, the urban biodiversity can constitute *per se* an ecosystem service essential for the residents' well-being (Keniger et al., 2013; Ratcliffe et al., 2013; Zhang et al., 2014). In this sense, urban avian communities ecologically more resilient can guarantee a significant continuity of ecosystem functions because they are better arranged when facing ecological stresses (Folke et al., 2002; Pillar et al., 2013). The ecological resilience of the community is its capacity to absorb environmental changes without altering its main functions (Bergman, 2009; Oliver et al., 2015).

For all the reasons mentioned above, urban biodiversity conservation is recognised uniformly by planners, managers, and local authorities, especially to achieve both direct and indirect benefits to citizenship (e.g., provision of ecosystem services) (Sattler et al., 2014). At the same time, the conservation and improvement of eco-friendly cities often require complex strategies and tools for urban planning (Gill et al., 2007; Pickett et al., 2013).

Using species as bioindicators constitutes a cost-effective strategy in ecological planning because it can help save a considerable number of resources, especially when the ecological process focused is costly or difficult to assess directly (Pérez-Garcia et al., 2016). Several studies focused on using bird species as indicators of process or ecological characteristics in different types of environments (Drever et al., 2008; Eglington et al., 2012; Morelli, 2015). The history of birds used as ecological indicators is long. The reasons why birds have been proposed as bioindicators are many and well documented: birds are easily detectable, present in all types of environments, and their occurrence is associated with specific characteristics of the ecosystem (Fleishman et al., 2005; Fraixedas et al., 2020; Morelli, 2015; Padoa-Schioppa et al., 2006). In the specific, birds were used as a surrogate of different characteristics of cities and urban sprawl, as, for example, the household density (Tratalos et al., 2007). The diversity of urban birds within a city was suggested as a potential surrogate of human social diversity and economic disparity among citizens (Melles, 2005). Additionally, urban bird populations were proposed as ecological indicators to identify and monitor factors that may pose both public and wildlife health concerns in urban areas (Pollack et al., 2017). This is because bird species are among the organisms most profoundly impacted by the urbanization process (Devictor et al., 2008; McKinney and Lockwood, 1999).

Even if there are several examples of bird species or groups of birds proposed as bioindicators in urban areas (Germaine et al., 1998; Herrando et al., 2012; Tratalos et al., 2007), a more systematic test at a large spatial scale, comparing the effectiveness of different species indicators across European cities is still missing. Moreover, identifying bioindicators with high transferability is essential to facilitate the development of survey strategies and guarantee more reliable comparisons of results among urban settlements, enhancing the management strategies for biodiversity and human well-being (Miller and Hobbs, 2002; Villaseñor et al., 2021).

In this study, we combined data on urban characteristics, which can be a good proxy of the overall environmental quality of cities for both citizens and wildlife. Specifically, we focused on the following urban features: urban green (cover and heterogeneity), level of light pollution, and the potential resilience of avian communities, since ecological resilience can guarantee ecosystem functioning. The main aim of our study was to identify common bird species suitable as ecological indicators in European cities to monitor urban areas characterized by high environmental quality. Then, we aimed to assess the efficiency of such bird-indicators at a large spatial scale through the comparison among cities and evaluating their potential transferability. Finally, we described the bird indicators in terms of life-history traits, considering if species selected are resident or migrant and characterized by territorial behaviour.

2. Methods

2.1. Study area and bird data collection

The study was performed through data collection in 15 cities along a continent-wide latitudinal gradient in 10 European countries (Fig. 1).

Standardised point count (Bibby et al., 1992; Voříšek et al., 2010) was used to collect data on bird species during the 2018 breeding season. Surveys were locally adjusted to the peak of the breeding season based on the local experts' knowledge (e.g., May in southern Spain or June in Finland) to minimise potential issues related to differences in the detectability of bird species (Kéry et al., 2005). All point counts were positioned in a gradient of urbanized areas not closer than 500 m from the city border to avoid sampling transitional suburban areas and separated by at least 150 m from the nearest point count. The expert ornithologists locally adjusted the position of point counts to match as much as possible a good balance of sampling sites through the urbanization gradient in each city. A total of 100 point counts were visited in each city, after the sunrise only during favourable weather conditions for a total of 5 min of observations. The location of each point was recorded with a GPS and mapped. Only local expert ornithologists were involved in the fieldwork to reduce detection issues due to observers' skills. All birds seen or heard within 50 m distance from the observer were recorded, except for nocturnal species that were not included in counts because they require a different strategy of surveying.

Our classification of environments as urban (proportion of built-up

Fig. 1. The fifteen European cities focused on this study. The background layer represents the artificial light at night (ALAN) for Europe. The image was produced by mosaicking Defense Meteorological Satellite Program (DMSP) Operational Linescan System (OLS) satellite images (source: ESRI, NASA - Visible Earth).

area > 50%, building density > 10/ha and residential human density > 10/ha) followed Marzluff et al. (2001), and it has been used in previous studies of urban avian ecology (Clergeau et al., 2006; Loss et al., 2009; Møller et al., 2015; Morelli et al., 2016). Around each point count, we described the vegetation cover within a distance of 50 m from the observer (Díaz et al., 2013). The total vegetation or green cover was evaluated by considering grass, bushes (including plants from gardens), and trees (isolated trees, tree lines and patches). Considering that green cover was negatively and significantly correlated with built cover (r^2 = -0.75, $p < 0.001$), we decided to use only green cover in further analyses, avoiding redundancy. Additionally, we estimated the Shannon diversity index on the proportion of three components of urban green (grass, bushes and trees) around each point count as a metric of green heterogeneity.

Light pollution values were extracted from the web https://www.lightpollutionmap.info. We used precalculated values from VIIRS satellite of the year 2018. The values extracted for each point count correspond to the Radiance 10–9 W/cm^2 * sr, where W = Watts and sr = steradian.

2.2. High environmental quality urban areas

To define high environmental quality (HEQ) urban areas, we followed a multifaceted approach 50 m around each point count, considering different characteristics that contribute to the quality of a city: 1) green coverage and heterogeneity, 2) light pollution, and 3) potential resilience of avian communities.

The potential resilience of bird assemblages was estimated by combining the species richness and redundancy of functional traits. Ecological resilience is associated with the capacity of environmental systems to resist invasions, climate or land-use changes (Haegeman et al., 2016). In species assemblages, ecological resilience is associated with a sort of functional redundancy of components of that community (Haegeman et al., 2016). The loss or gain of redundant species should not affect the overall ecosystem functions (Loreau, 2004). Combining the number of species and functional redundancy of avian communities to estimate the potential community resilience was previously proposed in a few ecological studies (Estevo et al., 2017; Morelli et al., 2020a).

The bird community at each point count was defined as the list of bird species recorded during the visit. Species richness was expressed as the number of bird species counted in each point count (Magurran, 2004). The level of functional redundancy was calculated using the functional evenness FEve index suggested by Villéger et al. (2008). FEve indicates the degree to which the species are distributed regularly in the niche space of the assemblage, which would allow effective utilisation of the entire range of resources available (Villéger et al., 2008). FEve was calculated using species body mass and feeding and breeding avian niche traits (73 traits in total) provided in Pearman (2014). The species traits include food type, food acquisition behaviour, feeding substrate, period of the day of species activity, and the primary type of habitat used (Pearman et al., 2014). All traits, with the sole exception of body mass, are scored as 0 or 1. FEve was estimated using the 'FD' package for R (Laliberté et al., 2015).

In the next step, the potential community resilience was estimated at each point count based on a discrete classification of species richness and FEve values into terciles (lower, medium and upper). This exercise was performed in each city separately by considering the intrinsic differences in the range of values related to the city identity. The potential community resilience was computed as a combination of species richness and FEve: 'Upper tercile' when species richness and FEve were both in the upper tercile, or one was in the upper and the second one was in the medium tercile. 'Lower tercile' when species richness and FEve were both in the lower tercile, or one was in the lower and the other was in the medium tercile. 'Medium tercile', in all the different combinations.

High environmental quality (HEQ) urban areas were characterized simultaneously by a high level of green coverage and green heterogeneity, low level of light pollution and high potential resilience of avian communities (Fig. S1). To perform this classification, we combined the three measures previously classified into terciles to obtain a categorical variable describing urban areas: HEQ urban areas were those with green coverage and heterogeneity being both in the medium or upper tercile, light pollution in the lower tercile and potential resilience of avian communities in the upper tercile. Non-HEQ urban areas were all other combinations (e.g., light pollution in upper or medium tercile, green coverage in lower tercile, etc.). The classification in lower, medium or upper terciles was based on the range of values recorded for each variable (green coverage, green heterogeneity, light pollution and potential resilience of avian communities). For further analyses, each point count assumed one of the two categories above described.

2.3. Statistical analyses and bird species indicators of HEQ urban areas

We used the Pearson correlation test to investigate the association between the coverage of green and built areas around the point counts. Exploration and visualisation of main environmental differences between HEQ and non-HEQ urban areas were performed using a principal components analysis (PCA), with the 'factoextra' package for R (Kassambara and Mundt, 2020).

We investigated the relationship between the occurrence of single bird species (potential indicator species) as surrogates of HEQ in urban areas. Species associated with HEQ and non-HEQ urban areas were identified using a species-level analysis, i.e., the indicator value (IndVal) analysis (De Cáceres et al., 2020). The IndVal analysis is based on two complementary parameters: "specificity", which is the conditional probability of a positive predictive value of a given species as an indicator of the target plot group and "sensitivity", which is the conditional probability that the given species will be found in a newly surveyed plot belonging to the same plot group (Dufrêne and Legendre, 1997), producing a percentage indicator value (IndVal) for each species. In this study, bird species with a value of IndVal $> 50\%$ and a p-value < 0.05 were considered indicator species for HEQ urban areas (Morelli et al., 2019). IndVal analysis was performed using the 'indicspecies' package for R (De Cáceres et al., 2020).

For all bird species selected as HEQ-indicator, we also complied information regarding their status in terms of resident, short or long migrant species, and presenting or not territorial behaviour. The data was extracted from a published dataset on life-history traits of European birds (Storchová and Hořák, 2018).

All statistical tests were performed using R software version 3.6.0 (R Development Core Team, 2021).

3. Results

A total of 128 bird species (Table S1) were recorded at 1441 point counts uniformly distributed in fifteen European cities (Table 1, Fig. 1). Overall, bird species more often recorded in the cities were House sparrow *Passer domesticus* (64%), Common swift *Apus apus* (46%), Blackbird *Turdus merula* (44%), Feral pigeon *Columba livia* (38%), Great tit *Parus major* (38%), Collared dove *Streptopelia decaocto* (36%), Wood pigeon *Columba palumbus* (35%), Magpie *Pica pica* (32%), Greenfinch *Chloris chloris* (28%), and Jackdaw *Corvus monedula* (23%) (Table S1). The average bird species richness per point count in European cities ranged from a minimum of 3.3 species in Jyväskylä (Finland) to a maximum of 12.3 species in Poitiers (France) and 11.7 species in Granada (Spain) (Table 1).

Areas classified as high environmental quality (HEQ) were distributed between a minimum of 11% of the total sites sampled (Ioannina, Greece) to a maximum of 33.7% (Groningen, Netherlands), with a mean values near 22.2% across all cities (Table 1). The exploration of the main characteristics used to identify the HEQ through a PCA, showed that the first two principal components explained nearly 60% of the total variation of the characteristics across the urban areas considered (PC1 = 40.5%, PC2 = 19.0%; Fig. 2). Based on the PCA loadings, the first dimension (PC1) was mainly associated with green cover and heterogeneity. In contrast, the second dimension (PC2) was positively related to the level of light pollution while negatively to the number of bird species (Table S2).

Bird species selected as indicators of HEQ urban areas were different for each European city (Table 2). Overall, the number of bird species selected as indicators ranged from 2 species for Budapest (Hungary) and Pesaro (Italy) to a maximum of 14 Granada (Spain) and 13 species for Zielona Góra (Poland) (Table 2). The complete list of species indicators of HEQ in each city is shown in Table S3.

The top ten birds indicators of high environmental quality in European cities are led by Eurasian blackcap *Sylvia atricapilla*, selected as an indicator in more than half of the survey cities (Table 2, Fig. 3). The other birds found as indicators of HEQ in multiple cities are Blackbird *Turdus merula* (47%), Great tit *Parus major* (40%), Blue tit *Cyanistes caeruleus*, Tree sparrow *Passer montanus* and Magpie *Pica pica* (all 33%) and Wood pigeon *Columba palumbus*, Chaffinch *Fringilla coelebs*, Redstart *Phoenicurus phoenicurus* and Starling *Sturnus vulgaris* (all 27%) (Table 2, Fig. 3). The mean specificity of the top-ranked species (Eurasian blackcap) as an indicator of HEQ urban areas was 0.778, with a min of 0.636 in Poitiers, France and a max of 1.000 in Zielona Góra, Poland (Table S3).

From the top ten birds' indicators of high environmental quality, 90% were species characterized by territorial behaviour during the breeding season (Table S1). The only species selected as HEQ-indicator characterized by not territoriality was Tree sparrow (Table S1). Finally, when considering life-history traits, most ot the species HEQ-indicators are resident (40%) or resident/short migrant (40%), with only one species classified as short-distance migrant (Wood pigeon) and one as long-distance migrant (Common redstart) (Table S1).

Table 1
List of the 15 European cities focused on this study, the number of point counts classified as high environmental quality (HEQ) and non-HEQ urban areas, and values of mean, max and min bird species richness (BSR) in each city surveyed.

City	Country	HEQ	Non-HEQ	BSR (mean)	BSR (max)	BSR (min)
Athens	Greece	25	75	9.870	19	2
Budapest	Hungay	22	78	3.680	10	0
Granada	Spain	17	82	11.687	24	3
Groningen	Netherland	34	67	6.188	13	1
Ioannina	Greece	11	89	5.900	15	0
Jyväskylä	Finland	32	71	3.291	8	1
Madrid	Spain	23	77	5.690	13	0
Pesaro	Italy	12	44	6.821	12	0
Poitiers	France	33	67	12.290	19	6
Poznan	Poland	14	86	6.510	15	2
Prague	Czechia	28	92	7.517	20	1
Tartu	Estonia	15	85	7.790	16	1
Toledo	Spain	16	84	7.160	16	2
Turku	Finland	19	83	3.863	8	1
Zielona Góra	Poland	19	41	9.117	16	3
Total		320	1121	7.103	24	0

4. Discussion

Bird species inhabiting cities are differentially responding to the effects of the urbanization process (Aronson et al., 2014; Beninde et al., 2015; Jokimäki et al., 1996; 2014; Morelli et al., 2021). Then, it is expected that some birds could be used as bio-indicators for different characteristics of urban areas. There are several criticisms for using single or multiple species as bird indicators, related to the site and species selection methods, to a bias introduced by seasonal changes in the occurrence of bird species or various statistical drawbacks (Fraixedas et al., 2020). However, the use of multi-species bird indicators still constitutes a valuable and biologically relevant tool for surveys and ecological assessment in heavily human-modified landscapes, characterized by fast and, many times, irreversible land-use changes (Caro and O'Doherty, 1999; Chiatante et al., 2021).

Here, we explored common bird species as potential indicators of high-quality areas within European cities in a large scale study. Identifying urban areas at high environmental quality is a hot topic in urban

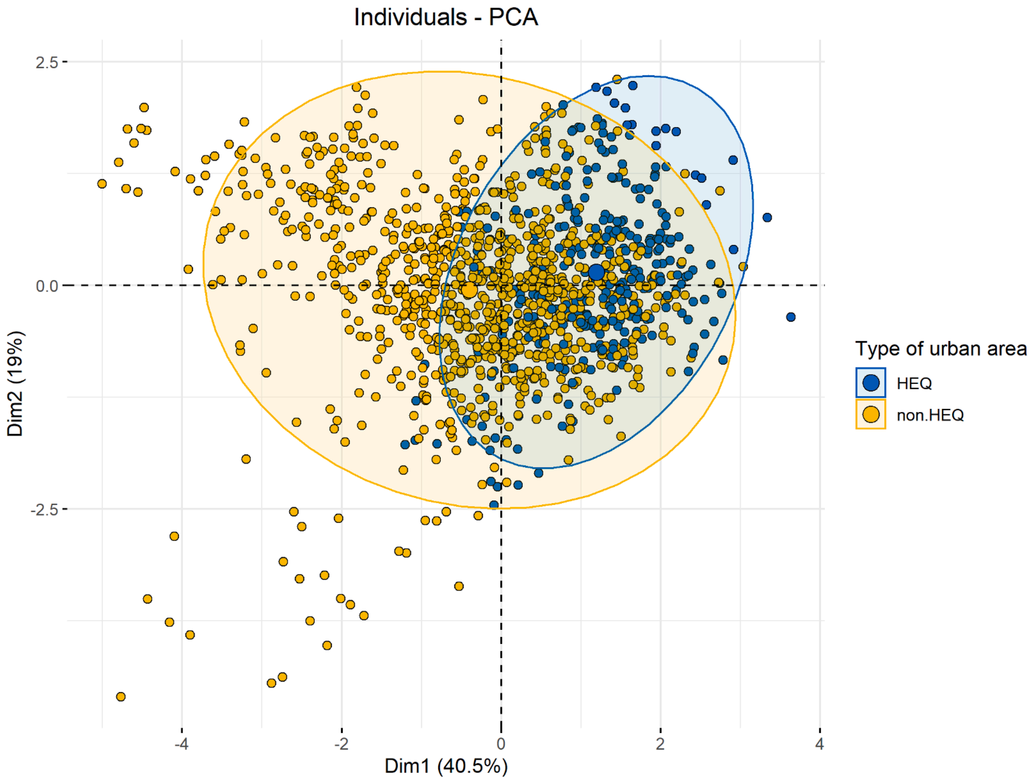

Fig. 2. PCA of sampling sites recorded in fifteen European cities focused on this study by the five environmental variables (green cover (grass, bushes and trees), green heterogeneity, light pollution, bird species richness and avian community functional redundancy) used to define the high environmental quality (HEQ) urban areas and non-HEQ urban areas. The association of each environmental variable to each dimension of the PCA is shown in Table S2. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ecology, primarily due to the current requirement to harmonise urban development and biodiversity conservation (United Nations, 2016). In this context, the possibility of taking advantage of a cost-effective tool to assess the overall environmental quality of the cities represents an excellent opportunity for landscape and urban planners.

In this study, we followed a multidimensional approach to characterize high environmental quality areas within cities. We paid attention to different components, which can improve human well-being, making cities more eco-friendly (Secretariat of the Convention on Biological Diversity, 2012). Specifically, we evaluated a) the cover and heterogeneity of vegetation around the building areas, a feature strongly linked with recreation and human health (Alcock et al., 2014; de Vries et al., 2003), but also associated with the connectivity for wildlife (Pena et al., 2017), refuge for native birds (Villaseñor et al., 2021), as well as source of many ecosystem services (Roeland et al., 2019); b) the level of light pollution as a potential factor of risk for the health of humans as well as for wildlife (Dominoni et al., 2016) and c) the potential resilience of the urban avian assemblages as an insurance of the ecosystem functioning (Morelli et al., 2020a). Based on these measures, we identified high environmental quality (HEQ) urban areas as those with large abundance and heterogeneity of greenery, relatively low light pollution and simultaneously avian communities with high potential resilience (Fig. S1).

The groups of bird species selected as indicators of HEQ urban areas in our study were different for each European city, ranging from a minimum of 2 species (Budapest, Hungary and Pesaro, Italy) to a maximum of 14 species (Granada (Spain)). However, few species were selected as HEQ-indicators in several cities, being virtually more "transferable" indicators. The Eurasian blackcap was selected as HEQ-indicator in more than half of the surveyed cities (8 cities, Fig. 3). This is a bird species with an extremely large range as a native resident and native breeding in Europe that often present a single brood per breeding season and a life span of 15 years on average (Cramp and Perrins, 1994). Eurasian blackcap breeds in many landcover types with shrubby vegetation such as woodland, farmlands and urban areas (Mason, 1995). This species also demonstrated to be a reliable indicator, considering that the component 'A' of IndVal ("specificity") was on average near to 0.8, indicating the high probability that a surveyed site is HEQ urban area given the fact that the indicator species has been found (De Cáceres et al., 2020). The performance of the species in terms of the component 'B' of IndVal ("fidelity") was lower, being near 0.53 (De Cáceres et al., 2020). This indicates that not all HEQ urban areas include the Eurasian blackcap, but if we found the species during the survey, we are in an HEQ urban area with a high probability.

Other common bird species were selected as HEQ-indicators in European cities. In the top-ten of indicator species, we can also highlight Blackbird, Great tit, Blue tit, Tree sparrow and Magpie (selected in 33–47% of the monitored cities). These species are common birds in urban areas and were present in all monitored cities, with different frequencies. Overall, the top-ten species HEQ-indicators are also well-spread species in European cities, showing a mean frequency of occurrence from 44% (Blackbird) to a minimum of 13% (Tree sparrow). The mean frequency of occurrence in European cities is another essential aspect, considering that reliable bioindicators should be not only sensitive to provide an early warning of environmental change but also being relatively widely distributed to provide a continuous assessment over a wide range of stress factors (Caro and O'Doherty, 1999; Loss et al., 2009; Noss, 1990). Then, rare or too ubiquitous species are not the best candidates as bioindicators (Caro, 2010).

The main reasons for this group of indicator species in HEQ urban areas could be determined by their specific ecological preferences. From the list of selected HEQ-indicator birds, most of the species are commonly found in natural habitats as open deciduous woodland, mixed forests and small forest patches or hedgerows (Eurasian blackcap, Blackbird, Great tit, Blue tit and Magpie) (Cramp and Perrins, 1994). So, we can associate the occurrence of such species in HEQ urban areas with small patches of urban forests, gardens densely covered by vegetation and urban parks (Morelli et al., 2018; Tryjanowski et al., 2017). Also, tree lines along the streets can offer refuge to such bird species (Ferenc et al., 2014). On the other hand, Tree sparrow is a species more

Table 2
List of bird species indicators of high environmental quality (HEQ) urban areas in fifteen European cities and the total number of indicator species selected for each city using IndVal analysis. The species selected as HEQ-indicator in each city are indicated as "1″, while species not selected are indicated as "0" in the table. In this study, only species with stat values of > 0.50 were selected at 0.05p-value. The complete outputs of IndVal analyses are shown in Table S3.

Species	Athens (Greece)	Budapest (Hungary)	Granada (Spain)	Groningen (Netherland)	Ioannina (Greece)	Jyväskylä (Finland)	Madrid (Spain)	Pesaro (Italy)	Poitiers (France)	Poznan (Poland)	Prague (Czechia)	Tartu (Estonia)	Toledo (Spain)	Turku (Finland)	Zielona Góra (Poland)
Sylvia atricapilla	0	0	1	1	1	0	0	0	1	1	1	0	1	0	1
Turdus merula	0	1	0	1	1	0	0	0	0	1	1	0	1	0	1
Parus major	0	0	1	1	1	0	0	0	0	0	0	0	1	1	1
Cyanistes caeruleus	0	0	1	1	1	0	0	0	1	0	0	0	0	0	1
Passer montanus	0	0	0	0	0	0	1	0	0	1	0	0	1	1	1
Pica pica	0	0	1	0	1	0	1	0	1	0	1	0	0	0	0
Columba palumbus	0	0	1	1	0	0	1	0	1	0	0	0	0	0	0
Fringilla coelebs	1	0	1	1	0	0	0	0	1	0	0	0	0	0	0
Phoenicurus phoenicurus	0	0	0	0	0	0	0	1	1	0	1	0	0	1	0
Sturnus vulgaris	0	0	0	0	0	0	0	0	1	0	1	1	0	0	1
Delichon urbicum	0	0	1	0	1	0	0	0	0	0	0	0	1	0	0
Luscinia megarhynchos	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0
Phylloscopus collybita	0	0	0	1	0	0	0	0	0	0	1	0	0	0	1
Chloris chloris	0	0	1	0	0	0	0	0	1	0	0	0	0	0	0
Corvus corone	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1
Erithacus rubecula	1	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Ficedula hypoleuca	0	0	0	0	0	1	0	0	0	0	0	1	0	0	0
Motacilla alba	0	0	1	0	0	0	0	1	0	0	0	0	0	0	0
Phylloscopus trochilus	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1
Serinus serinus	0	0	0	0	0	0	1	0	0	0	0	0	1	0	0
Streptopelia decaocto	0	1	0	0	0	0	0	0	0	0	1	0	0	0	0
Sylvia curruca	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
Troglodytes troglodytes	0	0	0	1	0	0	0	0	1	0	0	0	0	0	0
Turdus pilaris	0	0	0	0	0	1	0	0	0	0	0	0	0	1	0
Anas platyrhynchos	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Carduelis carduelis	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Columba oenas	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Corvus monedula	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Cuculus canorus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Dendrocopos major	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Falco tinnunculus	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Garrulus glandarius	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Hippolais pallida	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0

(*continued on next page*)

Table 2 (*continued*)

Species	Athens (Greece)	Budapest (Hungary)	Granada (Spain)	Groningen (Netherland)	Ioannina (Greece)	Jyväskylä (Finland)	Madrid (Spain)	Pesaro (Italy)	Poitiers (France)	Poznan (Poland)	Prague (Czechia)	Tartu (Estonia)	Toledo (Spain)	Turku (Finland)	Zielona Góra (Poland)
Hirundo daurica	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Hirundo rustica	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
Muscicapa striata	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Myiopsitta monachus	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Passer domesticus	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Phoenicurus ochruros	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Prunella modularis	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Regulus ignicapilla	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0
Streptopelia turtur	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Sturnus unicolor	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
Sylvia melanocephala	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Turdus philomelos	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
Upupa epops	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
No. species indicators	4	2	14	10	8	3	7	2	12	6	7	4	9	4	13

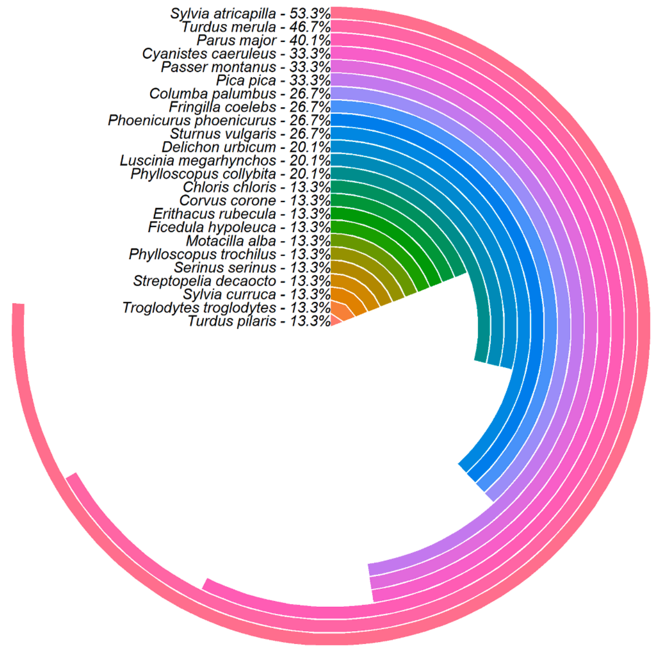

Fig. 3. Top bird species indicators of high environmental quality (HEQ) of urban areas in European cities. The circular bars represent the percentage of occurrence of each bird species as an indicator of HEQ considering the total number of cities analysed. Bird species more often selected as indicators are positioned in the outer part of the circle.

associated with rural or built-up areas, where it can nest in tree-holes and farm buildings or the eaves of houses and other human-related structures (Mainwaring, 2015; Reynolds et al., 2019). Our results are also congruent with the use of a niche-specialisation approach to studying urban birds (Liordos et al., 2021).

Among the most frequently selected HEQ-indicator, all species have a relatively broad or generalist diet. There are two omnivorous species (Eurasian blackcap and Blackbird), three granivorous-insectivorous species (Tree sparrow, Great and Blue tit), and one species with a more broad diet, using vertebrate items and also scavenging (Magpie) (Storchová and Hořák, 2018; Wilman et al., 2014). The fact that the HEQ-indicator species feed on diverse food types could be considered as a confirmation that a high diversity of vegetation characterizes such areas, offering a higher number of ecological niches for wildlife than more densely populated areas. Interestingly, we found that from the top ten birds HEQ-indicators 90% were species characterized by territorial behaviour during the breeding season (Table S1), with only a single species selected as HEQ-indicator without marked territoriality (e.g., Tree sparrow). The territorial behaviour of birds is clearly associated with an increased species detection rate, which makes easier the use of such species for survey purposes (Kułaga and Budka, 2019). Finally, when considering the life-history traits of best HEQ-indicators, we noticed how most of the species selected are resident or resident and short migrant species (overall 80% of the total species selected). Among the HEQ-indicators, only one species was a long-distance migrant (Common redstart). This underrepresentation of long-distance migrant species could indicate that migrants might be linked to other mechanisms than residents. They indeed suffer differently from local loss or transformation of habitat. Especially resident birds are the species more strongly related to environmental characteristics of urban areas, since spending the entire life cycle in such areas.

Our findings suggest that the multi-species approach is a valid strategy for monitoring different European cities and offer a framework to study the spatial distribution of high environmental quality areas within the cities. Several studies suggest higher effectiveness of multi-species surrogates versus single-species surrogates in ecology

(Butchart et al., 2010; Gregory et al., 2005; Morelli, 2015; Morelli et al., 2014). This approach could be used in urban planning or monitoring the urban-nature matrix through a cost-effective tool. Additionally, the fact that the HEQ-indicator species individuated in our study, even if they are multiple species, are all common species, make this approach rather suitable in citizen science initiatives (Jiguet et al., 2012). So, specific groups of few common species, associated with high environmental quality, could be used in different European cities to check periodically or in a long term program the status of such types of areas and - eventually - their changes.

CRediT authorship contribution statement

Federico Morelli: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jiri Reif:** Data curation, Writing – review & editing. **Mario Díaz:** Data curation, Writing – review & editing. **Piotr Tryjanowski:** Data curation, Writing – review & editing. **Juan Diego Ibáñez-Álamo:** Data curation, Writing – review & editing. **Jukka Suhonen:** Data curation, Writing – review & editing. **Jukka Jokimäki:** Data curation, Writing – review & editing. **Marja-Liisa Kaisanlahti-Jokimäki:** Data curation, Writing – review & editing. **Anders Pape Møller:** Data curation, Writing – review & editing. **Raphaël Bussière:** Data curation, Writing – review & editing. **Marko Mägi:** Data curation, Writing – review & editing. **Theodoros Kominos:** Data curation, Writing – review & editing. **Antonia Galanaki:** Data curation, Writing – review & editing. **Nikos Bukas:** Data curation, Writing – review & editing. **Gábor Markó:** Data curation, Writing – review & editing. **Fabio Pruscini:** Data curation, Writing – review & editing. **Leszek Jerzak:** Data curation, Writing – review & editing. **Olaf Ciebiera:** Data curation, Writing – review & editing. **Yanina Benedetti:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

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

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Data Availability

Data will be made available after publication, under reasonable request to the authors.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.108397.

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