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A core on the Atlantic margin of Europe: an urban bird assemblage in Cork City, Ireland

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Abstract
Urbanization threatens bird populations globally, however many urban habitats present important refugia for wildlife in this rapidly changing landscape. Additionally, birds at the periphery of their global range are more prone to landscape changes and thus these distributions are good indicators of the effects of urbanization on diversity; e.g., bird populations and communities of Cork City, Ireland. The aim of this study was to evaluate effects from urbanization on bird densities (birds/ha), species richness, and species composition throughout Cork City. I surveyed 32 points selected with a stratified random sample within commercial areas, residential habitats, and green spaces throughout Cork City during four breeding seasons between 2016-2019. Species richness was highest in green spaces with 18-34 species; whereas residential habitats had 14-27 species and commercial areas had 9-20 species. The most densely populated species citywide were rock pigeons (5.4-9.1 birds/ha), Eurasian jackdaws (2.9-3.8 birds/ha), rooks (4.5-6.4 birds/ha), European starlings (3.4-5.3 birds/ha), Eurasian blackbirds (2.4-3.6 birds/ha), and house sparrows (2.7-4.5 birds/ha). Overall a lack in urban green space surrounding survey points was most strongly associated with reduced species richness and population estimates. Also, both species richness and population densities tended to be higher in regions with less noise pollution and farther from the urban core. Ultimately these results corroborate other studies stressing the importance of urban green spaces for conserving biodiversity in cities. This is particularly important for the birds of Cork City given that these urban habitats are at the western edge of these species' distributions.

Keywords Urban ecology · Bird density · Species richness · Avian communities · Irish birds · Cork City

Introduction

Most bird species in Ireland are at the western most periphery of their European distributions (Billerman et al. 2020). These island isolated populations are smaller than their mainland counterparts and likely respond differently to environmental change (Fuller et al. 2007). Populations of 74% of Ireland's bird species are stable or increasing and 26% are in decline (Lewis et al. 2019). Specifically, some species that are common across continental Europe have shown declines in Ireland in recent decades (e.g., common swifts [*Apus apus*], European robins [*Erithacus rubecula*], and Eurasian magpies [*Pica pica;* Crowe et al. 2010]), whereas Eurasian wrens (*Troglodytes troglodytes)* and common wood-pigeons (*Columba palumbus)* have relatively high population levels in Ireland compared with other parts of their range on the European mainland (Crowe et al. 2014). These differences in relative abundances likely result in different bird assemblages in Ireland versus mainland Europe; therefore, it is important to not initiate conservation strategies in Ireland based on data gathered in mainland Europe. It is critically important to understand how Ireland's isolated and peripheral bird populations and communities respond to anthropogenic activities such as urbanization in order to inform future conservation strategies.

The main objective of this study was to evaluate the effects of urbanization on bird populations and communities in Cork City, Ireland with the aim of supplying conservation-focused recommendations for future urban planning programs for the city. Similar studies have been done elsewhere (Beninde et al. 2015; Biroli et al. 2020; Jokimäki et al. 2016; Loss et al. 2009; Marzluff 2001; Strohbach et al. 2009), however geographically (i.e., city-) specific research is essential for informing urban

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conservation (Nilon et al. 2017). To attain this goal, I surveyed breeding birds throughout the city for four years and measured a suite of habitat variables that might explain patterns in three response variables: (1) bird population densities (birds/ha), (2) species richness (#'s of species), and (3) species composition (i.e., percentage of species overlap). These response variables were evaluated throughout Cork City in commercial regions (i.e., gray spaces), residential areas, and managed habitats (e.g., green spaces). This research is necessary for informing conservation of urban birds in Ireland, specifically Cork City – the fastest growing urban areas in Ireland and one of the fastest growing metropolitan regions in all of Europe (Department of Housing, Planning and Local Government 2017).

Global urbanization has resulted in increased habitat heterogeneity across the landscape (Pickett et al. 1997). While many generalist bird species have responded positively to these increases in habitat heterogeneity, most populations have suffered. Cities often lack adequate habitat for local wildlife and do not function optimally as a network of communities (i.e., ecosystem services do not function efficiently; Marzluff 2001). However, many bird species have shifted their distributions into cities to take advantage of novel habitats with reduced predation (Samia et al. 2017) and increased access to food (albeit of questionable quality; Marzluff 2001). Consequently, cities often have higher levels of diversity compared with local natural spaces (Rebele 1994); however, this may not be true in cities at the periphery of species' distributions. Therefore, it is important to understand how urban variables affect Cork City bird populations and communities in order to inform future conservation strategies.

Two important variables likely affecting urban bird distributions are availability of green space (Soanes and Lentini 2019) and socioeconomic factors (Dow 2000; Kinzig et al. 2005; Melles 2005; Loss et al. 2009; Strohbach et al. 2009). Urban green spaces tend to have higher species richness than surrounding areas (Andersson et al. 2014; Dale 2018; Donnelly and Marzluff 2004; Jokimäki et al. 2014; Korányi et al. 2020; MacGregor-Fors et al. 2016); however, regions surrounding urban green spaces tend to have higher bird diversity and abundance due to increased habitat availability (Soanes and Lentini 2019). Additionally, more affluent neighborhoods may have more biodiverse gardens, bird feeders, and manicured green spaces compared with less affluent locations. While these neighborhoods may be dominated by non-native vegetation, they typically have greater diversity in habitat structure (i.e., a heterogeneous mix of herbs, shrubs, and trees; Hope et al. 2003). Also, some neighborhoods may have better trash management programs and thus fewer scavenging species (Preininger et al. 2019). Specifically, neighborhoods with higher densities of humans (e.g., multi-family homes and apartment complexes) have more trash to manage and thus likely have increased numbers of opportunistic animal species (e.g., corvids; Vuorisalo et al. 2003; Withey and Marzluff 2008). Few studies have evaluated variations in wildlife distributions by these socioeconomic variables.

I hypothesized that generalist bird species would have relatively high population densities in commercial regions of the city, but that these species also occur in both residential and managed areas. Also, it was reasonable to expect the densities of most species to be highest in managed habitats, and that the amount of vegetational cover, proximity to water, proximity to wooded areas, and more affluent neighborhoods would have positive effects on species richness. I predicted that managed habitats would differ the most in species composition given that these areas tend to have greater habitat structure and thus increased habitat availability, supporting a wider array of species.

Methods

Study area

Cork City is ~3,960 ha in County Cork on the southern coast of Ireland (Fig. 1). Cork City is the second largest city in Ireland with 125,657 inhabitants (Central Statistics Office 2016b). On 31 May 2019 Cork City expanded its boundary to 18,700 ha, adding ~85,000 humans (Cork City Council 2019); however, this study started prior to this expansion and so inference can be made only on the 3,960-ha area depicted in Fig 1. Cork City land area is comprised of 12% commercial, 25% managed, and 63% residential urban zones (GIS data from the Department of Housing, Local Government and Heritage 2020). Cork City is relatively monocentric as is apparent by the large commercial region located at the geographic center of the city. Commercial regions include shopping centers, industrial parks, etc. Managed zones include green spaces like city parks, college campuses, cemeteries, etc. Residential zones include neighborhoods with single-family and/or multi-family housing.

Cork City is situated within a greatly altered landscape. The island of Ireland is fragmented into ~66% agriculture and only ~10% forested land (based on 2006 land cover data as analyzed by Biodiversity Information System for Europe 2020). Specifically, County Cork is comprised of 12% forested land and has the largest forest area in the country (90,020 ha), but a majority of this is stocked with conifers for logging (Department of Agriculture, Food and the Marine 2020). Native trees in County Cork include ash (*Fraxinus* spp. L.), oak (*Quercus* spp. L.), and birch (*Betula* spp. L.); these species occur sparsely throughout Cork City (Mundy 2014). The most common trees in Cork City include non-natives to Ireland such as sycamore (*Acer pseudoplatanus*

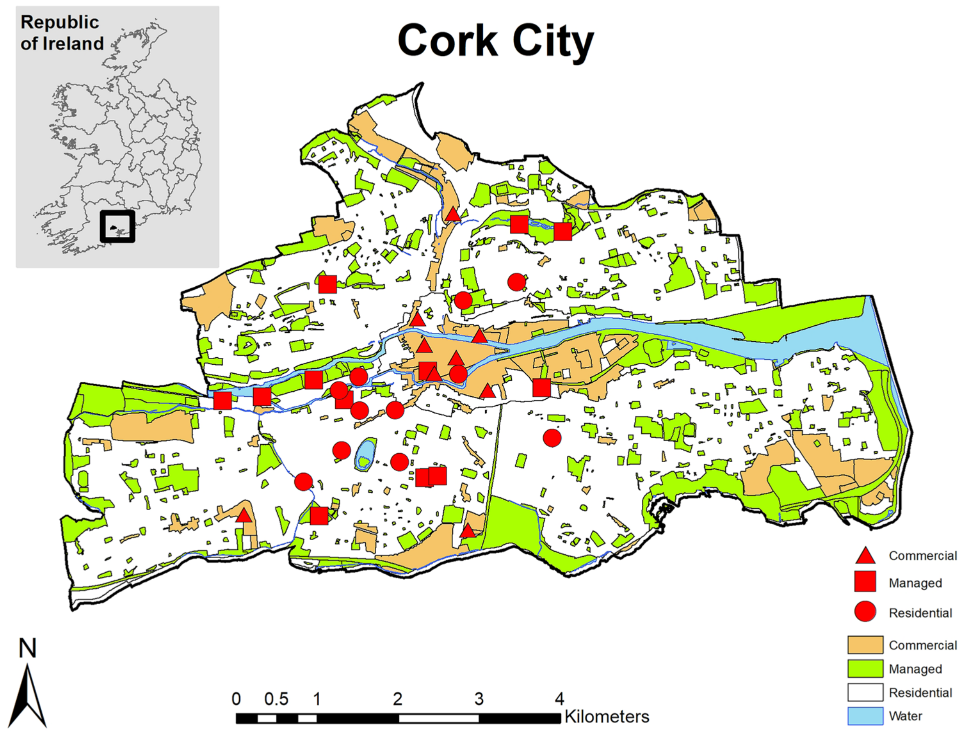

Fig. 1 Map of 32 survey sites within Cork City, County Cork, Ireland. Commercial habitats (9 points) include shopping centers and business districts. Residential areas (11 points) include neighborhoods with single-family and multi-family housing. Managed habitats (12 points) include green spaces like city parks and school campuses. The River Lee is the major waterway through the center of the city

L.), beech (*Fagus sylvatica* L.), horse chestnut (*Aesculus hippocastanum* L.), and Douglas fir (*Pseudotsuga menziesii* [Mirb.] Franco; National Biodiversity Data Centre 2020).

Data collection

Bird surveys I surveyed breeding birds from May through June during four years (2016-2019) at 32 points in commercial, residential and managed habitats. The survey points selection process occurred via two steps. First, I randomly selected a total of 12 points per habitat category - four points in each category within each of three regions of the city: (a) <1 km from the urban center, (b) 1-2 km from the urban center, and (c) 2-3 km from the urban center. Second, I used a power analysis with bird detection data collected from a series of pilot surveys to estimate an adequate number of survey points for obtaining density estimates with coefficient of variation of 20% for each habitat category (Buckland et al. 2001). This allowed me to survey a random subset of the 12 points in commercial and residential habitats, making data collection more logistically feasible for a single observer. Ultimately, I surveyed nine points in commercial habitats, 11 points in residential habitats, and 12 points in managed habitats (totaling 32 points). Randomly selected points that occurred on tops of buildings or on private properties were moved to the nearest public sidewalk for accessibility.

Bird surveys occurred from 06:00 to 13:00 on days with no rain and minimal wind (<20 kph) for optimal bird availability and detectability (Martin et al. 1997). During each 10-min survey I recorded species, numbers of individuals, and distances to each detection within 100 m of the survey point. Distances were measured with a Nikon® Forestry Pro© laser rangefinder. I used a sound meter to record the average urban noise level (dB) throughout each 10-min survey. Twenty-four points were surveyed once a year for a total of four surveys each. Three points were surveyed a total of five times (twice during 2016) and five points were surveyed only three times total due to high levels of precipitation during 2019 (and thus these points were not surveyed that year).

Habitat variables I measured nine survey- and site-specific habitat variables that might best explain patterns in bird densities, species richness, and species composition among the three habitat types (Table 1). Information was amassed from the peer-reviewed literature (the sources used for informing each variable are identified in the Table 1) to determine the most parsimonious (and logistically feasible) list of variables to measure. Many studies throughout the world have reported that habitat area and vegetational structure are important variables in determining urban diversity (Beninde et al. 2015). Therefore, I estimated area of gray space and area of woody vegetational cover within 100-m of each point (the distance within which bird detections were recorded). These habitat variables were included in candidate models explaining bird densities and species richness.

Table 1 Urban habitat variables measured at each site; these mnemonics were used in model notation for evaluating patterns in both bird densities and species richness. Citations lend support for including variables in candidate models for explaining bird population densities and species richness

Mnemonic	Variable	Description and methods
Habitat	Urban habitat type	This is a categorical variable representing the habitat type at each survey point: managed, residential, or commercial (as defined by Adams et al. 2006; Beninde et al. 2015)
DistWood	Distance (km) to nearest vegetation cover >1 ha	Measured the distance to the nearest wooded habitat patch ≥ 1 ha in size (Tilghman 1987; Fernández-Juricic 2000; Fernández-Juricic and Jokimäki 2001; Jokimäki et al. 2014).
AvedB	Average sound (dB)	Recorded with a sound meter during each 10-min survey period (Reijnen et al. 1995; Francis et al. 2009; Ortega 2012).
DistWater	Distance (km) to nearest water	Measured using ArcGIS; water was defined as any permanent water source such as streams, rivers, ponds, or lakes (Tilghman 1987).
DistCore	Distance (km) to urban core	Measured using ArcGIS; urban core was defined as the middle of the commercial city center (i.e., not the city's geographical center; Jokimäki et al. 2014).
DistPeriph	Distance (km) to urban periphery	Measured using ArcGIS; urban periphery was defined as the edge of continuous gray space at the periphery of the city (i.e., often extending beyond the political boundary of the city; Fernández-Juricic and Jokimäki 2001; Dale 2018).
Income	Average household income (€)	Data from Central Statistics Office (2016a) (Dow 2000; Kinzig et al. 2005, Melles 2005, Strohbach et al. 2009).
Vegetation	Vegetational cover (%)	Estimated percent woody vegetational cover (e.g., trees and shrubs) within a 100-m radius of each survey point using the most recent Google Earth® images (Duhl et al. 2012; Beninde et al. 2015; Dale 2018).
GraySpace	Amount of gray space (%)	Estimated percent of gray space within a 100-m radius of each survey point; the direct inverse of this would be percent of green space (different from Vegetation in that this would include mowed lawns, green roofs, etc.).

Data analysis

Principal components analysis I conducnted a principal component analysis (PCA) with package 'factoextra' (Kassambara and Mundt 2020) in R 3.6.2 (R Core Team 2019) to evaluate relationships among the nine habitat variables and the raw count data for each species. I used this approach to consider meaningful groups of variables in model construction and to eliminate from further analyses any habitat variables with minimal contribution to the variation in the data (James and McCulloch 1990). This aided in the construction of parsimonious candidate models for explaining density and species richness, respectively (explained below). Specifically, I used variables from the first two dimensions in the PCA in further analyses. Dimension 1 variables and dimension 2 variables, respectively, were combined in density and species richness models. Variables with minimal contribution to these first two dimensions were excluded from further analyses.

Estimating bird densities I used Program DISTANCE 7.3 (Thomas et al. 2010) to estimate population densities (birds/ha) corrected for imperfect detectability for each species breeding in Cork City. I conducted analyses separately for species with >60 detections (as per Buckland et al. 2001) across the 4-year period. Species with fewer than 60 detections were pooled together and 'species' was used as a covariate for evaluating variable detectabilities by species. I tested the fit of half-normal and hazard-rate detection functions with and without cosine and negative exponential series expansions in addition to survey-specific covariates. I obtained density estimates from the top-fitting detectability model. Then I used the package 'lme4' (Bates et al. 2020) in R 3.6.2 (Team 2019) to evaluate a set of nine linear mixed effects models incorporating urban habitat variables on species-specific density estimates. These models included solitary effects from each habitat variable, effects from the combinations of variables from the PCA, a global model (incorporating all variables), and a null model (suggesting none of the variables affected bird densities).

Estimating species richness Species have varying levels of detectability (e.g., some species may be more difficult to detect than others) and thus raw species counts can be misleading. Therefore, I used Program SPECRICH2 to compute avian species richness for each survey point during the 4-year period of this study (White et al. 1978; Rexstad and Burnham 1991). SPECRICH2 uses a mark-recapture approach whereby presence-absence encounter histories are used to estimate species richness ($\widehat{S}$) corrected for heterogeneous detection probabilities across species. Then, as with the bird density models described above, I used the package 'lme4' (Bates et al. 2020) in R 3.6.2 (R Core Team 2019) to assess the fit of nine linear mixed effects models that evaluated effects from habitat variables on estimated species richness. The nine candidate models included effects from each variable alone, effects from variables combined as a result of the PCA, a global model, and a null model (indicating effects from none of the habitat variables.

Evaluating species composition I used two approaches to characterize patterns in species composition across the city: (1) non-metric multidimensional scaling (NMDS) to evaluate species composition among the 32 survey points and three habitat categories, and (2) program COMDYN to estimate gamma diversity as a measure of species overlap among the three habitat categories. I used the package 'vegan' (Oksanen et al. 2020) in program R 3.6.2 (R Core Team 2019) to conduct the NMDS analysis - a distance-based ordination technique based on dissimilarities in rank-ordered relative abundances for each species (Bradfield and Kenkel 1987). In this NMDS analysis, I used Bray and Curtis (1957) distances which measures dissimilarities based on count information. This approach outperforms newer more data-hungry model-based methods for analyzing species composition data (Roberts 2020). Using NMDS to evaluate differences in species composition among points assumes that relative abundance supplies a measure of association or disassociation (i.e., number of detections supplies a measure of the degree of habitat association).

In conjunction with the NMDS analysis, I used Program COMDYN to estimate measures of species overlap among commercial, residential, and managed habitats. I used this approach because COMDYN incorporates estimates based on heterogeneous detection probabilities by species by utilizing a mark-recapture analysis framework (Hines et al. 1999; Nichols et al. 1998).

Model ranking I used an information theoretic framework (Burnham and Anderson 2002) to rank candidate sets of models evaluating effects of habitat variables on (1) bird densities and (2) bird species richness. I ranked candidate density and species richness models using Akaike's information criterion corrected for small sample size (AIC_c). As per Burnham and Anderson 2002, models with ΔAIC_c values <2.0 were considered most plausible given the data. Models with ΔAIC_c values >8.0 were considered least plausible. I model-averaged parameter estimates using AIC_c weights to evaluate the magnitude of effects from each habitat variable on species richness.

Comparing between estimates Density and species richness estimates were compared by examining the magnitude of confidence intervals around differences between estimates. For computing confidence intervals around differences, I calculated the variance of each difference as:

$$Var\left(\hat{S}_1 - \hat{S}_2\right) = Var\left(\hat{S}_1\right) + Var\left(\hat{S}_2\right) - 2 * Cov(\hat{S}_1, \hat{S}_2)$$

The magnitude of differences was considered ***strong*** when 95% confidence intervals were greater than 0.0, ***moderate*** when 90% CIs were greater than 0.0, ***weak*** when 85% CIs did not include 0.0, and ***no difference*** when 85% CIs included zero (Gerard et al. 1998; Skagen et al. 2005).

Results

A total of 45 species were detected during the breeding seasons of 2016-2019 throughout Cork City (Table 2). Overall I detected more species on average (SE) in managed habitats versus either residential or commercial – 22.8 (1.2), 16.5 (1.7), and 11.7 (0.9) detected species, respectively. Twenty-two species were detected in all three habitat categories. The most commonly detected species throughout the city were Eurasian jackdaw, rook, and European starling. Nine species were only detected in managed habitats: mallard, Eurasian moorhen, little egret, Eurasian jay, coal tit, Eurasian blackcap, mistle thrush, sand martin, and willow warbler. No species were detected exclusively in either residential or commercial habitats. European greenfinch was only detected during 2016 and not during the other three years of the study. Species known to occur in Cork City but not detected during bird surveys included little grebe (*Tachybaptus ruficollis*), stock dove (*Columba oenas*), European kingfisher (*Alcedo atthis*), and white-throated dipper (*Cinclus cinclus*) (Mundy 2014; eBird 2020; Irish Birding 2020; personal observations).

Principal components analysis

The PCA revealed two dimensions that described 75.2% of the variation in the data (Fig. 2). Dimension one included effects from distance to the periphery, distance to the core, amount of gray space, and urban noise levels at each point. Dimension two included strong effects from both income and distance to nearest wooded habitat. These seven variables were used in models evaluating effects on population densities and species richness. Both distance to water and vegetational cover contributed more to dimension 3 and thus neither varied substantially across survey points, resulting in minimal influence from these variables on the PCA. These two variables were excluded from the density and species richness models.

Bird densities

Density estimates ranged from only 0.01 birds/ha for both little egrets and sand martins (the two least abundant species) to 7.02 birds/ha for rock pigeons (the most abundant species; Table 2). Nine species had >60 detections across the

Table 2 Estimated breeding bird densities (birds/ha) and abundances for Cork City during 2016-2019. Estimated 95% confidence intervals are included in parentheses

Species name	Common name	Birds/ha	Total no.	
Cygnus olor	mute swan	0.04 (0.01, 0.24)	157	(26, 951)
Anas platyrhynchos	mallard	0.33 (0.13, 0.79)	1296	(534, 3145)
Columba livia	rock pigeon	7.02 (5.42, 9.08)	27779	(21451, 35973)
C. palumbus	common wood-pigeon	2.78 (2.36, 3.28)	11025	(9354, 12993)
Streptopelia decaocto	Eurasian collared-dove	0.17 (0.09, 0.33)	668	(337, 1323)
Apus apus	common swift	0.84 (0.55, 1.29)	3338	(2175, 5121)
Gallinula chloropus	Eurasian moorhen	0.06 (0.01, 0.25)	236	(56, 986)
Larus argentatus	herring gull	0.35 (0.18, 0.66)	1374	(724, 2610)
L. fuscus	lesser black-backed gull	0.07 (0.03, 0.16)	275	(120, 628)
L. marinus	great black-backed gull	0.02 (0.01, 0.06)	79	(24, 253)
Phalacrocorax carbo	great cormorant	0.03 (0.01, 0.11)	118	(33, 425)
Ardea cinerea	grey heron	0.12 (0.04, 0.36)	471	(158, 1407)
Egretta garzetta	little egret	0.01 (0.01, 0.05)	39	(8, 199)
Garrulus glandarius	Eurasian jay	0.02 (0.01, 0.10)	79	(15, 398)
Pica pica	Eurasian magpie	0.70 (0.46, 1.08)	2788	(1812, 4289)
Corvus monedula	Eurasian jackdaw	3.31 (2.85, 3.84)	13112	(11302, 15210)
C. frugilegus	rook	5.37 (4.54, 6.35)	21257	(17970, 25150)
C. cornix	hooded crow	0.40 (0.31, 0.51)	1572	(1224, 2020)
C. corax	common raven	0.03 (0.01, 0.11)	118	(32, 400)
Periparus ater	coal tit	0.07 (0.02, 0.25)	275	(77, 987)
Cyanistes caeruleus	Eurasian blue tit	0.44 (0.25, 0.75)	1728	(1001, 2982)
Parus major	great tit	0.23 (0.15, 0.35)	903	(590, 1382)
Phylloscopus collybita	common chiffchaff	0.14 (0.06, 0.31)	550	(248, 1217)
Aegithalos caudatus	long-tailed tit	0.09 (0.03, 0.23)	353	(137, 911)
Sylvia atricapilla	Eurasian blackcap	0.04 (0.01, 0.11)	157	(57, 429)
Regulus regulus	goldcrest	0.36 (0.21, 0.59)	1414	(850, 2350)
Certhia familiaris	Eurasian treecreeper	0.07 (0.03, 0.15)	275	(131, 576)
Troglodytes troglodytes	Eurasian wren	1.19 (0.82, 1.73)	4720	(3251, 6851)
Sturnus vulgaris	European starling	4.23 (3.38, 5.28)	16735	(13397, 20905)
Turdus viscivorus	mistle thrush	0.03 (0.01, 0.15)	118	(23, 598)
T. philomelos	song thrush	0.10 (0.05, 0.20)	393	(192, 804)
T. merula	Eurasian blackbird	2.95 (2.44, 3.57)	11682	(9647, 14149)
Erithacus rubecula	European robin	0.56 (0.33, 0.93)	2199	(1313, 3683)
Prunella modularis	dunnock	0.40 (0.27, 0.59)	1571	(1054, 2341)
Passer domesticus	house sparrow	3.49 (2.72, 4.48)	13820	(10775, 17733)
Motacilla cinerea	grey wagtail	0.03 (0.01, 0.11)	118	(33, 425)
M. alba	white wagtail	0.31 (0.18, 0.52)	1217	(724, 2047)
Riparia riparia	sand martin	0.01 (0.01, 0.05)	39	(8, 199)
Hirundo rustica	barn swallow	0.19 (0.09, 0.39)	746	(356, 1562)
Delichon urbicum	common house martin	0.41 (0.26, 0.64)	1610	(1015, 2553)
Phylloscopus trochilus	willow warbler	0.07 (0.02, 0.22)	275	(88, 863)
Fringilla coelebs	common chaffinch	0.74 (0.49, 1.13)	2945	(1933, 4486)
Pyrrhula pyrrhula	Eurasian bullfinch	0.15 (0.05, 0.46)	589	(190, 1827)
Chloris chloris	European greenfinch	0.03 (0.01, 0.09)	118	(39, 360)
Carduelis carduelis	European goldfinch	0.49 (0.25, 0.94)	1924	(999, 3707)

4-year period of this study and thus these were the species for which I estimated habitat-specific densities (Table 3) and analyzed effects from urban variables. Seven of these nine species had higher densities in managed habitats compared with either residential or commercial (Table 4). There were at least 0.8 more house sparrows/ha in residential areas versus managed green spaces (i.e., 74% more houses sparrows in residential areas compared with managed habitats). The

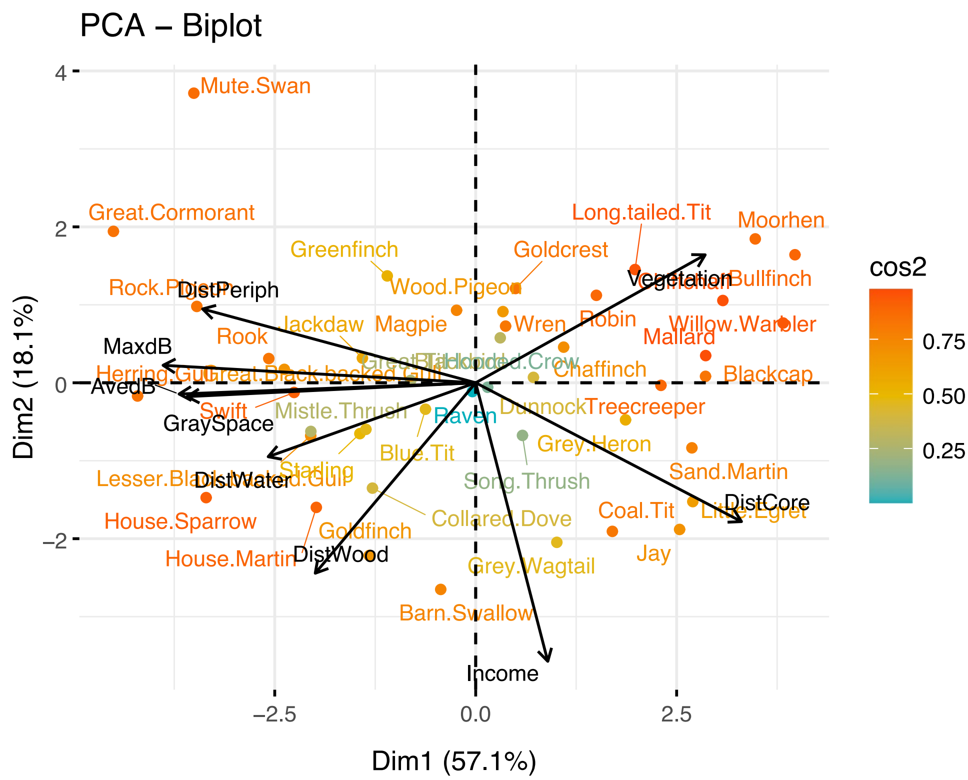

Fig. 2 Ordination via principal component analysis (PCA) with bird detection data and nine habitat variables (defined in Table 1). The color gradient indicates low importance (blue; low cos2) to high importance (red; high cos2) of each species to the PCA

rook was the only species with higher densities in commercial regions. Eurasian blackbird densities were higher in both managed and residential habitats compared with commercial. The biggest differences in estimated densities were between managed versus commercial regions for both Eurasian blackbirds and common wood-pigeons (both had >2.5 more birds/ha in managed habitats).

The amount of gray space appeared in top models for six of the nine species (Table 5). Model-averaged regression coefficients revealed that the amount of gray space had the greatest effect on densities of four of the nine species analyzed (Table 6). Densities of common wood-pigeons, Eurasian wrens, and Eurasian blackbirds were negatively related to the amount of gray space; however, rock pigeon densities were positively related to this variable.

The distance to urban core appeared in top models for five species. However, effects from the distance to urban core on bird densities was trivial (i.e., 95% CI's were very near zero) or inconclusive (i.e., 95% CI's included both biologically meaningful and trivial levels) for all nine species. Income did not affect the density of any of the nine species (i.e., the magnitudes of the 95% CIs were very low and included zero).

Eurasian wren densities also showed negative relationships with distance to nearest wooded area and average urban noise levels (however, the effect from noise pollution on wren densities may be biologically trivial given that the 95% CI for this beta is very close to zero). House sparrow densities increased with increasing distance to wooded areas. The null model was top-ranked for rook

Table 3 Habitat specific density estimates (with 95% CIs) for the nine most commonly detected species of birds breeding in Cork City during 2016-2019

	Birds/ha (95% CI)					
Species	Managed		Residential		Commercial	
Rock pigeon	7.1	(2.6, 19.8)	2.5	(1.3, 5.9)	8.2	(4.2, 19.8)
Common wood-pigeon	4.5	(3.4, 5.9)	2.3	(1.8, 3.1)	0.7	(0.5, 3.3)
Eurasian jackdaw	3.0	(2.3, 4.1)	4.3	(3.2, 6.0)	2.6	(1.9, 3.5)
Rook	3.8	(2.8, 5.1)	2.6	(1.8, 3.8)	6.3	(4.6, 8.6)
Hooded crow	0.6	(0.4, 0.8)	0.2	(0.2, 0.3)	0.3	(0.2, 0.4)
Eurasian wren	1.3	(1.0, 2.1)	1.1	(0.7, 1.6)	0.5	(0.3, 0.7)
European starling	5.3	(3.0, 10.6)	2.2	(1.3, 3.8)	1.3	(0.8, 2.9)
European blackbird	4.2	(3.4, 5.2)	2.3	(1.8, 3.0)	0.7	(0.6, 0.9)
House sparrow	1.1	(0.6, 2.1)	3.2	(2.1, 6.7)	1.9	(1.3, 3.6)

Table 4 Differences between estimated breeding bird densities at managed, residential, and commercial habitats in Cork City during 2016-2019. Three levels of confidence intervals were computed to evaluate the magnitude of each difference – 85% (weak), 90% (moderate), and 95% (strong). Bolded lower confidence limits (LCL) indicate the highest level of confidence for a difference

Comparisons	Est. difference (birds/ha)	CIs for estimated differences (birds/ha)						Conclusion
		85%		90%		95%		
		LCL	UCL	LCL	UCL	LCL	UCL	
Rock pigeon								
Managed v. Residential	4.6	-0.6	9.9	-1.3	10.5	-2.4	11.7	no difference
Managed v. Commercial	1.1	-5.7	7.8	-6.5	8.7	-8.0	10.1	no difference
Residential v. Commercial	5.7	1.2	10.2	**0.6**	10.8	-0.3	11.8	moderate - at least 0.6 more rock pigeons/ha in commercial (90%)
Common wood-pigeon								
Managed v. Residential	2.2	1.2	3.1	1.1	3.3	**0.9**	3.5	strong - at least 0.9 more wood-pigeons/ha in managed (95%)
Managed v. Commercial	3.7	2.9	4.6	2.8	4.7	**2.6**	4.9	strong - at least 2.6 more wood-pigeons/ha in managed (95%)
Residential v. Commercial	1.6	1.1	2.0	1.1	2.1	**1.0**	2.2	strong - at least 1.0 more wood-pigeons/ha in managed (95%)
Eurasian jackdaw								
Managed v. Residential	1.3	**0.2**	2.4	0.0	2.6	-0.2	2.8	weak - at least 0.2 more jackdaws/ha in managed (85%)
Managed v. Commercial	0.5	-0.4	1.3	-0.5	1.4	-0.6	1.6	no difference
Residential v. Commercial	1.8	0.7	2.9	0.6	3.0	**0.3**	3.2	strong - at least 0.3 more jackdaws/ha in residential (95%)
Rook								
Managed v. Residential	1.1	**0.1**	2.2	0.0	2.3	-0.3	2.6	weak - at least 0.1 more rooks/ha in managed (85%)
Managed v. Commercial	2.5	0.9	4.1	0.7	4.4	**0.3**	4.7	strong - at least 0.3 more rooks/ha in commercial (95%)
Residential v. Commercial	3.6	2.1	5.2	1.9	5.4	**1.6**	5.7	strong - at least 1.6 more rooks/ha in commercial (95%)
Hooded crow								
Managed v. Residential	0.3	0.2	0.5	0.2	0.5	**0.1**	0.6	strong - at least 0.1 more crows/ha in managed (95%)
Managed v. Commercial	0.3	0.1	0.5	0.1	0.5	**0.1**	0.5	strong - at least 0.1 more crows/ha in managed (95%)
Residential v. Commercial	0.1	0.0	0.1	0.0	0.1	0.0	0.2	no difference
Eurasian wren								
Managed v. Residential	0.2	-0.2	0.7	-0.3	0.8	-0.4	0.9	no difference
Managed v. Commercial	0.9	0.5	1.2	0.4	1.3	**0.3**	1.4	strong - at least 0.3 more wrens/ha in managed (95%)
Residential v. Commercial	0.6	0.3	0.9	0.3	1.0	**0.2**	1.0	strong - at least 0.2 more wrens/ha in residential (95%)
European starling								
Managed v. Residential	3.1	0.9	5.3	0.6	5.6	**0.1**	6.1	strong - at least 0.1 more starlings/ha in managed (95%)
Managed v. Commercial	3.9	1.8	6.1	1.5	6.4	**1.0**	6.8	strong at least 1.0 more starlings/ha in managed (95%)
Residential v. Commercial	0.8	0.0	1.7	-0.1	1.8	-0.3	2.0	no difference
Eurasian blackbird								
Managed v. Residential	1.8	1.1	2.6	1.0	2.7	**0.8**	2.9	strong - at least 0.8 more blackbirds/ha in managed (95%)
Managed v. Commercial	3.4	2.8	4.1	2.7	4.2	**2.5**	4.3	strong - at least 2.5 more blackbirds/ha in managed (95%)
Residential v. Commercial	1.6	1.2	2.0	1.1	2.1	**1.0**	2.2	strong - at least 1.0 more blackbirds/ha in residential (95%)

Table 4 (continued)

Comparisons	Est. difference (birds/ha)	CIs for estimated differences (birds/ha)						Conclusion
		85%		90%		95%		
		LCL	UCL	LCL	UCL	LCL	UCL	
House sparrow								
Managed v. Residential	2.1	1.1	3.1	1.0	3.2	**0.8**	3.4	strong - at least 0.8 more sparrows/ha in residential (95%)
Managed v. Commercial	0.8	0.1	1.5	**0.0**	1.60	-0.1	1.7	weak - at least 0.1 more sparrows/ha in commercial (85%)
Residential v. Commercial	1.3	0.2	2.4	**0.1**	2.5	-0.2	2.7	moderate - at least 0.1 more sparrows/ha in residential (90%)

and European starling, suggesting that densities for these two species may have been relatively ubiquitous across all combinations of habitat variables.

Bird species richness

Estimated avian species richness (95% CI) was 26.2 (17.9, 34.4) species in managed habitats, 20.1 (13.7, 26.5) species in residential habitats, and 15.1 (9.4, 20.8) species in commercial habitats. There was a strong difference (i.e., 95% CI was greater than zero) of 11.1 (1.0, 21.1) species between managed versus commercial habitats, suggesting there was at least 1.0 (but possibly 21.1) more species in managed versus commercial habitats. There was no difference (i.e., 85% CIs included zero) in estimated species richness between managed versus residential (6.1 [-1.7, 13.9] species) or residential versus commercial (5.0 [-1.4, 11.4] species) habitats.

The single top-ranked species richness model included the effects from dimension 1 in the PCA: distance to the urban periphery, distance to the urban core, noise levels, and amount of gray space (Table 7). This model had 79%

Table 5 Top-ranked models (<2.0 delta AIC_c [Δ_i]) for evaluating effects of urban habitat variables on breeding bird densities in Cork City during 2016-2019

Species	Models	Log(L)	No. of parameters	Δ_i	Akaike weight (w_i)
Rock pigeon	$\widehat{D} = DistPeriph + DistCore + AvedB + GraySpace$	-116.93	6	0.00	0.39
	$\widehat{D} = DistCore$	-121.27	3	0.16	0.36
Common wood-pigeon	$\widehat{D} = DistPeriph + DistCore + AvedB + GraySpace$	-52.74	6	0.00	0.66
	$\widehat{D} = GraySpace$	-57.69	3	1.40	0.37
Eurasian jackdaw	$\widehat{D} = DistPeriph * DistCore$	-59.43	5	0.00	0.54
Rook	$\widehat{D} = GraySpace$	-87.50	3	0.00	0.27
	$\widehat{D} = Intercept(null)$	.89.22	2	1.00	0.16
	$\widehat{D} = Habitat$	-86.87	4	1.36	0.14
	$\widehat{D} = AvedB$	-88.19	3	1.38	0.13
	$\widehat{D} = DistCore$	-88.50	3	1.99	0.10
Hooded crow	$\widehat{D} = DistPeriph * DistCore$	4.04	5	0.00	0.78
Eurasian wren	$\widehat{D} = GraySpace$	-37.28	3	0.00	0.46
	$\widehat{D} = AvedB$	-37.74	3	0.94	0.29
European starling	$\widehat{D} = Income$	-91.73	3	0.00	0.24
	$\widehat{D} = GraySpace$	-92.06	3	0.66	0.17
	$\widehat{D} = DistWood$	-92.35	3	1.02	0.14
	$\widehat{D} = Income + DistWood$	-91.15	4	1.46	0.12
	$\widehat{D} = Intercept(null)$	-93.87	2	1.83	0.10
Eurasian blackbird	$\widehat{D} = GraySpace$	-55.60	3	0.00	0.69
House sparrow	$\widehat{D} = DistWood$	-71.35	3	0.00	0.55

Table 6 Model-averaged regression coefficients (i.e., betas) for habitat variables included in density models. Estimated 95% confidence intervals are included in parentheses below each estimate. Coefficients are bolded if 95% CIs do not include zero

Species	GraySpace	DistWood	AvedB	DistCore	DistPeriph	Income
Rock pigeon	**19.16**	-6.21	**-1.12**	-5.71	0.77	0.03
	(0.80, 37.51)	(-17.24, 4.82)	**(-1.98, -0.26)**	(-16.83, 5.42)	(-11.97, 13.50)	(-0.49, 0.56)
Common wood-pigeon	**-4.98**	-0.71	-0.11	**-0.97**	-0.55	-0.01
	(-7.21, -2.74)	(-2.33, 0.91)	(-0.23, 0.01)	**(-1.86, -0.08)**	(-1.43, 0.33)	(-0.09, 0.07)
Eurasian jackdaw	-0.57	0.35	-0.03	-3.33	**-3.28**	0.01
	(-2.69, 1.55)	(-1.29, 1.98)	(-0.14, 0.09)	(-6.37, -0.30)	**(-5.95, -0.61)**	(-0.07, 0.08)
Rook	3.94	1.25	0.16	-1.21	-0.78	0.00
	(-0.48, 8.37)	(-2.22, 4.72)	(-0.09, 0.40)	(-3.95, 1.53)	(-4.13, 2.58)	(-0.17, 0.17)
Hooded crow	-0.03	-0.26	-0.01	**0.46**	0.06	0.00
	(-0.46, 0.41)	(-0.60, 0.09)	(-0.03, 0.01)	**(0.09, 0.83)**	(-0.31, 0.43)	(-0.01, 0.02)
Eurasian wren	**-1.38**	**-0.88**	**-0.07**	0.34	-0.31	0.00
	(-2.40, -0.37)	**(-1.62, -0.15)**	**(-0.12, -0.02)**	(-0.27, 0.95)	(-0.96, 0.33)	(-0.04, 0.04)
European starling	-4.8	2.86	-0.01	-0.78	-1.77	0.17
	(-10.01, 0.42)	(-1.22, 6.94)	(-0.40, 0.38)	(-7.18, 5.62)	(-7.90, 4.35)	(-0.01, 0.35)
Eurasian blackbird	**-4.42**	-0.22	**-0.16**	-0.25	-0.08	0.01
	(-6.44, -2.40)	(-1.94, 1.50)	**(-0.32, -0.01)**	(-1.14, 0.64)	(-0.96, 0.80)	(-0.07, 0.10)
House sparrow	1.9	**2.64**	0.03	-0.20	0.72	0.03
	(-1.15, 4.96)	**(0.63, 4.65)**	(-0.15, 0.21)	(-3.11, 2.71)	(-1.37, 2.81)	(-0.08, 0.14)

of the weight from the data. No other model was considered plausible (i.e., all other models had Δ AIC$_c$ > 4.0). Additionally, models that excluded amount of gray space were >300 times less plausible than the models that did. The model-averaged regression coefficients (SEs) for these variables suggested negative effects on species richness from distance to urban periphery ($\beta_{DistPeriph} = -2.16[1.39]$), noise levels ($\beta_{AvedB} = -0.37[0.18]$), and gray space ($\beta_{GraySpace} = -5.68[3.74]$), and positive effects from distance to core ($\beta_{DistCore} = 2.35[1.41]$). However, the high level of error in these estimates suggests weak support for the strength of the magnitude of these effects.

Species richness decreased with increasing distance to urban periphery, noise levels, gray space, and distance from wooded areas (Fig. 3). Species richness increased with distance from the urban core and may increase with increasing

Table 7 Ranking of linear mixed effects models relating breeding bird species richness estimates with six urban habitat variables for 2016-2019 in Cork City, Ireland. See Table 1 for detailed descriptions of habitat variables

Model	Log(L)	No. of parameters	Δ_i [a]	Akaike weight (w_i)
$\hat{S} = DistPeriph + DistCore + AvedB + GraySpace(PCADim.1)$	-88.94	7	0.00	0.79
$\hat{S} = GraySpace$	-95.76	4	4.45	0.09
$\hat{S} = DistPeriph$	-96.14	4	5.22	0.06
$\hat{S} = DistCore$	-96.16	4	5.26	0.06
$\hat{S} = DistPeriph + DistCore + AvedB + Income + GraySpace + DistWood$	-88.78	9	7.19	0.02
$\hat{S} = AvedB$	-98.98	4	10.90	<0.01
$\hat{S} = Intercept(habitat)$	-102.85	3	16.00	<0.001
$\hat{S} = DistWood$	-101.61	4	16.16	<0.001
$\hat{S} = Income + DistWood(PCADim.2)$	-101.10	5	17.96	<0.0001
$\hat{S} = Income$	-102.83	4	18.60	<0.0001

[a]Minimum AIC$_c$ = 196.54

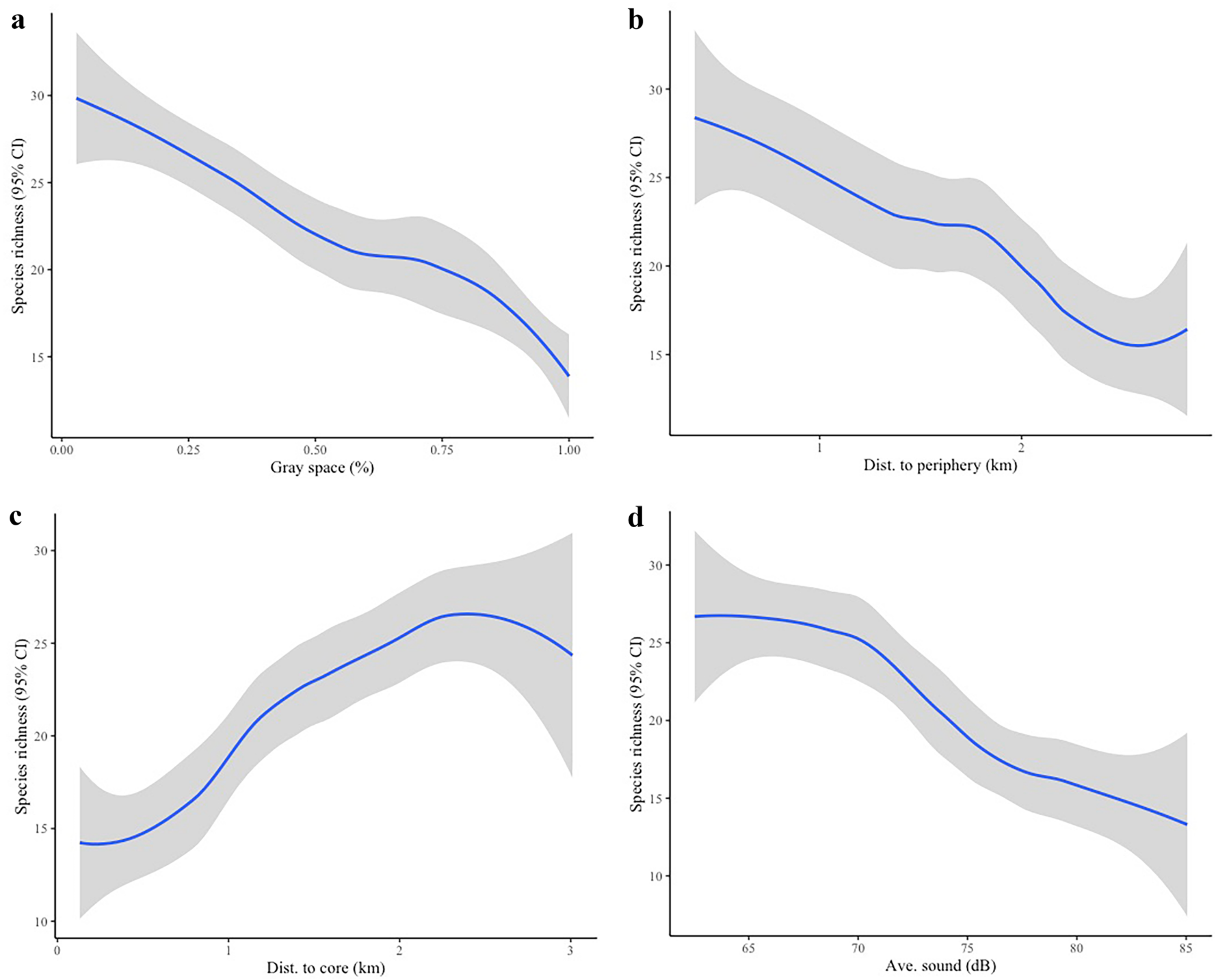

Fig. 3 Estimated bird species richness estimates for Cork City during the breeding seasons of 2016-2019. Estimates are plotted against four urban habitat variables: (**a**) percentage gray space within 100 m of each survey point; (**b**) distance (km) from each point to the urban periphery; (**c**) distance (km) from each point to the urban core; and (**d**) average urban noise pollution (dB) levels at each point. All variables are described in detail in Table 1. The gray shaded regions represent 95% confidence intervals

median household incomes; however there appears to be high variation in species richness in regions with high income levels and thus this variable is inconclusive due to imprecision (coincident with model selection results that indicate little evidence that this variable affected species richness).

Bird species composition

The NMDS analysis revealed substantial species overlap among the three habitat categories (Fig. 4); however, more species showed a stronger association with managed habitats than either residential or commercial habitats. No species showed strong association with commercial habitats. Estimated gamma diversity levels (95% CI) indicated substantial overlap in species composition across the habitats: 0.95 (0.80, 1.00) for managed versus commercial, 0.94 (0.75, 1.00) for managed versus residential, and 0.88 (0.63, 1.00) for residential versus commercial. Note that all gamma diversity estimates have 95% CI's that include 100% overlap.

Discussion

Bird species in Ireland are at the western periphery of their global distributions and most of these populations are isolated from those in Great Britain or mainland Europe. It is important to understand the effects of urbanization on these island isolated bird communities in order to inform future urban planning as Cork City continues to grow rapidly.

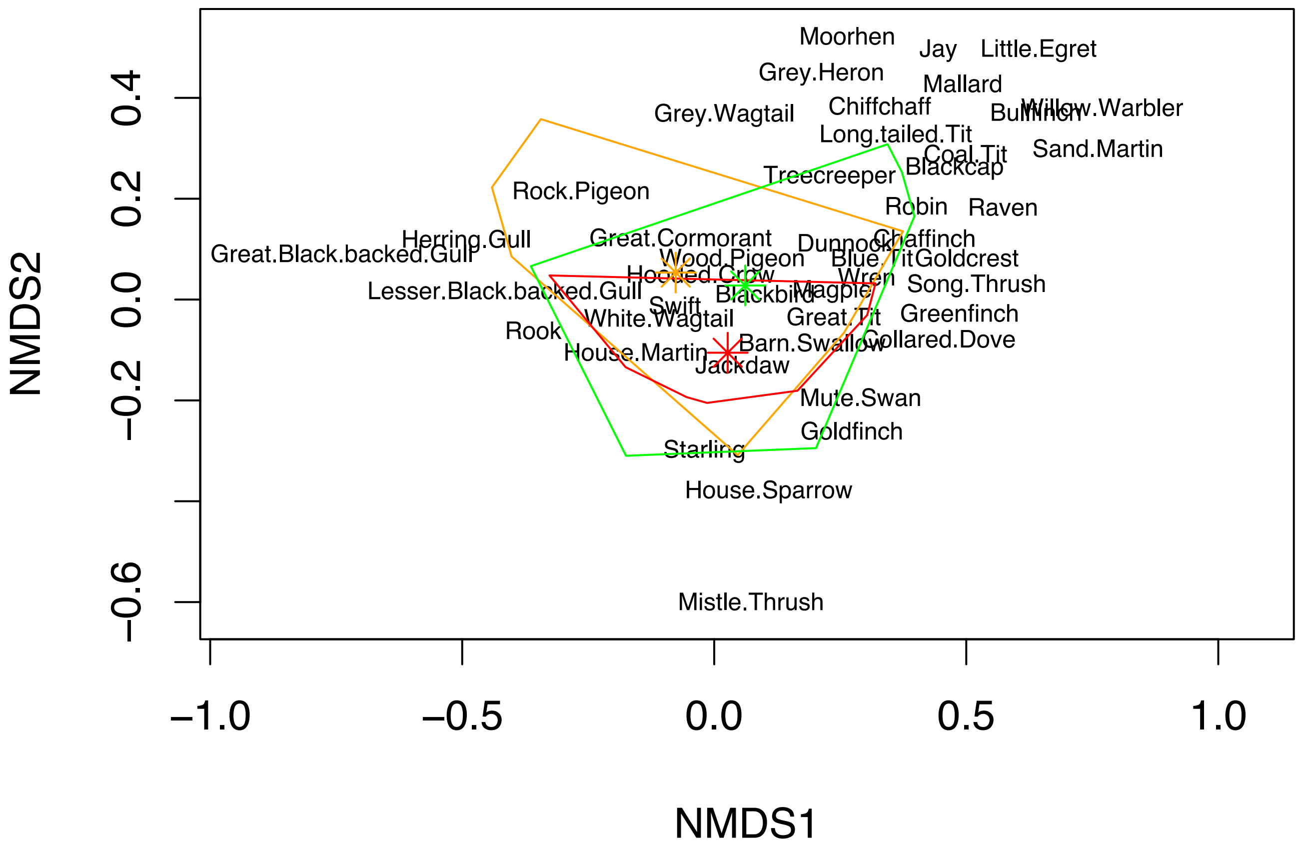

Fig. 4 Non-metric multidimensional scaling (NMDS) ordination of the numbers of detections by species (NMDS1) versus the three urban habitat categories (NMDS2; red represents commercial regions, orange represents residential areas, and green represents managed habitats)

The importance of managed green spaces for the birds of Cork City

It is not surprising that bird densities and species richness were positively related to urban green space in Cork City. Managed green spaces elsewhere typically have higher vegetation structural diversity (e.g., shrubs, hedgerows, trees, etc.), supplying increased cover for nesting and availability of food (e.g., arthropods and fruits) (Donnelly and Marzluff 2004). Several other studies have reported similarly positive effects on biodiversity from vegetation structural diversity in urban landscapes (Ferenc et al. 2014; MacGregor-Fors et al. 2016; Threlfall et al. 2017). The results from this study add to the body of literature supporting the importance of city green spaces for maintaining urban biodiversity.

Both Eurasian blackbirds and common wood-pigeons had substantially higher estimated densities in the urban green spaces compared with residential and commercial habitats. Eurasian blackbirds are known to be common throughout city centers across Europe with higher densities in regions near green spaces with open grass for foraging (Collar and Christie 2020). Common wood-pigeons are recently considered urban specialists throughout Europe, foraging and nesting in city parks and on buildings (Baptista et al. 2020). However, common wood-pigeons have been known to prefer green spaces for foraging which supports the negative relationship I found with amount of gray space (Baptista et al. 2020).

The Eurasian wren is considered the most abundant bird in Ireland (Crowe et al. 2014). While wrens are habitat generalists and thus maintain distributions in cities, urban distributions are generally associated with highly vegetated areas (Kroodsma et al. 2020). This may explain the negative relationship I found with distance to wooded vegetation in Cork City. The negative relationship between Eurasian wren densities and urban noise pollution may be because birds may vocalize less frequently in a noisy environment or may be more difficult to detect.

The distance to water variable did not contribute much to the variation in these data likely because most locations throughout Cork City were within 200 m of water (e.g., the River Lee running through the middle of the city).

The role of commercial and residential habitats for birds in Cork City

Only a few species had higher densities and/or associations with commercial or residential habitats compared with green spaces. Rooks are known to be associated with large city parks throughout Europe (Madge 2020); however, I found higher densities in commercial regions of Cork City. This is likely because they are opportunistic generalists (i.e., scavengers) that have benefited from anthropogenic activities (Kark et al. 2007; Madge 2020). House sparrows had higher densities in residential habitats because their breeding ecology includes nesting on houses (Lowther and Cink 2020). Both house sparrows and rock pigeons are generally associated with human modified habitats all around the globe, and thus populations of these species tend to increase or remain stable in urban locations (Lowther and Cink 2020; Lowther and Johnston 2020).

The urban habitat variable that had the broadest negative effect on densities and species richness was the amount of gray space. Regions with high coverage of gray space consequently have reduced vegetational coverage and thus a reduction in breeding habitat for most species. Rock pigeons directly utilize gray spaces for nesting (Lowther and Johnston 2020), explaining why this was the only species with densities that were positively correlated (albeit weakly so) to the amount of gray space.

In addition to gray space, estimated densities and species richness were negatively affected by distance to the urban periphery, proximity to woody habitat patches, and noise pollution levels at each point. These results corroborate many other studies having shown similar effects in other cities throughout the world (Dale 2018; Francis et al. 2009; Ortega 2012). There are several potential reasons why densities and richness estimates were negatively related to increased distance to the urban periphery and positively related to distance to the urban core. Species that were detected closer to the urban periphery and farther from the city center may be more neophobic and thus less tolerant of increased human activity. An alternative explanation may be that these species are in competition with the species that are concentrated in the urban center. Many species that thrive in urban environments have broad niches and thus are strong competitors to species less tolerant of urbanization (Bonier et al. 2007; Jokimäki et al. 2016).

Socioeconomic factors such as neighborhood median household income levels have been shown in other studies to affect bird populations and distributions (Strohbach et al. 2009). However, Howes and Reynolds 2021 showed that socioeconomic factors of adjacent neighborhoods had no effect on bird diversity in green spaces in Johannesburg, South Africa. My results agreed with this study and suggested that variable income levels had minimal effect on birds in all habitat types in Cork City during this 4-year study. This may change as Cork City continues to grow as a global economic hub. Future research should continue to monitor this variable as well as neighborhood age as this has been shown to be an important variable in other cities (Loss et al. 2009).

Conservation implications

As Cork City continues to grow both geographically and economically, management should focus on adding additional green spaces and improving the existing locations. This is particularly important for these populations that are isolated and at the western periphery of their global distributions. Certainly, adding new green spaces may be difficult given the extent to which current urban land uses are established; however, as the city expands geographically, planners could prioritize the development and protection of new green spaces. Additionally, existing green spaces of marginal quality could be enhanced by increasing vegetational heterogeneity of native plants. Ultimately, green spaces in Cork City should be designated as *important bird areas* (by conservation groups like BirdLife International and BirdWatch Ireland) to provide support for conservation to maintain urban biodiversity in this core on the Atlantic margin of Europe.

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Consent to participate Not applicable.

Consent for publication Not applicable.

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