Urban Ecosystems
https://doi.org/10.1007/s11252-022-01283-y

Landscape -scale predictors of persistence of an urban stock dove *Columba oenas* population

James Richardson[1] · **Alexander C. Lees**[1,2] · **Stuart Marsden**[1]

Accepted: 9 August 2022

Abstract

While a few species may thrive in urban areas, urban expansion is a major driver of biodiversity loss. Columbids such as feral Rock Doves (*Columba livia domestica*) and Common Woodpigeon (*Columba palumbus*) have adapted extremely well to the urban environment in Europe and beyond, but the Stock Dove (*Columba oenas*), a bird of farmland and woodland edge in the UK and of national conservation concern, is encountered infrequently in urban areas. Here we explore the multi-scale landscape associations of the little-studied Stock Dove within the urban matrix of Greater Manchester, UK, in order to identify its habitat requirements. We built a pilot model from historical citizen science records to identify potentially occupied sites within the city, and then surveyed these sites for Stock Dove during Spring 2019. We combined the survey results with citizen science records from the same period and described the habitat and landscape characteristics of sites occupied by Stock Dove using four variables at different scales plus twelve unscaled variables. We used a three-stage random forest approach to identify a subset of these variables for interpretation and a subset for prediction for the presence of Stock Dove within these sites. Key variables for predicting Stock Dove presence were their relative abundance in the landscape immediately beyond the core urban area, the greenness (NDVI) of the environment around sites, and the canopy cover of individual trees over 20 m high within sites. Stock Doves tended to be associated with habitats with more surface water during the non-breeding season than the breeding season. Our results highlight the importance of large trees within urban greenspace for this cavity-nesting species, softer boundaries around urban sites for Stock Doves and stock dove presence in nearby areas. While Stock Dove share many traits with species that are successful in the urban environment, they remain relatively poor urban adapters.

Keywords Avian habitat selection · Citizen science · eBird · Spatial scales · Urban matrix

Introduction

Urbanisation drives the loss, degradation and fragmentation of natural habitats (Bar-Massada et al. 2014; McKinney 2006). Urban matrices typically consist of a patchwork of different habitats, varying in size and quality (Crooks et al. 2004; Davis et al. 2014) including novel habitats with no historical analogues (Werner 2011). Urbanisation results in biodiversity loss and turnover, favouring generalist species that adapt better to novel environments (Werner 2011), which can lead to homogenisation of urban faunal and floral assemblages (Chace and Walsh 2006; Grimm et al. 2008; McKinney 2006). Increasing urbanisation may lead to an increase in animal biomass but a decrease in species richness (Chace and Walsh 2006; Threlfall et al. 2012) and an increase in non-native species (McKinney 2006). Cities that retain more remnant habitat are more likely to host more native species (Chace and Walsh 2006; Faeth et al. 2011).

Research into the responses of biodiversity to urbanisation has often focused on the rural-urban gradient (Nielsen et al. 2014; Beninde et al. 2015), a goal which may miss variation in the underlying structure of the urban matrix

✉ James Richardson
james@e-richardson.uk

Alexander C. Lees
alexander.lees@mmu.ac.uk

Stuart Marsden
s.marsden@mmu.ac.uk

[1] Department of Natural Sciences, Manchester Metropolitan University, Manchester, UK

[2] Cornell Lab of Ornithology, Cornell University, Ithaca, NY, US

(Werner 2011; Beninde et al. 2015). Instead, an approach that identifies individual habitats as urban sites (sometimes referred to as urban greenspaces or urban patches) within an interconnected urban matrix allows a more finely grained understanding of species response to urbanisation (Aronson et al. 2017). Sites are connected by their proximity to others or through functional habitat corridors (Lepczyk et al. 2017) such as river valleys, canals, or wooded streets. Species responses to urbanisation can then be understood by local habitat features determining habitat suitability and landscape features defining the permeability of the landscape for species dispersal (Beninde et al. 2015). The response of an individual species to these habitat and landscape features will vary due to species-specific niche differences (Jokimäki et al. 2016) and their dispersal capacity (Martin et al. 2017). Thus, while a site might provide the required habitat, and the landscape the required corridors for dispersal - a species' life history (such as sensitivity to disturbance) may still prevent successful colonisation which could be limited by failure to adapt to novel resources available in the urban environment (Spotswood et al. 2021; Shochat et al. 2006), or interspecific competition (Lees 2018).

The pigeons and doves (Columbidae) are a speciose avian family including some urban adapters found across most of the world (Sol et al. 2014). Five species of pigeons are native breeders in the UK, three of which have large urban populations: feral Rock Doves (*Columba livia domestica*) (McKinney 2006; Isaksson 2018), Common Woodpigeons (*Columba palumbus*) (hereafter Woodpigeons) and Collared Doves (*Streptopelia decaocto*). Two other species are more rarely recorded in urban areas; the Stock Dove (*Columba oenas*) and the migratory European Turtle Dove (*Streptopelia turtur*). In rural and agricultural habitats Woodpigeons occur in sympatry with Stock Doves, more so than the other native UK *Columbidae* species (Snow et al. 1998; Murton et al. 1964). Although present throughout the UK, other than the Scottish Highlands, there are estimated to be just 320,000 Stock Dove territories compared with an estimated 5,400,000 Woodpigeon territories (Woodward et al. 2020). While Woodpigeons have adapted to the urban environment (Fey et al. 2015; Ó and hUallacháin 2014; Bea et al. 2011), Stock Doves remain uncommon in urban areas (Robinson 2005). A major life history difference between the two species is their choice of nest sites; Stock Dove are cavity nesters whereas Woodpigeon nest on open branches. Stock Doves prefer ecotonal areas between woodland and open country where mature trees have cavities and hollows for nesting. These nest sites are within easy access of fields for foraging and a source of drinking water (Snow et al. 1998). Nest site requirements may affect Stock Dove's urban abundance as tree cavities are sparser in urban areas relative to natural woodland (Davis et al. 2014).

Stock Doves have suffered recent declines in the UK. They are classified as Amber, the 2nd highest conservation priority in the UK, under the Birds of Conservation Concern 5: The Red List for Birds (Stanbury et al. 2021) as the UK holds an important European breeding population (Stanbury et al. 2021) and thus an internationally important breeding population. Understanding their habitat requirements is a necessary step towards improving their conservation status.

We aim to discover the spatial distribution of Stock Dove in Manchester, a major UK city, and to identify the landscape-scale and habitat predictors that best explain this distribution. We undertook a field survey across Greater Manchester to identify sites occupied by Stock Doves and combined the results with citizen science data. We then identify the predictors for the landscape associations, including habitat associations, at courser and finer spatial scales of Stock Doves based on the field survey results. Finally, we explore differences in these landscape (and habitat) associations between the breeding and non-breeding seasons.

Methods

Study area

Greater Manchester (53°29′N 2°14′W) is a metropolitan county in the Northwest of England with a population of 2.8 million. The metropolitan county has a mean elevation of 38 m and a temperate oceanic climate (Peel et al. 2007). The M60 ring-road, a multilane highspeed highway, forms a physical border around the city and contains parts of the metropolitan boroughs (local administrative districts and subdivision of a metropolitan county) of Manchester, Salford, Trafford, Stockport, Tameside, Rochdale and Bury. 26% of Greater Manchester is covered by urban greenspace (Greater Manchester Green Summit 2021). That greenspace consists of heterogeneric sites from remnant woodland to brownfield regrowth and has a variety of land-use including local nature reserves (LNRs), managed parkland, cemeteries, and sports fields. Many greenspaces are connected via canals, rivers, green cycleways, and treelined streets. Our study area is the entire area encapsulated by the M60 ring-road. The city is bordered by a variety of landscapes with the fringes of moorland to the north and east, and more lowland arable land to the southwest (Fig. 1). The rural Stock Dove outside of the city are more abundant to the West (Fig. 2; BTO 2019b) which correlates with lowland arable land.

Citizen Science Records

We used citizen science data submitted to eBird (eBird 2019), The Manchester Birding website (Manchester

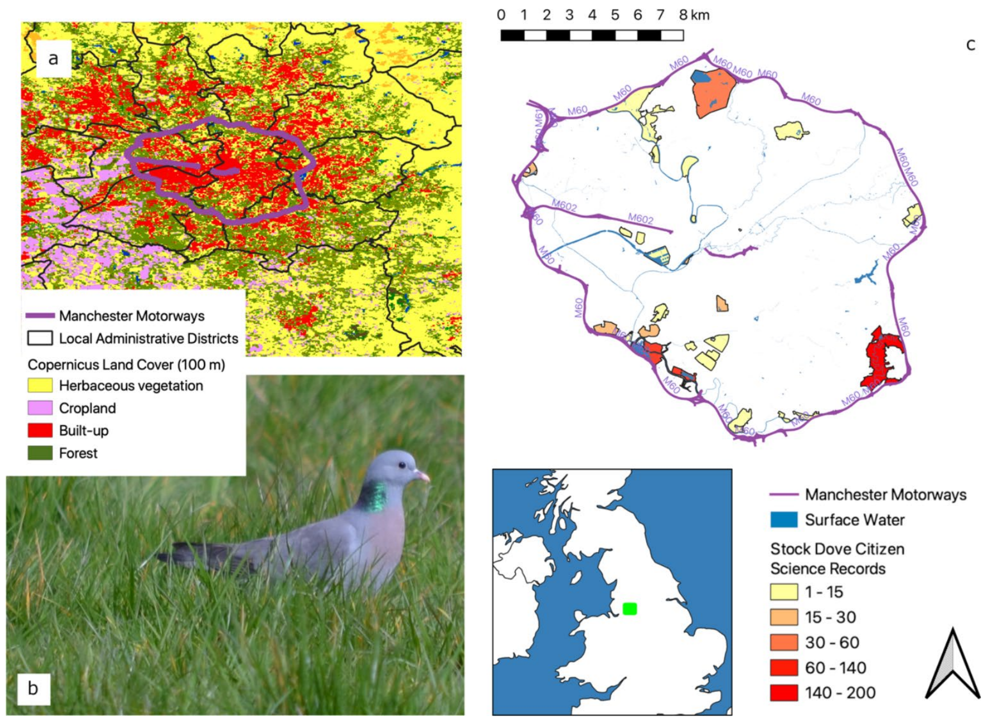

Fig. 1 (a) Land cover in the region surrounding Manchester (Buchhorn et al. 2020). (b) Urban Stock Dove in Alexandra Park (April 2020 by JR). (c) Sites with previous Stock Dove sightings inside the Manchester M60 Ring-Road from Citizen Science sources (combined from eBird (2019), Bird Track (BTO 2019a) and Manchester Birding (2019))

Fig. 2 Each site from the OS Greenspace dataset (Ordnance Survey, 2018a) with the habitat suitability for Stock Dove calculated using the R random forest package (Liew and Wiener 2002) using the model selected for prediction (Table 1)

Birding 2019) and Bird Track (BTO 2019a) to provide a list of Stock Dove records from inside the Manchester M60 ring-road prior to the study period. These were combined to produce a list of all sites within the M60 ring-road with Stock Dove sightings recorded since 2007 (Fig. 1), all of which were greenspaces of various sizes. These records included the site name, the record source, and the date and time of the observation. We treated this information as presence only data because some of the datasets lack systematic data collecting which could represent sample selection bias (Yackulic et al. 2012), this also allowed us to use all presence records from eBird no matter which protocol was used. Stock dove is, we believe, a species that the great majority of birdwatchers would choose to record in their eBird lists if detected. This is especially the case if the records come from a site where the species has never, or seldom, been recorded.

Survey

A field survey was undertaken between 1 March-31 May 2019 to identify greenspaces within the study area occupied by Stock Doves. We identified potential sites for Stock Dove where they had not been previously recorded by using a 'pilot' Maxent model built using the citizen science records along with environmental data from the Ordnance Survey and Forestry Commission (Appendix I). The uniform sampling assumption with Maxent requires that the environmental conditions are sampled in proportion to their availability (Merow et al. 2013), additionally Maxent is sensitive to detection rates varying with a given environmental covariate (Yackulic et al. 2012). Environmental variables potentially relevant to describe species distributions should be free of varying detection rates and equally sampled across their limits to help contain sampling bias. JR visited each of the potential candidate twice during the survey period, during which every hectare was visited, and each survey took at least 2.5 min (but no more than 10 min) per hectare for open habitat and up to 5 min per hectare for sites with more closed habitat (but not more than 20 min). Additionally, in May 2019 JR visited sites that had previous Stock Dove sightings recorded but not during the survey period (on eBird or Manchester Birding. In these sites, where possible, to maximise the chance of detection JR used knowledge from the person who had made the previous citizen-science record and targeted his visits to the most probable areas of those sites.

We considered Stock Doves to be present if any individual was present on the site excluding flyovers. For the survey results, presence records were created for each site where either Stock Doves were found during our survey; an eBird checklist was submitted containing a Stock Dove; a sighting was recorded on Manchester Birding; or a sighting was sent to us from the South Manchester Raptor Group. Absence records were logged for each site earmarked for surveys where JR failed to find Stock Dove; or any area of at least 0.25 km^2 for which eBird checklists have been submitted or a list submitted to Manchester Birding which did not include Stock Dove. All records, checklists, and lists considered were recorded as occurring during the survey period.

Predictor variables

We included variables for tree density, canopy cover, average tree height, extent of woodland cover, extent of water cover and minimum distance to water (Appendix 2), as Stock Dove require habitat with large trees for cavity nesting, ideally close to both water and to grassland for foraging (Snow et al. 1998). The exact dimensions of trees (or other cavities) required by nesting Stock Dove is unclear, so we include tree density and canopy cover for trees over a certain height at 2 m scales from 12 to 24 m high. Additionally, as we wanted to test the position of that habitat within the wider landscape, landscape variables for distance from city centre and surrounding greenness (NDVI) were included. The NDVI value in a buffer around an urban site measures landscape greenness around the sites and thus can be used as a measure of how soft the site edge is in comparison with the surrounding urban matrix, as well as a metric of connectivity between sites (Purevdorj et al. 1998). The exact scale that NDVI is important at is unknown, thus average NDVI was measured in scaled buffers, with buffer sizes at every 50 m from 0.05 km to 1 km. We also used the average relative abundance of Stock Dove from the British Trust for Ornithology's Stock Dove Breeding Relative Abundance map (2008-11) (BTO 2019b) within the buffers surrounding the sites. The dispersal distance of Stock Dove around Manchester is unknown and so we include the relative abundance of Stock Dove within 500 m scales from 0.5 to 13 km. These are all spatial variables and were measured using a shape file containing vectors for each surveyed site which came from the Ordnance Survey Greenspace dataset (Ordnance Survey 2018a), the LNR dataset (Natural England 2019), or were created using QGIS (QGIS Development Team 2019) based on the Open Street Map (OpenStreetMap contributors 2015). This gives a total of 16 predictor variables including four with many scales, we should also expect some of these predictor variables to be correlated.

Modelling Approach

The number of predictors we choose is large for the potential sample size which may result in overfitting (Kuhn and Johnson 2013) and poor estimates (Austin and Steyerberg 2015) when using conventional general linear model approaches. Furthermore, as our predictors are likely to be correlated, conventional linear model approaches cannot find exactly which variables are important (James et al. 2013).

We used the approach of Genuer et al. (2010) based on random forests (Breiman 2001) for variable selection. This performs well for high dimensional problems where the number of predictors (p) is high compared to the number of samples (n). The approach also handles highly correlated predictor variables. This has been shown to work well in ecological studies (Fox et al. 2017) and has been previously adapted for selecting the scale of landscape variables (Bradter et al. 2013). The approach has four stages: ranking variables, removing variables, selecting variables for interpretation, and finally selecting variables for prediction. The first stage ranks the variables based on their average importance (mean decrease in accuracy) from 50 runs with 2000 decision trees in each random forest (ensemble of decision trees). The second stage drops variables when the standard deviation of their importance is below the minimum prediction value of the CART (Classification and Regression Trees) model fitted to the curve of all predictor variables' standard deviations (Genuer et al. 2010).

The stage for selecting variables for interpretation computes the error rate of random forests from 50 runs of nested models starting with the model with the single most important predictor variable and then adding each remaining predictor variable in turn. A minimal model (with the lowest number of predictors) is selected with a mean error rate below the lowest mean error rate augmented by the lowest error rate's standard deviation. The final stage for selecting variables for prediction starts with the most important predictor variable selected for interpretation and then adds in each remaining variable in turn; however, a variable is only added when the error rate exceeds a threshold. The threshold is set to the mean of the absolute values of the first order differentiated out of the bag (OOB) errors between the model selected for interpretation and the one with all predictors. This ensures the error-decrease from adding additional predictors is greater than variation added by noisy predictors (Genuer et al. 2010).

While some studies have chosen to include every scale, due the small study size and for ease of interpretation we only included the 'best' spatial scale of each scaled variable. To select the most appropriate spatial scale for the scaled variables, the first stage of this approach was initially run with every predictor variable at every scale. The highest ranked scale for each variable was then selected and all other scales were discarded. The first stage was then repeated with just the 'best' scale for each scaled variable, the rest of the approach was then followed in full, and two models were selected: one for interpretation and one for prediction. Finally, a random forest model was generated from the survey data using the variables selected for prediction which we used to generate habitat suitability scores for each site from the OS Greenspace data set (Ordnance Survey 2018a). All random forest calculations were performed using in R in RStudio (RStudio Team 2015) using the random forest package (Liew and Wiener 2002).

To understand if there is a seasonal variation in Stock Dove distribution the historical sightings from eBird, Bird Track, and Manchester Birding, were examined to see if the landscape and habitat predictor variables identified from the survey data varied between breeding and non-breeding seasons. The historical citizen science records (from before 2019 and our survey) were split into breeding (March – August inclusive) and non-breeding season (September – February inclusive) and then reduced to ensure there was at most one presence record per site per annual season. Wilcoxon signed-ranked tests were then performed for each predictor variable to compare the means between the breeding and non-breeding season sites. Such an analysis assumes that survey effort is similar across seasons at sites. While this may not always be the case, most sites within the study area are reasonably well visited, and importantly tend to be visited in both seasons.

Results

Field Survey results

In total, we found Stock Doves at 28 of 65 sites (43%) included in the analysis: nine LNRs (total 20, 45%), eight parks (total 20: 40%), four playing fields (total: 8: 50%), four golf courses (total: 7, 57%), and a water treatment works (total: 1: 100%), a cemetery (total 4: 25%) and a long-distance cycle path (total 1: 100%) (Fig. 3). The 65 sites included 28 sites visited during the survey, 23 sites where Stock Dove were recorded by citizen science initiatives or by the South Manchester Raptor Group, and 14 sites which were added as absences using the absence criteria. The area of the 65 sites averaged 0.4 ± 0.49 km^2 (min 0.04 – max 2.9 km^2) compared to the area of the 28 presence sites which averaged 0.51 ± 0.69 km^2 (min 0.04 – max 2.9 km^2) and the 37 absence sites which averaged 0.24 ± 0.19 (min 0.05 – max 0.8 km^2). Eight of the 28 presence sites (29%) were sites identified from the pilot Maxent model where Stock Dove had not previously been recorded. Many presence sites lay along rivers, either the Mersey in the South, or the Irwell in the North.

Landscape and Habitat Associations

The spatial scales selected for the four scaled predictor variables (Table 1) were a 13 km buffer around sites for average BTO relative abundance; a 500 m buffer around sites for average NDVI; 20 m for minimum tree height in the calculation of tree density; and 20 m for the minimum tree height for the calculation of canopy cover. We entered the resulting 16 variables for variable selection (each of the four selected scale variables plus the 14 unscaled variables). The first two stages of Genuer's method reduced these 16 variables to six (Table 1); the top three were selected for interpretation and a prediction model.

The prediction model showed a clustering of potentially suitable sites for Stock Dove in the northwest and south of

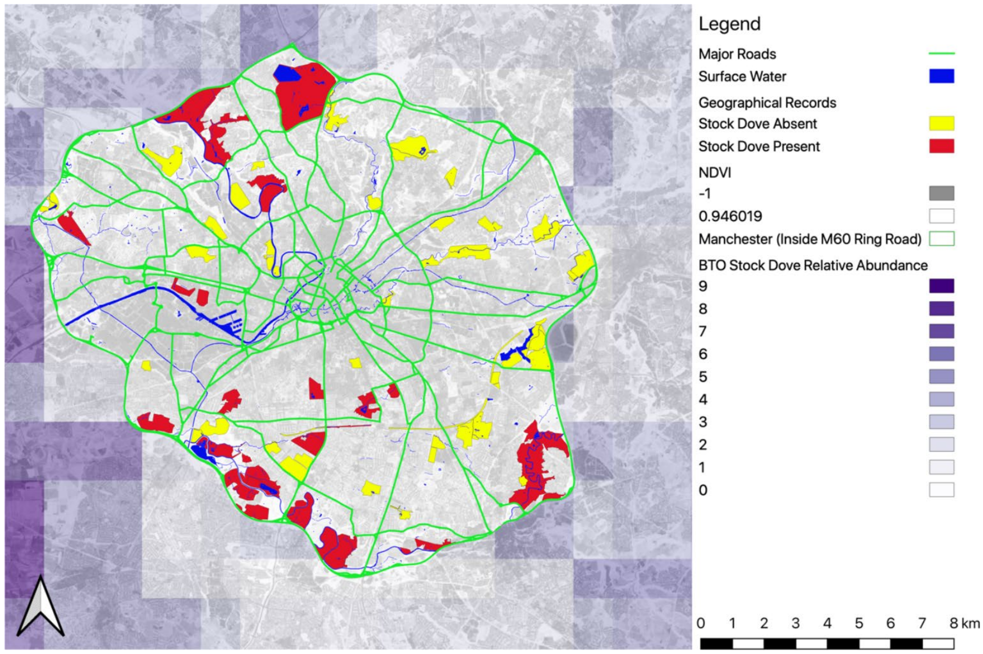

Fig. 3 The 65 sample sites across Manchester showing where Stock Dove were present and absent. Base layers for some predictor variables are shown including NDVI, BTO Relative Abundance (outside of the M60 only) and surface water

Table 1 Predictor variables selected (S) for Interpretation and Prediction of Stock Dove presence from the variables remaining (from full-list in Appendix 2 Table A2.1) after stage 2 of variable selection. Wilcoxon signed-ranked tests used to compare the means of sites with and without Stock Dove

Predictor Variable	S	Mean ± SD for Presence sites	Mean ± SD for Absence sites	Wilcoxon signed-ranked Test (p-value)
Average BTO Relative Abundance within 13 km	Y	3.6 ± 0.4	3.2 ± 0.6	< 0.0001
NDVI within 0.5 km	Y	0.53 ± 0.11	0.46 ± 0.10	0.001
Canopy Cover of individual trees over 20 m (km^2)	Y	0.008 ± 0.010	0.005 ± 0.012	0.03
Tree density of individual trees over 20 m ($trees/km^2$)		99.1 ± 125.9	113.6 ± 190.2	0.3
Maximum individual tree height (m)		26.7 ± 4.5	23.2 ± 5.1	0.02
Total area (km^2)		0.51 ± 0.69	0.24 ± 0.19	0.6

the study area (Fig. 2). This distribution mirrors the average BTO relative abundance around the study area. The average BTO relative abundance of Stock Dove within the study area was lower (2.2) than that in rural areas in the 13 km buffer outside the ring-road (4.2). Moreover, the average relative abundance within the 13 km buffer was higher in the West than in the East, reflected in higher Stock Dove abundance west of the city (average relative abundance within each quarter of the 13 km buffer: northwest 4.2, southwest 6.2, northeast 3.0, southeast, 3.7).

The citizen science data contained records from 38 sites, 23 (61%) were occupied in both seasons, 36 (95%) in the breeding season and 25 (66%) sites in the non-breeding season (of which two had no breeding season records). The only predictor variable to have had a significant difference between the breeding and non-breeding season was the total area covered by water. Sites with Stock Dove in the non-breeding season had a larger area of water cover than sites with Stock Dove in the breeding season (Table 2). There was also a near-significant difference in the total area covered by grassland ($0.05 < p < 0.1$). There was no significant difference between the land-use type (Brownfield, Cemetery, Flood Plain, Golf Course, LNRs, Sports Field, Parkland, Urban, Water Treatment Works) of the sites used between breeding and non-breeding seasons ($\chi^2 = 5.65$ df = 8, p = 0.69); however, there were four records of Stock Dove in the breeding season on golf courses but none in the non-breeding season.

Discussion

Ours is the first detailed study of the spatial distribution and habitat choice of Stock Doves within an urban environment and provides insight into the impacts of urbanisation on the species. We found Stock Doves to be largely restricted to 'greener' habitat sites with large trees geographically proximate to rural source populations. The broader scale

Table 2 Differences between predictor variables for sites with citizen science Stock Dove records (combined from eBird (2019), Bird Track (BTO 2019a) and Manchester Birding (2019)) in the breeding season (March - August) and the non-breeding season (September - February)

Variable	Mean ± SD for Breeding Season	Mean ± SD for Non-Breeding Season	Wilcox Test p-value
Average BTO Relative Abundance within 13 km	3.70 ± 0.46	3.62 ± 0.48	0.37
Average NDVI within 0.5 km	0.54 ± 0.13	0.55 ± 0.13	0.41
Canopy Cover of individual trees over 20 m (km^2)	0.007 ± 0.011	0.010 ± 0.014	0.21
Tree density of individual trees over 20 m ($trees/km^2$)	57.5 ± 99.4	42.1 ± 81.7	0.70
Max tree height (m)	23.5 ± 7.06	24.9 ± 6.51	0.29
Total area (km^2)	0.62 ± 0.79	0.89 ± 1.01	0.22
Total area covered by grassland (km^2)	0.19 ± 0.30	0.30 ± 0.38	0.06
Total area covered by water (km^2)	0.09 ± 0.13	0.14 ± 0.15	0.007
Distance to city centre (km)	5.59 ± 1.69	5.90 ± 1.60	0.17

differences in Stock Doves outside of the city are likely aligned to the topoedaphic differences, which define habitat quality for Stock Doves, and so may explain the relative rarity of the species in the eastern half of the city in comparison to the west – if areas outside of the city are important as source populations for colonists of the urban area. The higher levels of NDVI around occupied sites indicate that Stock Dove may prefer greener areas of the city (Purevdorj et al. 1998), indicating that the amount of landscape-level greenspace is also important and not just site-level characteristics. The near-significant ($0.05 < p < 0.1$) difference in the total area covered by grassland between breeding and non-breeding season suggests that Stock Dove may choose more open habitats in the non-breeding season.

Species responses to urbanisation depend on their niche requirements (Jokimäki et al. 2016); we have shown that large trees are important in explaining Stock Dove's distribution, as the species is a secondary cavity nester (Kosiński et al. 2011). These larger trees are more likely to offer suitable nest holes, with trees over 20 m high selected as the scale for two different predictor variables (tree canopy cover and tree density). Previous studies have shown that Stock Dove prefer nest sites in large Scots Pine (*Pinus sylvestris)* or Beech (*Fagus spp.)* with two or more cavities (Kosiński et al. 2011) and taller trees are more likely to have more cavities (Struebig et al. 2013). Urbanisation benefits cavity nesters over ground nesters, as cavity nesters may more readily adapt to manmade cavities (Jokimäki et al. 2016), which may be necessary if the number of natural cavities in urban environments is lower (Davis et al. 2014; Newson et al. 2011).

Cavity availability for Stock Doves may be further reduced by interspecific competition with other cavity nesters (Strubbe and Matthysen 2007), in the UK, this may include native Tawny Owls (*Strix aluco)* (Broughton 2019) and introduced Grey Squirrel (*Sciurus carolinensis*) (Hewson and Fuller 2003; Newson et al. 2009; Broughton 2019) and, in some cities, including Manchester, Ring-necked Parakeets (*Psittacula krameria*) (Newson et al. 2011; Strubbe and Matthysen 2007). While neither of these latter two species has been shown to have direct impacts on the abundance of native cavity nesters (Craig et al. 2016; Hewson and Fuller 2003; Newson et al. 2009, 2011; Strubbe and Matthysen 2007; Broughton 2019), they could still have a significant impact on cavity availability and suppress the abundance of other species without being the primary driver of community change (Didham et al. 2005). With insufficient large natural cavities, nesting sites could be a limiting factor for Stock Doves' success in urban environments.

Stock Dove are primarily granivorous (Snow et al. 1998) and urbanisation can favour granivores both in Europe (Jokimäki et al. 2016) and around the world (Pinho et al. 2016; Sol et al. 2020). Stock Dove abundance has been shown to increase with grassland improvement (when inorganic fertilizer has been added) over unimproved grassland due to an increase in grass seed availability (Barnett et al. 2004) but in this study we did not differentiate between types of grassland (such that monocultural playing fields were lumped with pasture and grassland managed for wildlife).

While there is potentially suitable habitat available in urban areas, Stock Dove may need to cross substantial areas of unsuitable habitat to find acceptable sites. Habitat loss and land-use intensification increases the costs of dispersal any species that moves from their birthplace to breed, more so than of relatively sedentary species like Stock Doves (Martin et al. 2017). During our field survey we observed Stock Doves in habitat corridors such as cycle paths, canals and rivers, - dispersing birds following these linear features into the city may be more likely to find suitable breeding habitat. However, in Madrid there was no evidence of Stock Doves using treelined streets (Fernández-Juricic 2000). The significance of high NDVI around sites with Stock Dove indicates that they prefer sites without hard edges; a sensitivity to edge effects may limit a species' ability to occupy some urban areas (With and King 2001). A sensitivity to edges was also indicated by the finding that the species has a clear preference for habitat away from roads in farmland in England (Fuller et al. 2001) and a preference for the interior of parks in Spain where Woodpigeon were found largely at the park edges (Fernández-Juricic 2001). We used NDVI as a proxy for softer edges and boundaries to the urban areas outside greenspaces, however, further studies would be required that specifically look at perimeters and Stock Dove locations within greenspace to properly address their sensitivity to edges.

While Stock Dove exhibit some traits associated with urban adapters such as granivory and cavity-nesting, they do not appear to be flourishing in urban Manchester. However, in London, Stock Dove appear to be maintaining healthy population in some parks (e.g. Regents Park, eBird 2019). London has less green space than Manchester (42.6% covered by greenspace (Greenspace Information for Greater London CIC 2022) compared to 54.2% (Greater Manchester Green Summit 2021)) but its parks are larger and older. It is possible that these large mature parks could provide more suitable habitat for Stock Dove with more natural cavities in older trees. Additionally, the rural population of Stock Doves is higher in south-eastern England around London than in north-western England around Manchester (BTO 2019b), and thus, there may be more individuals available to colonise London's greenspaces. Further studies are required to compare Stock Dove distribution and abundance across multiple cities to understand the balance between resource availability and Stock Dove habitat requirements in urban environments (or ecosystems).

Appendix I: Survey Site Selection

To identify potential new sites containing Stock Dove, we produced a Maxent (Phillips et al., 2019) model which established 28 new potential sites within the M60 ring-road. The Maxent model was produced using presence records generated from the previous Stock Dove sightings. For each previous recorded sighting at a site, a random presence point was generated within a spatial polygon for that site. These vectors either came from the Ordnance Survey Greenspace dataset (Ordnance Survey, 2018a), the Local Nature Reserves (LNR) dataset (Natural England 2019), or were created using QGIS (QGIS Development Team, 2019) based on the Open Street Map (OpenStreetMap contributors, 2015). The environmental layers used for the model were land cover based on the OS Open MasterMap (Ordnance Survey, 2018b), the management regime of the greenspace from OS Open Greenspace (Ordnance Survey, 2018a), the proximity to woodland using the woodland inventory dataset (Forestry Commission, 2017), and proximity to water using the OS Open MasterMap (Ordnance Survey, 2018b). The output of the model is a raster file with each pixel representing the habitat suitability for Stock Dove presence. Singular pixels with a high probability were excluded by adjusting each pixel's value to be the sum of its probability and all of its neighbours' probabilities. The 300 pixels with the highest probability were nominally taken and geographically grouped. The greenspaces that were spatially correlated with the grouped points were identified from the OS Greenspace dataset (Ordnance Survey, 2018a) and Open Street Map (OpenStreetMap contributors, 2015).

Appendix 2: Predictor Variables

Table A2.1 Predictor variables explored for the landscape and habitat association of Stock Dove presence; scales given when multiple scales were investigated.

Variable	Unit	Scales
Density of trees over X metres *	trees/km^2	12, 14, 16, 18, 20, 22 and 24 m
Total area covered by canopy of trees over X metres *	km^2	12, 14, 16, 18, 20, 22 and 24 m
BTO Relative Abundance within X km around site †	0–9	0.5 km, 1 km, and then every km to 13 km
Average NDVI within X metres around site ‡	NDVI	Every 50 m, from 50 m to 1000 m.
Woodland cover *	km^2	-
Percentage of total area covered by woodland *	%	-
Maximum individual tree height *	m	-
Average individual tree height *	m	-
Water cover §	km^2	-
Distance to water §	m	-
Grassland cover ‖	km^2	-
Percentage of total area covered by grassland ‖	%	-
Total area ¶	km^2	-
Distance from centre of Manchester #	km	-

Table A2.1 Predictor variables explored for the landscape and habitat association of Stock Dove presence; scales given when multiple scales were investigated.

Variable	Unit	Scales
Function of the greenspace **	-	-
Land cover smoothness ††	-	-

* Measured from Manchester City of Trees Team and the GM Combined Authority (2019). This contains two datasets for trees across Greater Manchester. The first is a Lidar dataset for individual trees and includes the height and canopy cover of each tree. The second is for denser areas of woodland where individual trees could not be measured by Lidar and only includes the area covered by that woodland. This allows large individual trees to be identified but adds complexity by spreading tree data across two datasets

† Measured from relative abundance maps published by the BTO (British Trust for Ornithology) (BTO, 2019b). These maps contain 10 levels from 0 to 9 with 9 being the highest relative abundance.

‡ Measured from imagery published by European Space Agency (2020). The image from the 29 June 2018 was used as being the day closest to the survey period with 0% clouds and including all of Manchester. The 20x20m pixel image was used as a compromise between accuracy and computation speed

§ Measured from OS Open MasterMap (Ordnance Survey, 2018b). Includes all topography with a theme of water

‖ Measured from vectors using QGIS (QGIS Development Team, 2019). Includes all topography with a theme of land, a primary description of general surface, an empty secondary description, and a make of natural

¶ Measured from vectors using QGIS (QGIS Development Team, 2019)

Measured from vectors using QGIS (QGIS Development Team, 2019). Centre of Manchester defined as Albert Square at (383797, 398105; EPSG:27700)

** Function from Ordnance Survey Greenspace dataset (Ordnance Survey, 2018a), LNR, or Brownfield

†† The standard deviation of the percentage grassland and woodland cover

Acknowledgements Assistance provided by Chris Sutton from the South Manchester Raptor Group with both Stock Dove records from birds nesting in raptor nest boxes as well as insight into Stock Dove behaviour was greatly appreciated. Detailed information on historical Stock Dove sightings from the members Manchester Birding forums was very valuable. We are particularly grateful to all those who submitted Stock Dove records to eBird during the Survey Period. We would also like to acknowledge Bryan Cosgrove from Manchester City of Trees Team and the GM Combined Authority for providing us with the Manchester City of Trees datasets.

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by James Richardson. The first draft of the manuscript was written James Richardson and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding No funds, grants, or other support was received.

Data availability Presence records available via eBird (https://ebird.org/). Habitat variables provided as supplementary material.

Code availability Custom code available via request to authors. QGIS, R and RStudio are software applications freely available to download.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethics approval Approved by Manchester Metropolitan University.

Consent to participate Not applicable.

Consent for publication Not applicable.

References

Aronson M, Lepczyk C, Evans K, Goddard M, Lerman S, MacIvor J, Nilon C, Vargo T (2017) Biodiversity in the city: key challenges for urban green space management. Frontiers in Ecology and the Environment, vol 15. Wiley-Blackwell, 4

Austin PC, Steyerberg EW (2015) The Number of Subjects per Variable Required in Linear Regression Analyses. J Clin Epidemiol 68(6):627–636

Bar-Massada A, Radeloff VC, Stewart SI (2014) Biotic and Abiotic Effects of Human Settlements in the Wildland–Urban Interface. Bioscience 64(5):429–437

Barnett PR, Whittingham MJ, Bradbury RB, Wilson JD Use of unimproved and improved lowland grassland by wintering birds in the UK. Agriculture(2004)Ecosystems & Environment, 102(1):49–60

Bea A, Svazas S, Grishanov G, Kozulin A, Stanevicius V, Astafieva T, Olano I, Raudonikis L, Butkauskas D, Sruoga A (2011) Woodland and Urban Populations of the Woodpigeon *Columba palumbus* in the Eastern Baltic Region. Ardeola Span Soc Ornithol 58(2):315–321

Beninde J, Veith M, Hochkirch A (2015) Biodiversity in cities needs space: a meta-analysis of factors determining intra-urban biodiversity variation. Ecol Lett 18:581–592

Bradter U, Kunin WE, Altringhan JD, Thorn TJ, Benton TG (2013) Identifying appropriate spatial scales of predictors in species distribution models with the random forest algorithm. Methods Ecol Evol 4:167–174

BTO (2019a) Bird Track. BTO, Thetford, Norfolk. Available: https://www.bto.org/. [Accessed: 22nd February 2019]

BTO (2019b) Map Store: Breeding Relative Abundance of Stock Dove. Available: https://app.bto.org/mapstore/StoreServlet?id=269 [Accessed: 11th July 2019]

Breiman L (2001) Random Forests. Mach Learn 45:5–32

Broughton RL (2019) Current and future impacts of nest preditation and nest-site competition by the invasive eastern grey squirrels *Sciurus carolinensis* on European birds. Mammel Rev 50:38–51

Buchhorn M, Smets B, Bertels L, De Roo B, Lesiv M, Tsendbazar NE, Herold M, Fritz S(2020) Copernicus Global Land Service: Land Cover 100m: collection 3: epoch 2019: Globe (Version V3.0.1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.3939050

Centre for Ecology & Hyrdology (2017) Landcover Map 2015 (LCM2015). [Online] [Accessed: 3rd March 2021] http://mapapps2.bgs.ac.uk/ukso/home.html?layer=CEHLCM2015

Chace JF, Walsh JJ (2006) Urban effects on native avifauna: a review. Landsc Urban Plann 74(1):46–69

Craig S, Selonen V, Koprowski J(2016) Grey squirrel nesting ecology and the use of nest sites in European population management. In:349–368

Crooks KR, Suarez AV, Bolger DT (2004) Avian assemblages along a gradient of urbanization in a highly fragmented landscape. Biol Conserv 115(3):451–462

Davis A, Major RE, Taylor CE (2014) Distribution of tree-hollows and hollow preferences by parrots in an urban landscape. Emu - Austral Ornithology Taylor & Francis 114(4):295–303

Didham RK, Tylianakis JM, Hutchison MA, Ewers RM, Gemmell NJ (2005) Are invasive species the drivers of ecological change? Trends Ecol Evol 20(9):470–474

eBird eBird: An online database of bird distribution and abundance [web application]. eBird(2019) Ithaca, New York. Available: https://www.ebird.org/. [Accessed: 2nd January 2019]

European Space Agency (2020) Sentinel Online - ESA. [Online] [Accessed on 6th May 2020] https://sentinel.esa.int/web/sentinel/home

Faeth SH, Bang C, Saari S (2011) Urban biodiversity: patterns and mechanisms, vol 1223. Annals of the New York Academy of Sciences, pp 69–81

Fey K, Vuorisalo T, Lehikoinen A, Selonen V (2015) Urbanisation of the wood pigeon (*Columba palumbus*) in Finland. Landsc Urban Plann 134(February):188–194

Fernández-Juricic E (2000) Avifaunal Use of Wooded Streets in an Urban Landscape. Conserv Biol 14(2):513–521

Fernández-Juricic E (2001) Avian spatial segregation at edges and interiors of urban parks in Madrid. Spain Biodivers Conserv 10(8):1303–1316

Forestry Commission (2017) National Forest Inventory for England 2017. Available: https://data.gov.uk/dataset/08312b42-006c-48d9-8ddc-4544d4dbe9bf/national-forest-inventory-woodland-england-2017 [Accessed: 27th December 2018]

Fox EW, Hill RA, Leibowitz SG, Olson AR, Thornburgh DJ, Weber MH (2017) Assessing the accuracy and stability of variable selection methods for random forest modeling in ecology. Environ Monit Assess 189:316

Fuller RJ, Chamberlain DE, Burton NHK, Gough SJ (2001) Distributions of birds in lowland agricultural landscapes of England and Wales: How distinctive are bird communities of hedgerows and woodland? Agriculture. Ecosyst Environ 84(1):79–92

Genuer R, Poggi JM, Tuleau-Malot C (2010) Variable selection using random forests. Pattern Recognit Lett 31(14):2225–2236

Greater Manchester Green Summit [Online] [Accessed 2nd February 2022](2021) https://gmgreencity.com/measuring-greater-manchesters-green-and-blue-spaces-creating-an-urban-green-infrastructure-baseline/

Greenspace Information for Greater London CIC (2022) [Online] [Accessed 2nd February 2022] https://www.gigl.org.uk/keyfigures/

Grimm NB, Foster D, Groffman P, Grove JM, Hopkinson CS, Nadelhoffer KJ, Pataki DE, Peters DP (2008) The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients. Front Ecol Environ 6:264–272

Hewson CM, Fuller RJ (2003) Impacts of Grey Squirrels on Woodland Birds: An Important Predator of Eggs and Young? The Nunnery, Thetford, Norfolk, IP24 2PU. British Trust for Ornithology, UK

Isaksson C (2018) Impact of Urbanization on Birds. In: Tietze DT (ed) Bird Species: How They Arise, Modify and Vanish. Springer International Publishing, Cham, pp 235–257. (Fascinating Life Sciences)

James G, Witten D, Hastie T, Tibshirani R (2013) An Introduction to Statistical Learning: with Applications in R. Springer, New York

Jokimäki J, Suhonen J, Jokimäki-Kaisanlahti ML, Carbó-Ramírez P(2016) Effects of urbanization on breeding birds in European towns: Impacts of species traits. Urban Ecosystems. Springer New York LLC, 19(4):1565–1577

Kosiński Z, Bilińska E, Dereziński J, Kempa M(2011) Nest-sites used by Stock Doves *Columba oenas*: what determines their occupancy?Acta Ornithologica, 46(2)

Kuhn M, Johnson K (2013) Over-Fitting and Model Tuning. Applied Predictive Modeling. Springer, New York, NY. https://doi.org/10.1007/978-1-4614-6849-3_4

Lees AC(2018) Interspecific conflict structures urban avian assemblages. Proceedings of the National Academy of Sciences of the United States of America.National Academy of Sciences:12331–12333

Lepczyk CA, Aronson MFJ, Evans KL, Goddard MA, Lerman SB, Macivor JS (2017) Biodiversity in the City: Fundamental Questions for Understanding the Ecology of Urban Green Spaces for Biodiversity Conservation. BioScience. Oxford University Press, pp 799–807

Liew A, Wiener M (2002) Classification and Regression by randomForest. R News 2(3):18–22

Manchester Birding (2019) Manchester Birding Forums. [Online] [Accessed: 10th April 2019] https://manchesterbirding.activeboard.com/

Manchester City of Trees Team and the GM Combined Authority (2019) Manchester City of Trees Audit Data. Salford. (Provided: 19th March 2019). https://www.cityoftrees.org.uk/

Martin AE, Desrochers A, Fahrig L (2017) Homogenization of dispersal ability across bird species in response to landscape change. Oikos Blackwell Publishing Ltd 126(7):996–1003

McKinney ML (2006) Urbanization as a major cause of biotic homogenization. Biol Conserv (Urbanization) 127(3):247–260

Merow C, Smith MJ, Silander JA (2013) A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. Ecography 36:1058–1069

Murton RK, Westwood NJ, Isaacson AJ (1964) The Feeding Habits of the Woodpigeon *Columba Palumbus*, Stock Dove *C. Oenas* and Turtle Dove *Streptopelia Turtur*. Ibis 106(2):174–188

Natural England (2019) Local Nature Reserves (England). [Online] [Accessed on 15th January 2019] https://naturalengland-defra.opendata.arcgis.com/datasets/local-nature-reserves-england

Newson SE, Leech DI, Hewson CM, Crick HQP, Grice PV (2009) Potential impact of grey squirrels *Sciurus carolinensis* on woodland bird populations in England. J Ornithol 151(1):211

Newson SE, Johnston A, Parrott D, Leech DI (2011) Evaluating the population-level impact of an invasive species, Ring-necked Parakeet *Psittacula krameri*, on native avifauna. Ibis 153(3):509–516

Nielsen AB, van den Bosch M, Maruthaveeran S, van den Bosch CK (2014) Species richness in urban parks and its drivers: A review of empirical evidence. Urban Ecosyst 17(1):305–327

Ó hUallacháin D(2014) Nest Site Location and Success Rates of an Urban Population of Woodpigeon *Columba Palumbus* in Ireland. Biology and Environment: Proceedings of the Royal Irish Academy. Royal Irish Academy, 114B(1):13–17

Open Source Geospatial Foundation (2019) GeoTools: an open source (LGPL) Java code library which provides standards compliant methods for the manipulation of geospatial data. Open Source

Geospatial Foundation. Available: https://geotools.org/ Version: 19.4

OpenStreetMap contributors (2015) Planet dump [Data file included with QGIS]

Ordnance Survey (2018a) OS Open Greenspace: the location of public parks, playing fields, sports facilities, play areas and allotments. Includes function and name. Available: https://www.ordnancesurvey.co.uk/business-government/products/open-map-greenspace [Accessed: 23rd December 2018]

Ordnance Survey (2018b) OS Open Master Map Topography: the most detailed and accurate view of Great Britain's landscape – from roads to fields, to buildings and trees, fences, paths and more. Available: https://www.ordnancesurvey.co.uk/business-government/products/mastermap-topography [Accessed: 16th January 2019]

Ordnance Survey (2018c) OS Open Roads: Motorways, A-roads, B-roads, road classification, road name, primary route information, motorway junction information. Available: https://www.ordnancesurvey.co.uk/business-government/products/open-map-roads [Accessed: 21st December 2018]

Peel MC, Finlayson BL, McMahon TA(2007) Updated world map of the Koppen-Geiger climate classification. Hydrol. Earth Syst. Sci. 2007 (11):1633–1644

Phillips SJ, Dudík M, Schapire RE(2019) Maxent software for modelling species niches and distributions (Version 3.4.1). Available: http://biodiversityinformatics.amnh.org/open_source/maxent/. [Accessed: February 2019]

Pinho P, Correia O, Lecoq M, Munzi S, Vasconcelos S, Gonçalves P, Rebelo R, Antunes C, Silva P, Freitas C, Lopes N, Santos-Reis M, Branquinho C (2016) Evaluating green infrastructure in urban environments using a multi-taxa and functional diversity approach. Environ Res 147:601–610

Purevdorj TS, Tateishi R, Ishiyama T, Honda Y (1998) Relationships between percent vegetation cover and vegetation indices. Int J Remote Sens 19:18:3519–3535

QGIS Development Team (2019) QGIS Geographic Information System. Open Source Geospatial Foundation Project. http://qgis.osgeo.org. Version: 3.8.3

Robinson RA BirdFacts: profiles of birds occurring in Britain & Ireland.BTO, Thetford(2005) (http://www.bto.org/birdfacts, accessed on 24 February 2021)

RStudio Team (2015) RStudio: Integrated Development for R. RStudio, Inc., Boston, MA URL http://www.rstudio.com/ Version: 1.2.5042

Shochat E, Warren PS, Faeth SH, McIntyre NE, Hope D (2006) From patterns to emerging processes in mechanistic urban ecology. Trends Ecol Evol 21:186–191

Snow D, David W, Perrins C, Gillmor R (1998) The birds of the western palearctic. Non-passerines, vol 1. Oxford University Press, Concise ed., Oxford

Sol D, González-Lagos C, Moreira D, Maspons J, Lapiedra O (2014) Urbanisation tolerance and the loss of avian diversity. Ecol Lett 17(8):942–950

Sol D, Trisos C, Múrria C, Jeliazkov A, González-Lagos C, Pigot AL, Ricotta C, Swan CM, Tobias JA, Pavoine S (2020) The worldwide impact of urbanisation on avian functional diversity. Ecol Lett 23:962–972

Spotswood EN, Beller EE, Grossinger R, Grenier JL, Heller NE, Aronson MFJ (2021) The Biological Deserts Fallacy: Cities in Their Landscapes Contribute More than We Think to Regional Biodiversity. BioScience. Oxford University Press (OUP), January

Stanbury A, Eaton M, Aebisher N, Balmer D, Brown A, Douse A, Lindley P, McCulloch N, Noble D, Win I (2021) The status of our bird populations: the fifth Birds of Conservation Concern in the United Kingdom, Channel Islands and Isle of Man and second IUCN Red List assessment of extinction risk for Great Britain. Br Birds 114:723–747

Strubbe D, Matthysen E (2007) Invasive ring-necked parakeets *Psittacula krameri* in Belgium: habitat selection and impact on native birds. Ecography 30(4):578–588

Struebig MJ, Turner A, Giles E, Lasmana F, Tollington S, Bernard H, Bell D(2013) Chapter Three - Quantifying the Biodiversity Value of Repeatedly Logged Rainforests: Gradient and Comparative Approaches from Borneo. In Woodward G and O'Gorman EJ (eds) Advances in Ecological Research. Academic Press (Global Change in Multispecies Systems: Part 3):183–224

Threlfall CG, Law B, Banks PB(2012) Influence of Landscape Structure and Human Modifications on Insect Biomass and Bat Foraging Activity in an Urban Landscape.PLOS ONE7(6)

Werner P (2011) The ecology of urban areas and their functions for species diversity. Landscape Ecol Eng 7(2):231–240

With KA, King AW (2001) Analysis of landscape sources and sinks: the effect of spatial pattern on avian demography. Biol Conserv 100(1):75–88

Woodward I, Aebischer N, Burnell D, Eaton M, Frost T, Hall C, Stroud DA, Noble D (2020) Population estimates of birds in Great Britain and the United Kingdom. Br Birds 113:69–104

Yackulic CB, Chandler R, Zipkin EF, Royle JA, Nichols JD, Grant EHC, Veran V (2012) Presence-only modelling using MAXENT: when can we trust inferences? Methods Ecol Evol 4:236–243

Supplementary information The online version contains supplementary material available at https://doi.org/10.1007/s11252-022-01283-y.