

# DO HABITAT AND THERMAL CONDITIONS EXPLAIN THE PAST, PRESENT AND FUTURE DISTRIBUTIONS OF BRITISH ROSE-RINGED PARAKEETS?

by

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## Abstract

The distributions of birds around the world are rapidly changing due to anthropogenic habitat and climate change. In this changing world, birds are indicators of the health or ill health of natural systems. Knowing the distributions of birds allows us to monitor the impacts of the changes humans have made to the planet, identify future threats to biodiversity, ecosystem services and to monitor potential hosts of zoonotic diseases. Introduced, invasive species can be especially harmful as they are released from their natural predators, and once established can adapt to their introduced range. Invasive species are those species that can cause harm to natural ecosystems or reduce populations of native species, or affect the profitability of economic activities, or cause ill-health in humans.

One well known invasive species is the Rose-ringed Parakeet (RRP) (*Psittacula krameri*), introduced to Great Britain (GB) through the trade in cage birds, from their native range in sub-tropical and tropical Africa and Asia. Having established a population of 8,600 breeding pairs in GB by 2013, mostly in or close to London, RRP are showing signs of colonising wider parts of GB.

This study uses data collected by volunteer bird surveyors on behalf of the British Trust for Ornithology (BTO) for the Bird Atlas 2007-2011, and supplements it with data gathered through a newly created website for gathering sighting details of RRP in GB. The website data shows that colonisation of GB by RRP is ongoing. The Atlas data combined with habitat data, data on the density of humans and other environmental data at a 1km resolution, was then used to create Species Distribution Models (SDMs), using statistical and spatial software and validated using the website data, for the winter and the breeding season, that show RRP distributions are limited mainly by

ambient temperatures, but have the potential to colonise wider parts of the milder south-western GB.

Those SDMs were then adapted to 5km resolution to enable use of predictions of future climates made by the Met Office Hadley Centre. The new SDMs enabled the creation of predicted future distributions of RRP in GB for 2021, 2031, 2061 and 2071. These show that as ambient temperatures rise with climate change, RRP will be able to expand their range in GB. Expanding their range will bring RRP into contact with more native species. Although RRP are often thought of as birds of suburbia in GB, occupying more towns and cities will lead to easier access to rural areas surrounding those towns, which is likely to lead to more serious depredations on crops.

RRP distributions have been mainly within the cities of GB, and the pattern of colonising cities before rural areas may be one means of natural colonisation of GB by birds able to utilise human-altered habitats, or by other newly introduced species.

## **Dedication**

For Jane Flowers, thank you.

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## Abbreviations and Definitions

|         |                                                              |
|---------|--------------------------------------------------------------|
| AUC/ROC | Area under the curve/Receiver Operating Characteristic curve |
| BBC     | British Broadcasting Corporation                             |
| BNG     | British National Grid                                        |
| BTO     | British Trust for Ornithology                                |
| CEH     | UK Centre for Ecology and Hydrology                          |
| CI      | Confidence Interval                                          |
| COR     | Correlation                                                  |
| DEFRA   | Department for Environment, Food and Rural Affairs           |
| Dev     | Deviance                                                     |
| GB      | Great Britain                                                |
| GIS     | Geographical Information Systems                             |
| GLM     | Generalised Linear Model                                     |
| ha      | hectare                                                      |
| HDD     | Heating Degree Days                                          |
| km      | Kilometre                                                    |
| LCM     | Land Cover Map                                               |
| LCT     | Lower Critical Temperature                                   |
| m       | Metre                                                        |
| MaxEnt  | Maximum Entropy                                              |
| NetCDF  | Network Common Data File                                     |
| NR      | Not Retained                                                 |
| NS      | Not Significant                                              |
| OS      | Ordnance Survey                                              |
| ROC     | Receiver Operating Characteristic curve                      |
| RRP     | Rose-ringed Parakeet                                         |
| RSPB    | Royal Society for the Protection of Birds                    |
| SD      | Standard Deviation                                           |
| SDM     | Species Distribution Model                                   |
| sen     | Sensitivity                                                  |
| sp      | Specificity                                                  |
| TNZ     | Thermo-neutral Zone                                          |
| TSS     | True Skills Statistic                                        |
| TTV     | Timed Tetrad Visit                                           |
| UHI     | Urban Heat Island                                            |
| UK      | United Kingdom                                               |

# CHAPTER 1: GENERAL INTRODUCTION

## 1.1 Animal distributions and niches

There has long been a fascination with the reasons why species are found in certain areas, but not others. While some animals are widespread, others have limited distributions, no species can be found everywhere in the world (Krebs, 2014). There are a number of factors that influence distributions of animals, including habitats, climate and many others (Krebs, 2014).

For individuals of all species, three factors are always required. These are an available space; a space where all the climate variables and other non-biological factors are appropriate for the species to live, known as an abiotic space; and a space where the species can access food, shelter and breed: the biotic space. Where these three factors overlap, available space, abiotic space and biotic space, is known as the fundamental niche (Kearney and Porter, 2009).

The fundamental niche describes the area in which a species is capable of surviving without any competitors or predators. Some areas of the fundamental niche may be unsuitable for a species due to excessive competition or predation risks due to other organisms. The area of the fundamental niche where an organism is able to live despite competitors and predators, is the realised niche (Kearney and Porter, 2009).

The realised niche is basically the area within which the species is normally found, its native range. The climate variables that are found all over this realised niche, the temperature range, rainfall range and other climatic variables, is termed the climate

envelope (Krebs, 2014). The climate envelope includes all of the climatic variables that the species will normally encounter in its native range.

## **1.2 Biotic and abiotic factors**

The biotic space includes all of the biological factors that define the area within which the species lives. This covers the habitats that the species uses, such as woodlands, heaths, grassland, etc. Some areas of habitat are better than others. Habitat that is not ideal, may be occupied by some individuals of the species that are not able to compete against conspecifics for better quality habitats. In habitats that are less good than others, individuals may struggle to survive or reproduce, but as long as the species can persist in those areas, they remain part of the realised niche.

For some species, such as the Great Spotted Woodpecker (*Dendrocopus major*), the presence of mature trees in a woodland habitat is essential for excavation of nesting cavities (Pasinelli, 2007). Other bird species, such as Blue Tits (*Cyanistes caeruleus*) and Great Tits (*Parus major*), also require tree cavities in which to nest but are unable to excavate them themselves, instead relying on cavities previously excavated by woodpeckers (Robles et al., 2011). For woodpeckers the woodland is part of the realised niche, but for Blue Tits, the woodland can only be part of the realised niche if there are suitable nesting cavities present in the woodland. Without the nest cavities in a woodland, the woodland cannot sustain the Blue Tits as they have nowhere to breed. Occupation of habitat by individual species is density-dependent. Where an area of habitat has too many individuals and competition is too fierce, some individuals may move to another location in order to find better access to their required resources: this is density-dependent dispersal (Matthysen, 2005; Maag et al., 2018). An example

of density-dependent dispersal is the movement of birds away from the densest parts of a Blue-footed Booby (*Sula nebouxii*) breeding colony (Kim et al., 2009).

Habitats often change over time because of ecological processes such as natural succession (Zhang et al., 2017; Miller-Adamany et al., 2019), changes in fauna that impact, for example, flora (Holt et al., 2011; Newson et al., 2012), and anthropogenic impacts such as scrub clearance to improve European Nightjar (*Caprimulgus europaeus*) breeding habitats (Mitchell et al., 2020) and canal dredging altering the hydrodynamics of coastal lagoons used by breeding seabirds (Mellink and Riojas-López, 2017). Anthropogenic impacts on habitat can involve the conversion of natural habitats into heavily managed ones such as farmland (Clark et al., 2006; Jeanneret et al., 2021) or into built space such as if found in villages, towns and cities (Bai et al., 2019; Wang et al., 2020). The urbanisation of areas of countryside has already happened in many places, resulting in large cities such as London and Birmingham. Cities can be good habitats for many birds due, in part, to the variety of trees and plants to be found in many parks and gardens (Schütz and Schulze, 2015; Tryjanowski et al., 2017; Kotsiotis et al., 2019).

The primary abiotic factors that influence the distributions of animal species are water availability and temperature. Mallards (*Anas platyrhynchos*) feed mostly in or close to water (Cramp, 1983) and White-throated Dippers (*Cinclus cinclus*) require the right rate of flow in rivers and streams (Royan, 2015). Elevation can be highly influential in influencing distributions of animals. For example, Bridled Titmice (*Baeolophus wollweberi*), Juniper Titmice (*Baeolophus ridgwayi*) and Mountain Chickadees (*Poecile gambeli*) occupy similar habitats but their distributions are defined by a vertical gradient which alters the ambient temperatures, with each species being found

within different altitude bands (Weathers and Greene, 1998; Cooper and Gessamen, 2004).

### 1.3 Ambient temperature and energetics of birds

One energetic demand on birds (endotherms) is to maintain a stable body temperature: homeothermy. If ambient temperatures are above or below a certain range of temperatures, known as the thermo-neutral zone (TNZ) (Scholander et al., 1950), a bird needs to expend energy reducing or increasing its body temperature (see Figure 1.1). Each species has its own range of temperatures, within which it can maintain its body temperature through adjusting the rates of heat production and heat loss, whilst expending minimal energy.

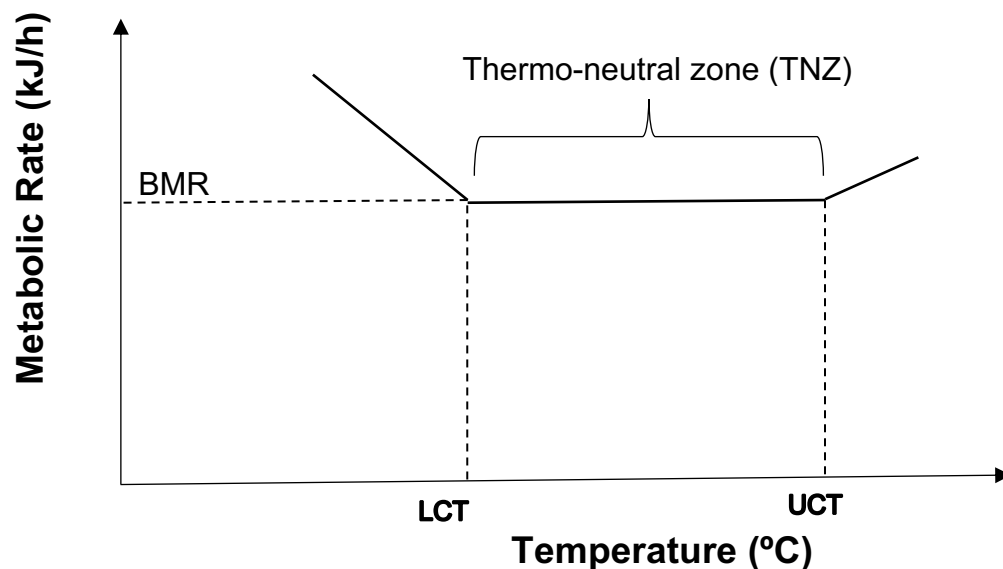


**Figure 1.1** The relationship between metabolic rate (kJ/h), basal metabolic rate (BMR) (kJ/h) and ambient temperature (°C) for an endothermic bird. Showing the increase in metabolism at temperatures below the Lower Critical Temperature (LCT) and above the Upper Critical Temperature (UCT), and the metabolically neutral range of temperatures known as the Thermo-Neutral Zone (TNZ) in a hypothetical bird (after Scholander et al., 1950)

The TNZ is bounded by the lower critical temperature (LCT; Fig. 1.1) and the upper critical temperature (UCT; Fig. 1.1). Each species of endothermic animal has a unique TNZ (Scholander et al., 1950b). Within the TNZ body temperature is maintained by mechanisms that require little energetic investment above the basal metabolic rate, but when ambient temperatures fall below the LCT, the organism must generate more heat and raise its metabolic rate. When ambient temperatures fall below the LCT, the extra heat is generated through shivering, mostly involving the large muscle groups (Marjoniemi and Hohtola, 1999; Milbergue et al., 2018; Roussel et al., 2020). Energy can be made available by either increasing energy intake, or maintaining the same energy intake but reducing the amount of energy expended on activities other than generating heat.

#### **1.4 Energy investment strategies to survive cold weather**

For the majority of volant bird species the response to reduced ambient temperature is either to remain in situ, increasing energetic investment to survive, as Petit et al., (2013) found in resident Black-capped Chickadees (*Parus atricapillus*), or to invest energy in dispersing to areas where ambient temperatures are less challenging to their survival, as in migrating Mallard (*Anas platyrhynchos*) (. Another strategy is to move to warmer areas only when the temperature gets very cold, as demonstrated by the GB population of Northern Lapwing (*Vanellus vanellus*) (Wernham et al., 2002). The last strategy is to remain in the same place, all year round, as in the Winter Wren (*Troglodytes troglodytes*) (Wernham et al., 2002). Longer movements require more energy than short movements, have the advantage of more reliable warm weather, but are risky and the return in spring tends to be later than for shorter movements giving a possible advantage to earlier arrivals (Newton, 2010).

Staying in one location year-round requires more energy expenditure in winter to maintain body temperature, a time when ambient temperatures are more likely to fall below the LCT.

## 1.5 Climate

Ambient temperature and moisture/rainfall are often influential in determining the distributions of organisms (Krebs, 2014). The world can be divided into biomes: the characteristic vegetation type of areas of the world that share a similar climate (Krebs, 2014). Moderate temperatures (a temperate climate) and moderate rainfall favours the development of deciduous forests, higher rainfall produces temperate rainforests and lower rainfall tends to favour scrub.

Most terrestrial bird species exist within a certain range of climate variables, in the same way as plants. This range of climate variables can be deduced by examining the climate over the native range of a species and is known as a climate envelope. The climate envelope describes the abiotic features that apply over the native range (Cardador and Blackburn, 2020). The climate envelope is often used in species distribution modelling (Hijmans and Graham, 2006; Magness and Morton, 2018; Hanley et al., 2021). Although climate envelopes are often used to examine species distributions, 57 species of birds introduced into the UK are able to persist despite their UK range being completely outside the climate envelope of the native range (Border et al., 2018).

The fact that a species can live in a climate that differs from that in its native range can be explained. The native range is the realised niche of a bird species: the area where the bird's abiotic needs are met, **and** its biotic needs are met, despite competition and

predation. The fundamental niche of a species is the area within which a species could live if there were no competitors or predators. For most species, the realised niche is smaller than the fundamental niche and deriving a climate envelope from the species native range will not describe all areas in which the species is capable of living. In the case of an introduced species living in GB, the fundamental niche of that species may include GB, while the realised niche excludes GB. For a sedentary bird species introduced to GB from another continent, GB may never have been available for colonisation because a sedentary species would not normally cross an ocean.

## **1.6 Climate change**

Since 2002, the UK has experienced its top 10 warmest years since 1884 (Kendon et al., 2021). The decade 2011-2020 has been 0.5°C warmer on average compared to 1981-2010 and 1.1°C warmer than in 1961-1990 (Kendon et al., 2021). Over the last six decades ambient temperature, rainfall and periods of sunny weather have all markedly increased (Kendon et al., 2021). The UK's mean ambient temperature has increased marginally faster than the global average (Kendon et al., 2021). The comparison of mean temperatures at a global scale is difficult and complex (Stainforth et al., 2013). In Europe, the fastest warming is occurring on the coldest winter nights (Stainforth et al., 2013). For a bird whose distribution is limited by cold temperatures, temperatures rising most at the coldest time of year, will make it easier to survive in the coldest part of its range, and will enable colonisation of colder areas.

## 1.7 Study species

Among the more than 600 species of bird recorded in GB (McInerny et al., 2018) is the Rose-ringed Parakeet (*Psittacula krameri*) (RRP). This species is present in high numbers in London and in lower numbers in Birmingham, Manchester, and some other cities in GB (Balmer et al., 2013; Stanbury et al., 2021) and had a breeding population estimated at 12,000 breeding pairs in 2016 (Woodward et al., 2020). The species is native to sub-Saharan Africa and the Indian sub-continent (see Fig.1.2), having been brought to this country as cage birds (Butler, 2003; Peck, 2013; Peck et al., 2014; Jackson et al., 2015a; Arnold et al., 2017). They are medium-sized parrots (Juniper and Parr, 2003), with a body length of 30 cm and a wingspan of 45 cm. Males weigh 130-140 g and females approximately 110-120 g (Robinson, 2005; Butler et al., 2013).

The native range of RRP is sub-Saharan Africa, the Indian sub-continent and surrounding countries (Fig. 1.2), but established populations exist in at least 35 countries (Jackson et al., 2015a; Shiels et al., 2018). In GB, RRP is both alien (i.e. introduced) and invasive, i.e. capable of colonising an area and causing harm to biodiversity, native species, economic damage or injury to human health (Keller et al., 2011). The climate of GB does not match that of the native range of RRP, and the species is outside its climate window in GB (Border et al., 2018). In the native range RRP is found at up to 1,600 m elevation in the Indian Peninsular Highlands, and up to 1,300 m in the foothills of the Himalayas (Cramp, 1985). They are widespread and abundant in moist and dry areas, lightly wooded areas, secondary jungle, gardens, parks, orchards and cultivated lands, semi-desert and frequently close to human habitation, and avoid rocky areas, full deserts, forests and wetlands (Cramp, 1985).

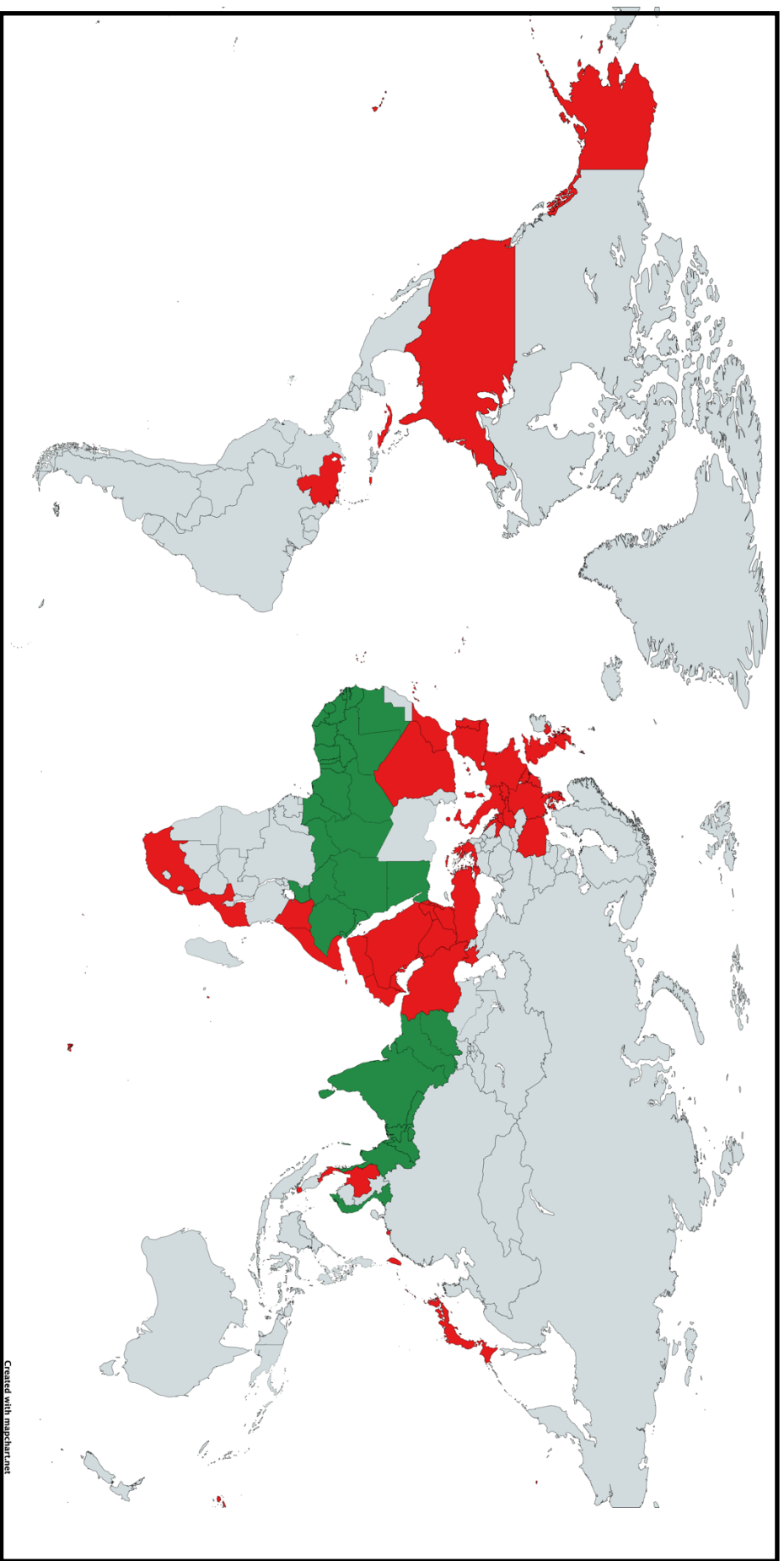


Figure 1.2 Map showing the countries where Rose-ringed Parakeets (RRP) (*Psittacula krameri*) occur naturally, in green, and countries with introduced populations, in red. RRP are not necessarily present across the whole country depicted here.



Figure 1.3 Adult male Rose-ringed Parakeet (*Psittacula krameri*), photographed in Richmond Park, London. © R. Bufton.

RRPs are well known as an agricultural pest in the native range where they consume Maize (*Zea mays*), Rice (*Oryza sativa*) and Sunflowers (*Helianthus annuus*) and others (Cramp, 1985; Babu and Muthukrishnan, 1987; Ahmad et al., 2011). In its introduced range RRP's can also be destructive, feeding on Apples (*Malus domestica*), Cherries

(*Prunus spp.*), Peas (*Pisum sativum*) and others (Butler, 2003; Shiels et al., 2018; Shiels and Kalodimos, 2019; Borray-Escalante et al., 2020). The diet of RRP in GB is broad and includes fruits, flowers, buds and seeds of many trees and plants (Butler, 2003; Peck, 2013) and are frequent visitors to many bird feeders (Butler, 2003; Clergeau and Vergnes, 2011; Peck, 2013; Peck et al., 2014; Pârâu et al., 2016).

While there are yet to be any proven impacts of RRP on native species of bird in GB (Newson et al., 2011), there is experimental evidence to show competitive exclusion from nest sites of Eurasian Nuthatches (*Sitta europaea*) in Belgium (Strubbe and Matthysen, 2009b) and reduced population numbers of Eurasian Nuthatch where RRP occur (Strubbe and Matthysen, 2007) and Eurasian Scops Owls in Italy (*Otus scops*) (Mori et al., 2017). Other impacts of RRP include killing native birds (Quesada et al., 2017) and Black Rats (*Rattus rattus*) (Hernández-Brito et al., 2014b) and impacts of parakeet droppings on vegetation below roost sites (Menchetti et al., 2016).

## **1.8 Thesis aims**

The first aim was to identify the current distribution of RRP in GB for comparison with their distribution found during timed tetrad visits (TTVs) for the British Trust for Ornithology's (BTO's) *Bird Atlas 2007-2011* (Balmer et al., 2013). This will enable the study to determine whether RRP are continuing to spread across GB. The second aim was to identify the environmental factors that explain the distribution of RRP in GB, through the use of Species Distribution Models (SDMs), in both the winter and the breeding seasons. The third aim was to attempt to establish the likely future distributions of RRP across GB using the SDMs to forecast future potential distributions by considering those variables that had the most explanatory power in describing past and current distributions of birds.

## 1.9 Thesis structure

Chapter 2 describes the creation of a website to collect RRP sightings and to compare sightings to the present day with those employed in the BTO's *Bird Atlas 2007-2011* (Balmer et al., 2013). This will identify whether the distribution of RRP in GB is currently stable, contracting or expanding.

Chapter 3 uses the census data from the BTO's *Bird Atlas 2007-2011* (Balmer et al., 2013) to develop a SDM of RRP distribution in GB in the winter and breeding seasons to identify the most powerful factors that best explain where RRP were present.

Chapter 4 uses the SDMs developed in winter and breeding seasons in the BTO's *Bird Atlas 2007-2011* (Balmer et al., 2013) to examine the predicted future distributions of RRP in GB in these seasons. This relied upon the availability of future predictions of important explanatory variables identified in previous chapters.

Chapter 5 contextualises the previous chapters' findings within a discussion framework examining the implications for RRP in GB. Challenges from increased conflicts between RRP, humans and native species will be discussed as part of considerations of further research that may enable better understanding of the colonisation mechanism for RRP expanding their range in GB.

## **CHAPTER 2: HARNESSING CITIZEN SCIENCE TO COLLECT PUBLIC RECORDS OF ROSE-RINGED PARAKEETS (*PSITTACULA KRAMERI*) IN GREAT BRITAIN**

### **2.1 ABSTRACT**

The distribution of Rose-ringed Parakeets (*Psittacula krameri*) (RRPs) in Great Britain (GB) has changed extensively since birds first bred less than six decades ago. These changes are documented in the four British Trust for Ornithology (BTO) Bird Atlases produced since this first breeding event in 1969. However, for distribution studies to be most relevant in the present day, recent data are imperative. To meet this need, a website was created to collect records of recent feral parakeet sightings made by observers in GB since the last BTO's *Bird Atlas 2007-11* (Balmer et al., 2013) was published. A total of 134 sightings of RRP's was collected via the website, including records beyond the limits of western and northern margins of range reported in the most recent BTO atlas, suggesting possible further colonisation of GB. Birds appeared to remain within urban/suburban areas as has been shown historically from BTO atlases. The records collated by the website will be used to validate models of the distribution of RRP's in GB produced from BTO data, to inform further analysis of the factors influencing the British distribution of RRP's.

**Keywords:** distributions; sightings; website.

## 2.2 INTRODUCTION

Knowing the distribution of birds enables assessments of their conservation status (Santini et al., 2019) the targeting of efforts to protect them and identification of threats to bird species (Morales and Bretagnolle, 2021). In addition, birds are often indicators of problems in ecosystems due to pollution (Vorkamp et al., 2009) and can act as reservoirs of zoonotic diseases, such as H5N1 'Bird 'Flu' (Matchett et al., 2013) and West Nile Virus (Brugman et al., 2013; Niczyporuk et al., 2015). In the United Kingdom, a report on the "State of the UK's Birds" is published annually, to aid in the producing and implementing policy and planning (Burns et al., 2020). In order to achieve all of these aims, some knowledge of where birds can be found is necessary, particularly when dealing with an introduced species that has the potential to cause, or may already be causing, harm to the native natural environment, such as Rose-ringed Parakeets (RRPs).

To examine the factors influencing the current distribution of RRPs, it is clearly essential to know where RRPs can be found. Ideally, this would come from official sources such as ongoing census efforts of the British Trust for Ornithology (BTO) atlas team but in the absence of these records, other methods need to be explored. There are three potential ways to obtain these data. The first is to collect them oneself which is clearly impractical at such a wide spatial scale. The second is to ask the general public (i.e. citizen scientists) for their assistance to gather current observations of birds. There is also the third option of using data collected for other projects, if there is an up-to-date source of such data. Therefore, this chapter sets out to collate RRP sightings data to the present day through the engagement with citizen scientists as

has been so effective in generating previous BTO atlases (Sharrock, 1976; Lack, 1986; Gibbons et al., 1993; Balmer et al., 2013).

The internet has enabled ecological and behavioural studies to be carried out effectively over broad spatial and temporal scales through the submission of records by citizen scientists. For example, murmurations of Common Starlings (*Sturnus vulgaris*) in the United Kingdom (UK) have been studied using surveys, photographs and video footage (Goodenough et al., 2017). The distribution, management and environmental conditions associated with the occurrence of non-native reeds (*Phragmites* spp.) in North America have been examined by Hunt et al. (2017) via an internet-based network of wetland managers. Furthermore, a large-scale project has allowed more integrated conservation management across the 17,504 islands of Indonesia (Vatresia et al., 2016, 2017; Ernawati et al., 2019), using Geographical Information Systems (GIS), satellite mapping and reports from wildlife sites across the country. Aide et al. (2013) even used sound recordings and automatic recognition of animal sounds to identify the species at listening stations, saving the recordings, species' identity, and location and time of each detection automatically to a web server. As in the case of the latter study in particular, such studies have the potential to generate large datasets on avian, amphibian, mammalian and insect vocalisations, activities, and occurrences. Citizen science is a commonly used approach by the BTO which runs several surveys that utilise the internet to collate and store information from the UK public. These surveys include the annual Breeding Bird Survey (Pearce-Higgins et al., 2020), the Ringing Scheme (British Trust for Ornithology, 2021), the Nest Recording Scheme (Robinson et al., 2020), the Non-Estuarine Waterbird Survey (NEWS) of 2015/2016 (Humphreys et al., 2020), and BirdTrack (Boersch-Supan et al., 2019; Johnston et al., 2020).

The main acknowledged limitation with citizen science approaches is the ongoing concern that citizen scientists may produce misleading information (Blaney et al., 2016; Wessels et al., 2019). However, several studies have found them to be robust as long as the coordinating researchers check all records post-submission for veracity and accuracy, removing any records that are considered to be unreliable (e.g. Boersch-Supan et al., 2019; Brown and Williams, 2019). Collecting sighting records of feral parakeets in GB has the advantage that there are few parakeet (Psittacidae) species in GB. The population of Monk Parakeets (*Myiopsitta monachus*) has been reduced from at least 76 birds in 2006, to possibly just 33 birds in 2015 (Arnold et al., 2017), through control measures taken by Natural England on behalf of the Department of Environment, Food and Rural Affairs (DEFRA) at a cost of £259,000 to remove 62 birds, 212 eggs and 21 nests over 4 years (DEFRA, 2014), leaving only individuals of a few other parrots, such as Alexandrine Parakeet (*Psittacula eupatria*), Blue-crowned Parakeet (*Aratinga acuticaudata*), Budgerigar (*Melopsittacus undulatus*) and other newly escaped birds, as possible confusion species.

This chapter describes the process of developing a web-based citizen science approach to collect data on sightings of RRP across Great Britain (GB). The ultimate aim of the chapter is to map the current locations of birds and to compare them with those presented in the BTO's *Bird Atlas 2007-2011* (Balmer et al., 2013), which totalled 382 sightings in the breeding season Timed Tetrad Visits (TTVs) and 599 in the winter TTVs, the former sightings occurring in almost all of the latter tetrads.

## 2.3 METHODS

As a preliminary investigative step, the harvesting of social media feeds for sightings of RRP's was explored. However, this quickly ran into difficulties as location data were rarely reported by users. This was most likely a result of privacy concerns but also could have been due to a desire to protect RRP's. As RRP's are an alien, invasive species in GB (Roy et al., 2020), many parakeet lovers are wary of disclosing information on the location of RRP's for fear of the possible culls that are reported in newspapers (Daily Mail Reporter, 2011; May, 2021; Gardner and Horton, 2021; Williams, 2021), though no cull has been authorised to date. To overcome this limitation, a website was developed to record sightings of RRP's.

The production of the website used a full stack of web coding tools (Anders, 2011; Abraham, 2015), including Python v.3.6.8 (Van Rossum and Drake, 2009), Django v.2.1 (Django Software Foundation, 2019), PostgreSQL v.11.14 (PostgreSQL Global Development Group, 2018) and SQLite v.3.27.2 (Hipp, 2019) with the code stored in GitLab for version control (<https://gitlab.bham.ac.uk>). The primary aim of the website was to enable citizens to log sightings of RRP's. To ensure that this was as simple as possible for the observer, web forms linked to a relational database were used to ensure that the observer's details only needed to be recorded once. Sightings were recorded for RRP's, with options selected from drop-down boxes to record supplementary information. The flow of information through the relational databases is shown in Figure 2.1 and the structure of the website and the drop-down box options are shown in Figures 2.2 to 2.9.

The website was hosted on a University of Birmingham server, run by the College of Life and Environmental Sciences as part of the Compute and Storage for Life Sciences (CaStLeS) resource.

The screenshot displays the 'Feral Parakeet Sightings' website interface. The top section, 'Observer Details', includes fields for Name, Address, and Email Address, along with a dropdown menu for 'Are you:' and a consent checkbox for 'I consent to be contacted about this sighting:'. The bottom section, 'Sightings Details', includes a large text area for 'Location of sighting:', a dropdown menu for 'Country of sighting:', and a 'Finding Latitude and Longitude' section with instructions and input fields for Latitude and Longitude. At the bottom, there are fields for 'Date of Sighting:' (dd/mm/yyyy), 'Do humans put out food for the birds in this area?', and 'Are woodpeckers breeding (making nest cavities) in this area?'.

## Feral Parakeet Sightings

Observer Details

Name:

Address:

Are you:

Please choose...

Email Address (to allow checking and feedback):

I consent to be contacted about this sighting:

Yes No

## Sightings Details

Location of sighting:

Country of sighting:

Please choose...

### Finding Latitude and Longitude

To find latitude and longitude on a computer, find the location on Google Maps, click on it, a box will appear on the map giving the latitude and longitude.

To find latitude and longitude on a mobile, find the location on Google Maps, tap and hold, a pin description will appear at the bottom of the screen, scroll down and next to a pin symbol will be the latitude and longitude.

Latitude (e.g. 52.4508):

Longitude (e.g. -1.9338):

Date of Sighting:

dd/mm/yyyy

Do humans put out food for the birds in this area?

Please choose...

Are woodpeckers breeding (making nest cavities) in this area?

Please choose...

Figure 2.1 Screenshot of Observer Details and Sightings Details sections of the Feral Parakeet Sightings website.

## Parakeet Details (We welcome records of no parakeets being seen)

Add another species

Species 1
Remove species 1

Species of parakeet sighted:

Please choose...

If "Other parakeet/parrot" selected above, please state scientific species name or hybrid type here:

Number of parakeets for each species seen:

Population Size:

1-5
6-10
11-20
21-50
51-100
101-1,000
1,001-10,000
10,000+

Foraging Range (please select all that apply):

Urban
Suburban
Rural
Unknown

Breeding Range (please select all that apply):

Urban
Suburban
Rural
Unknown

Population Trend:

Increasing
Stable
Decreasing
Unknown

Date this species was first seen at this location, where known

dd/mm/yyyy

☐ Date First Sighted Unknown

If a survey has been carried out, please give the name of the organisation that carried out the survey:

Date the survey was carried out, where known

dd/mm/yyyy

☐ Survey Date Unknown

Is this species of parakeet kept in captivity in this area?

Please choose...

Submit

Contact us: [parakeetsightingsstudy@contacts.bham.ac.uk](mailto:parakeetsightingsstudy@contacts.bham.ac.uk)

This website has been developed by Richard Bufton at [the University of Birmingham](#) with [the BEAR Software team](#).

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Figure 2.2 Screenshot of Parakeet Details section of the Feral Parakeet Sightings website.

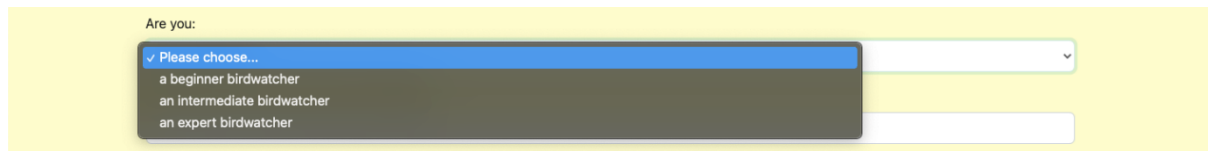


**Figure 2.3** Screenshot of options for expertise of observer on the Feral Parakeet Sightings website.

In addition to the fundamental code underpinning the website, additional tools were developed for data analysis and also added to GitLab. For example, as the location used for Geographical Information Systems (GIS) is normally either latitude and longitude or a projected national grid system, code was written for a program to convert a tetrad grid reference (identifying a  $2 \times 2$  km square of the British National Grid [BNG]) into a fully numerical grid reference for the centre of the tetrad and accurate to the nearest metre (Tetrad conversion.py; see Appendix 2.1). This enabled the use of GIS in the analysis of RRP distributions from the Bird Atlas data. The README file for the website is shown in Appendix 2.1. All other code can be found at <https://gitlab.bham.ac.uk/rdb781>.

The website (<https://www.parakeetsightings.bham.ac.uk>) went live in April 2019, and was launched via a dedicated social media campaign utilising both Twitter and Facebook, where a number of photographs and tweets were posted across groups (e.g. ornithological groups, wildlife trusts and other conservation/research groups) using the hashtags: #feralparakeets; #parakeets; #parakeetsightings; and #AlienInvasiveSpecies. These groups were identified by searching Facebook and Twitter using search terms such as 'Wildlife Trust', 'Bird', 'Birdwatching', 'Ornithology', 'Conservation', and 'Nature'.

There was also an opportunity to promote the website on the BBC's Springwatch programme (Springwatch, 2019), where the researcher was interviewed about feral RRP's and their presence in cities across GB. A T-shirt was worn with the website's web address on it, inviting reports of sightings. The item was broadcast live (no recording is currently available on either the BBC iPlayer or the YouTube.com website) from the Royal Society for the Protection of Birds' (RSPB's) Sandwell Valley Nature Reserve, where RRP's are regular visitors to the bird feeders located close to the visitor centre.

It was hoped that the BBC Springwatch appearance might result in a link to the sightings website being posted on the BBC Springwatch website (<http://bbc.co.uk/programmes/b007qgm3>). This did not happen, as the programme's website was carrying out its own survey and the website organisers decided against featuring any other survey's website.

## **2.4 RESULTS**

The social media campaign had an immediate impact, resulting in a number of sightings being recorded through the website. Initial activity on social media was intense. As soon as posting on social media was reduced from 50+ posts per day by the researcher to more normal levels of just one or two posts per day, sighting records reduced dramatically. More sightings were recorded during another social media campaign in late-May 2019. Thirty-eight sightings recorded via the website related to sightings made before the website went live. The number of sightings reported rose from 19 at the end of May, 2019, to 53 in late June, 2019, the Spring Watch programme having aired in early June, 2019.

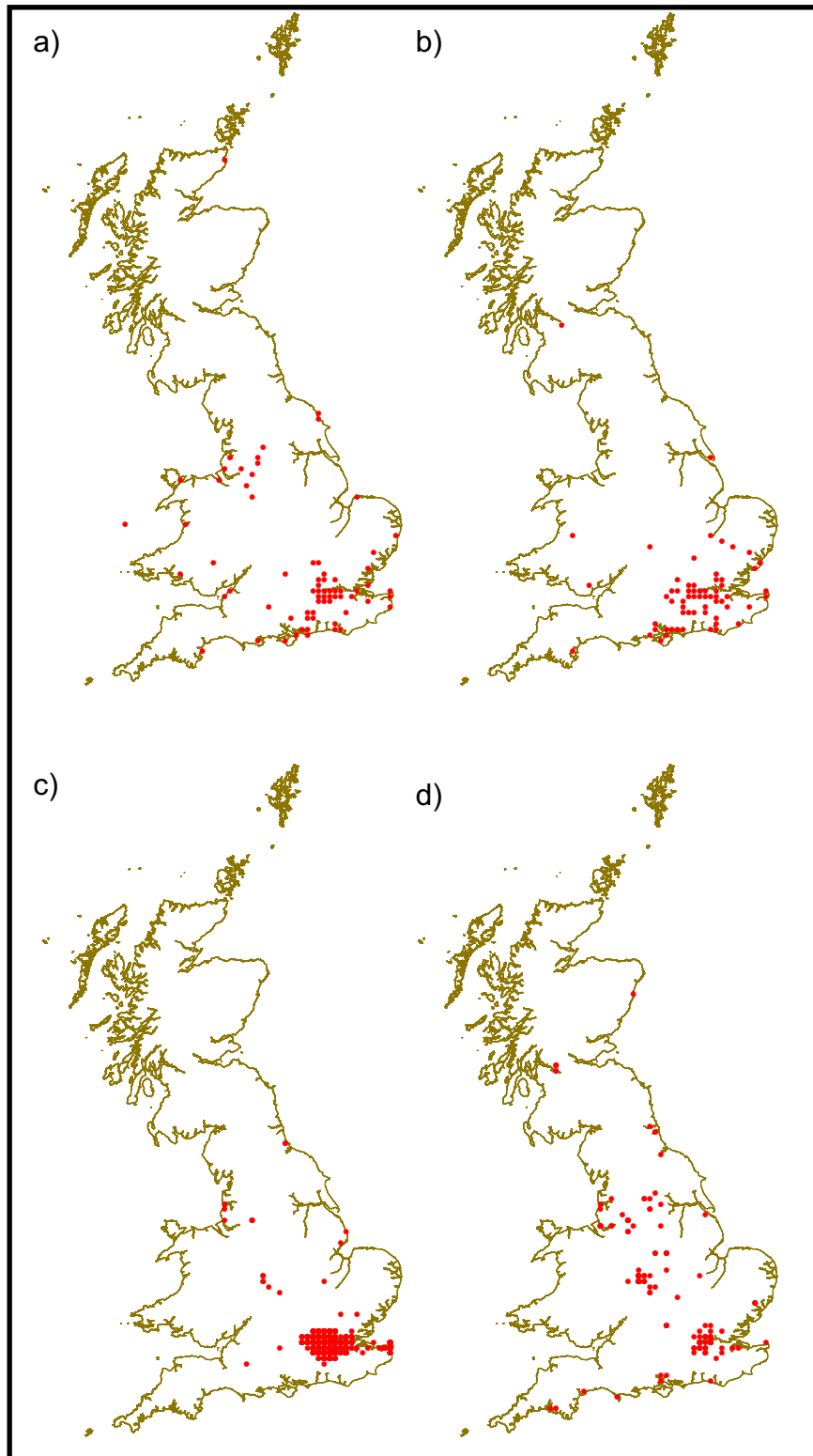


**Figure 2.4** The distributions of Rose-ringed Parakeets (*Psittacula krameri*) in GB from census work associated with the BTO atlases of birds in a) 1980-1984 (Lack, 1986), b) 1998-1991 (Gibbons et al., 1993), and c) 2007-2011 (Balmer et al., 2013), and d) from birds reported in 2019-2021 to the Feral Parakeets Sightings Website (<https://www.parakeetsightings.bham.ac.uk>).

The website brought in a total of 161 GB sighting records of feral parakeets. These sightings were screened to remove those where the species may have been misidentified and where the location was inaccurate, leaving 133 RRP records. Of these, 60 were submitted by observers who self-rated their expertise as “Beginner Birdwatcher”, 14 from “Intermediate Birdwatchers” and 60 from “Expert Birdwatchers”. The distribution of RRP sightings across GB is shown in Figure 2.4d. Also plotted are the distributions of RRP from census work associated with the BTO bird atlases from the 1980s (Fig. 2.4a), 1990s (Fig. 2.4b), and 2007-2011 (Fig. 2.4c).

When reporting sightings to the website, in addition to recording the latitude and longitude of the sighting location, it was possible for the observer to give extra contextual details of the sightings. The extra detail highlighted that most of the sightings (91.7%) were from parks and gardens in built-up areas, particularly in large conurbations (e.g. London, Birmingham, Manchester) and seaside towns (e.g. Plymouth, Margate, and Lytham St Anne’s), while only 8.3% of sightings were from rural areas (all close to an urban area).

Table 2.1 shows that the London region had most reports of RRP, with the West Midlands close behind. It is likely that this study being carried out at the University of Birmingham, and the Spring Watch program (Spring Watch, 2019) being hosted just outside Birmingham played some part in so many reports of RRP being seen in the West Midlands. The North-West region saw many reports from Manchester and around the Mersey estuary. The South-East region also saw plenty of reports of RRP, mainly close to London or along the south side of the Thames estuary, with another grouping of reports in Southampton.

**Table 2.1** The number of sightings of Rose-ringed Parakeets (*Psittacula krameri*) reported to the parakeet sightings website by region of England and Scotland (no sightings were reported from Wales).

| Country  | Region                   | Number of Sightings Reported |
|----------|--------------------------|------------------------------|
| England  | London                   | 32                           |
|          | West Midlands            | 31                           |
|          | North-West               | 18                           |
|          | South-East               | 16                           |
|          | Yorkshire and the Humber | 9                            |
|          | East of England          | 7                            |
|          | East Midlands            | 7                            |
|          | South-west               | 4                            |
|          | North-East               | 4                            |
| Scotland | Glasgow                  | 5                            |
|          | North-East of Scotland   | 1                            |

The reports from the North-East included reports from Newcastle-upon-Tyne and Sunderland. The East of England saw reports from Ipswich (2) and Peterborough (1), with the other reports being close to London. The East Midlands sightings were clustered mainly around Nottingham but included single reports from Derby and Leicester. Yorkshire and the Humber had one report from the coast of South Humberside, with the others being in the towns and cities of South and West Yorkshire.

The South-West region saw reports from Weymouth, Exmouth and two from Plymouth (one report mentioned that RRP had been present for several years). Scotland saw five sightings reported from Glasgow and one sighting reported from Aberdeen.

During the 2007-2011 TTVs, RRP was found as far north as Hartlepool. The website data shows a presence of RRP in Newcastle, Aberdeen and Glasgow. In discussion with an employee of NatureScot (formerly Scottish Natural Heritage), the author was told of rumours of RRP breeding in Glasgow. This is confirmed by the fact that RRP is now listed on the Scottish Bird List (maintained by the Scottish Birds Records Committee) as a naturalised breeding bird (Scottish Birds Records Committee, 2021).

## **2.5 DISCUSSION**

Whilst it is clear that a citizen science approach can produce numerous records of RRP, it is also true that concerted and continuous effort is needed to encourage observers to report sightings. It is necessary to remember that the likelihood of an RRP being seen and reported will play a role in the number of sightings reported. In areas where the RRP is present in large numbers, observers may be less likely to report sightings of RRP because they are so common. In areas where RRP are new arrivals, the novelty of the birds may lead to an increased probability of the sighting being reported.

The Feral Parakeet Sightings website was successful in that it provided a set of more recent sightings of RRP sightings from across GB. The number of sightings reported each month appeared to relate to the effort put into the social media campaign. The total of 133 sightings submitted to the website was smaller than the 382 during the

breeding season and the 599 in the winter generated from TTVs for the BTO's *Bird Atlas 2007-2011* (Balmer et al., 2013). The smaller number of sightings recorded on the website reflects the shorter period of collection of records and the relatively low publicity for the website, compared to the publicity required for the BTO to attract surveyors to cover the whole of Britain and Ireland.

The sightings of RRP recorded by the website included records in parts of GB where RRP were not present during the Timed Tetrad Visits that formed the bulk of the survey work for the Bird Atlas 2007-2011 (Balmer et al., 2013). Records from further west (Plymouth) and further north (Newcastle, Glasgow and Aberdeen) suggest that RRP are continuing to expand their range in GB.

Figure 2.4 appears to demonstrate that RRP reported to the website (Fig. 2.4d) have a similar distribution to those produced from the TTVs (cf. Figs 2.4a-c). However, Table 2.1 shows that the distribution of sightings around GB, is somewhat different from the London-dominated distribution of the TTVs for the Bird Atlas. Figure 2.4d has a number of sightings of RRP in a small area around the West Midlands conurbation, which are not clearly differentiated at such a small scale. London remains a stronghold for RRP in GB, with RRP being the most numerous bird species recorded during TTVs for nine tetrads in London, suggesting an under-reporting of RRP sightings to the website in London, when compared to the coverage of the three Atlases whose distributions are highlighted in Figure 2.4 (Lack, 1986; Gibbons et al., 1993; Balmer et al., 2013). It is worth noting that the methodology used for the TTVs for the Bird Atlas 2007-2011 (Balmer et al., 2013), aiming to cover every tetrad in GB, is very different to the methodology of the sightings reported to the website, asking members of the public to

report sightings of RRP. This different methodology will explain some of the difference in the distribution of records found through TTVs and the website.

Figure 2.4 and Table 2.1 demonstrate that RRP can be found across most of GB, though there were no sightings of RRP reported to the website. RRP has now appeared in Newcastle-upon-Tyne and Glasgow, and has been confirmed as breeding in Glasgow (Scottish Birds Records Committee, 2021). In addition, RRP was reported to the website as having been present in Plymouth for some years. The distribution of RRP across GB appears to still be widening.

The colonisation of GB by RRP has been ongoing since the first successful breeding in 1969 (Lever, 1973) on the borders of Kent and London. The first atlas of breeding birds covered the period within which the first successful breeding of RRP in GB occurred, and did not include RRP as the population was very small and at that point not proven to be self-sustaining (Sharrock, 1976). Figure 2.4 shows the gradual spread of RRP across GB, as demonstrated by the three BTO-produced bird atlases to feature the species (Lack, 1986; Gibbons et al., 1993; Balmer et al., 2013) and the data from the Feral Parakeet Sightings website.

The majority of sightings reported to the website were from towns and cities (91.7%). The distributions of RRP reported by the three Bird Atlases to include the species also appears to be mainly city and town based. While the colonisation of GB by RRP is clearly extending beyond the initial founder colony in London, the lack of sightings in rural areas is clear, particularly with regard to the Bird Atlas 2007-2011 (Balmer et al., 2013), which aimed to survey every tetrad in GB. This comprehensive coverage of

GB implies that RRP's are not normally found in rural areas, and yet the species is managing to colonise new cities across GB.

Forensic techniques used to investigate crimes, have been used to examine the establishment of RRP's in GB, suggesting that the London population of RRP's came from repeated escapes or releases of captive birds (Heald et al., 2020). Studies elsewhere in Europe have also found repeated escapes/releases to be crucial in establishing invasive species (Lockwood et al., 2005; Blackburn et al., 2013; Jackson et al., 2015a; Cardador et al., 2016; Cardador and Blackburn, 2020). RRP's are relatively sedentary with a reported mean natal dispersal distance of only approximately 400 m (Butler, 2003), although birds often fly several miles to reach their communal roost sites (Pithon and Dytham, 1999; Peck, 2013). While it is possible that some RRP's disperse over greater distances looking for suitable habitats in which to breed and conspecifics with which to breed, no such movements have been confirmed in GB (Wernham et al., 2002).

The absence of RRP's in rural areas of GB is interesting, because In the native range, RRP's are well known as agricultural pests (Cramp, 1985; Babu and Muthukrishnan, 1987; Lambert et al., 2010; Ahmad et al., 2012; Pest and Disease Information Service (PaDIS), 2018). The occurrence of RRP's in more rural areas would inevitably be of concern to farmers and fruit growers (Fletcher and Askew, 2007), which should have increased the likelihood of sightings of RRP's in rural areas being reported.

The absence of RRP's from rural areas suggests that there is a factor that limits their distribution in some way to towns and cities. There are a number of factors that could be restricting the distribution of RRP's in this way. Bird-feeders are widely used by

RRPs (Clergeau and Vergnes, 2011; Peck, 2013; Peck et al., 2014; Le Louarn et al., 2016; Deguines et al., 2020) but could RRP be so dependent on anthropogenic food sources that they are unable to find sufficient food resources in rural areas? Habitats suitable for RRP are clearly available in towns and cities, but are similar habitats not likely to be available in rural areas? RRP are native to sub-tropical and tropical areas (Cramp, 1985; Juniper and Parr, 2003; Khan et al., 2004, 2011; Ahmad et al., 2012), the Lower Critical Temperature (LCT) of RRP in South Africa has been found to be 15°C (Thabethe et al., 2013), it is therefore possible that the distribution of RRP in GB is limited by cold ambient temperatures.

## **2.6 CONCLUSION**

It is evident that citizen science can play a useful role in the acquisition of up-to-date data on species distributions. The data acquired from this exercise have provided increased confidence in the current distribution of RRP beyond the latest BTO atlas (Balmer et al., 2013), and provided evidence of their expanding colonisation of GB, as shown in Figures 2.4c and d. A larger number of records of feral parakeet sightings than the 133 records gathered by the Feral Parakeets Sightings website would have been better, but the collection of more data would have required greater investment of time in posting on social media and more extensive media coverage.

The distribution of RRP in GB appears to follow a pattern of towns and cities being favoured over rural areas, which is odd for a bird known to be a destructive agricultural pest in both the native (Cramp, 1985; Babu and Muthukrishnan, 1987; Lambert et al., 2010; Ahmad et al., 2012; Pest and Disease Information Service (PaDIS), 2018) and

the introduced ranges (Shiels et al., 2018; Shiels and Kalodimos, 2019; Borray-Escalante et al., 2020). Factors that could limit the distribution of RRP in GB, include anthropogenic food resources, habitat availability and ambient temperatures.

The next chapter of this thesis will analyse the relationship between habitats, human density, temperatures, and measures of urbanisation to examine possible factors influencing the distribution of RRP in GB. As well as this current chapter allowing comparison between current RRP distributional data and historic data from previous work supplying BTO atlases, the 133 records of birds in this chapter will also provide data for validation of the species distribution models (SDMs) created and used in subsequent chapters.

## CHAPTER 3: MODELLING THE DISTRIBUTION OF ROSE-RINGED PARAKEETS (*PSITTACULA KRAMERI*) IN GREAT BRITAIN IN 2011

### 3.1 Abstract

The distribution of birds has long been studied in Great Britain (GB). A recent addition to the avifauna of GB, the Rose-ringed Parakeet (*Psittacula krameri*) (RRP) has a large and expanding population, with a limited geographical distribution. This study explored how environmental factors influence RRP distribution in GB, particularly concentrating on habitat type, human population density, urbanisation and ambient temperature. The study used survey data from the British Trust for Ornithology (BTO), geospatial datasets and state-of-the-art species distribution analyses to model and explain the species' distribution during winter and breeding seasons. The species distribution models (SDMs) revealed that RRP distributions in both seasons were predominantly explained by ambient temperature, elevation and the presence of broad-leaved woodlands. The model of breeding distribution was more limited than the winter distribution, and the mean variable importance of ambient temperatures and broad-leaved woodlands were higher than in winter, suggesting the importance of ambient temperatures and broad-leaved woodlands were higher during the breeding season. Because this species breeds earlier than most native species in GB and is outside its climate envelope in GB, breeding may be more temperature limited.

**Keywords:** ambient temperature; breeding season; food availability; habitat; winter.

## 3.2 Introduction

To examine the distribution of a species in detail, it is important to understand the difference between a fundamental niche and a realised niche. The fundamental niche is the area within which a species can find all of the resources that it needs to survive and reproduce. The realised niche is the area within which it is able to survive and reproduce, despite facing competition and predation from other organisms. When examining the distribution of any organism through Species Distribution Modelling (SDM) techniques, the distribution produced by the SDMs will be the fundamental niche. Only in species with no distribution limiting competitor or predator species is the realised niche likely to match the fundamental niche.

### 3.2.1 Introduced Rose-ringed Prakeets in GB

For a newly arrived species in an area, its realised niche can be much smaller than its fundamental niche, as newly arrived species take time to establish a population and expand the realised niche (Blackburn et al., 2009; Sutherland et al., 1996). This is particularly true of species that have been introduced to areas outside of their natural ranges by human intervention (Blackburn et al., 2009). Such a species in GB is the RRP. This species is a relatively new addition to the British avifauna, after their introduction from accidental/deliberate releases from captivity (Heald et al., 2020). British birds successfully bred for the first time in 1969 (Lever, 1973), after which they increased in population size and distribution with increasing speed, as shown in the BTO's *New Atlas of Breeding Birds in Britain and Ireland: 1988-1991* (Gibbons et al., 1993). It was not given a full species account in the BTO's earlier *Atlas of Breeding*

*Birds in Britain and Ireland* (Sharrock, 1976), as at the time of the fieldwork for that atlas between 1968 and 1972, the population was very small, found in only four locations and had not been found to have a self-sustaining population. The BTO's *Bird Atlas 2007-2011* (Balmer et al., 2013) showed their distribution to be mostly urban/suburban and predominantly in the south-east of GB, with other small populations in towns and cities across the Midlands and the north of England (Fig. 3.1a). Its GB population was estimated to be 8,600 breeding pairs in 2013 (Musgrove et al., 2013) and 12,000 breeding pairs in 2016 (Woodward et al., 2020). As seen in Chapter Two, my Feral Parakeet Sightings website gathered a more recent dataset of sighting records (Fig. 3.1b) and revealed a more expansive distribution of RRP's still mainly in urban/suburban areas but as far north as Glasgow and west as Plymouth.

In GB, RRP's are not only an alien species but also an invasive species (likely to cause harm to biodiversity, economic interests or human health) (Davey et al., 2012; Heald et al., 2020), as they are in many parts of the world (Jackson et al., 2015b). Their population in GB is expanding in size and distribution. They are agricultural pests in their native range (Cramp, 1985; Lambert et al., 2010; Ahmad et al., 2012), and have negative impacts on crops in Europe, including: orchards, maize (*Zea mays*), tomatoes (*Solanum lycopersicum*), almonds (*Prunus amygdalus*), figs (*Ficus carica*), vineyards, peas (*Pisum sativum*), pistachio (*Pistacia vera*) and cereals (Menchetti and Mori, 2014; White et al., 2019).

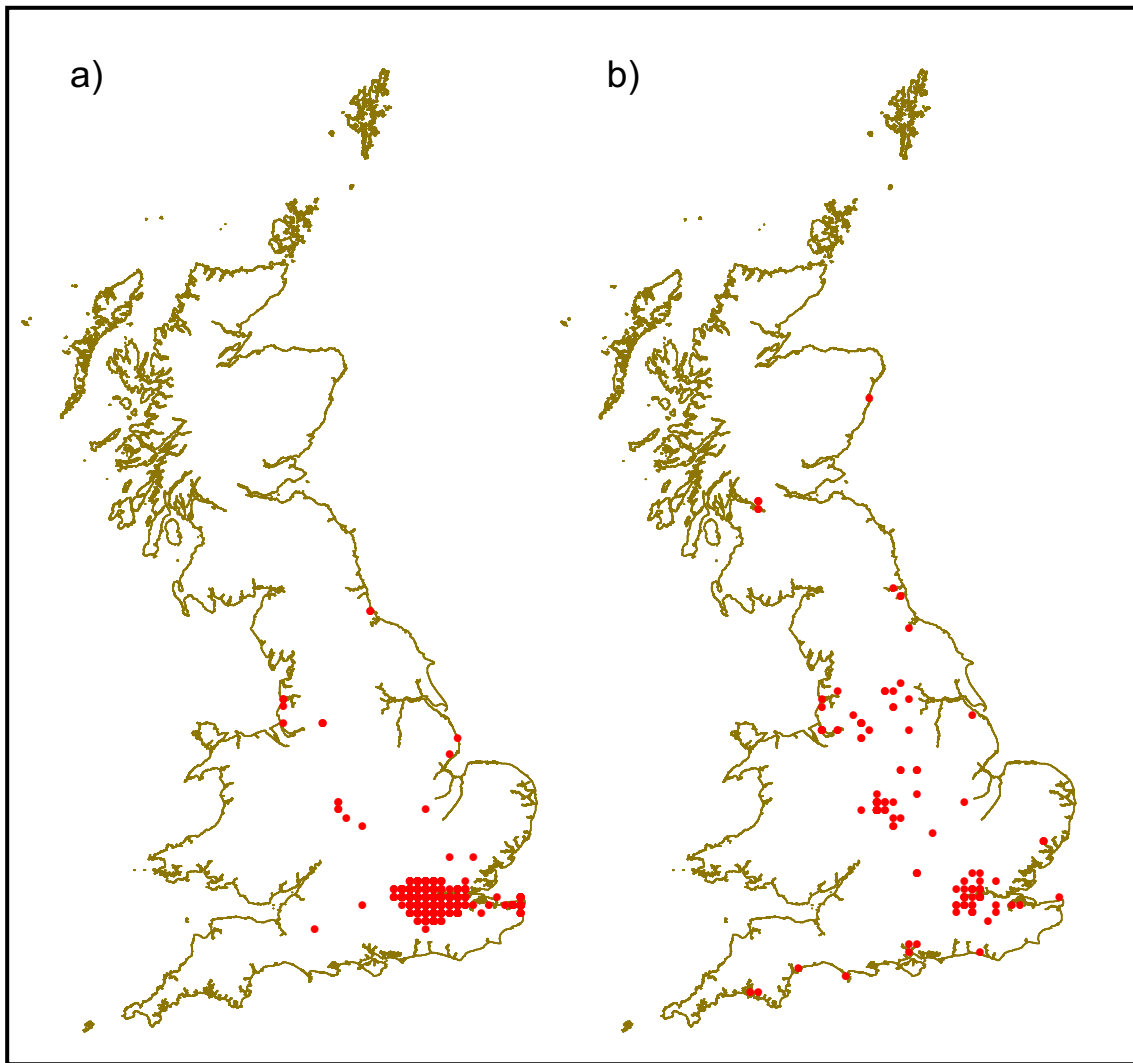


**Figure 3.1.** The GB distribution of Rose-ringed Parakeets (*Psittacula krameri*) in: (a) 2007-2011 (from Balmer et al., 2013); and (b) 2019-2021 (from the Feral Parakeet Sightings website; Chapter 2).

### 3.2.2 Biotic influences on distribution

Biotic factors can be major determinants of distribution for many species (Krebs, 2014)

In the case of RRP, they out-compete for nesting cavities native species such as Eurasian Nuthatches (*Sitta europaea*) (Strubbe and Matthysen, 2009b), Common Starlings (*Sturnus vulgaris*) (Dodaro and Battisti, 2014), and Eurasian Scops Owls (*Otus scops*) (Mori et al., 2017). They are also known to disrupt the foraging behaviour

Blue Tits (*Cyanistes caeruleus*) and Great Tits (*Parus major*) at bird feeders (Peck et al., 2014) because of their broad foraging niche that includes buds, leaves, flowers, nectars and seeds (Cramp, 1985), accessing these mostly in the tops of trees.

That there are no competitors for food and nesting cavities means that competition is unlikely to limit the distribution of RRP. Instead, habitat availability and abiotic factors (factors that are not biological) are the more likely constraints on RRP distribution in GB. Trees are the favoured feeding location for RRP (Cramp, 1985; Butler, 2003; Peck, 2013) where they also nest (Cramp, 1985; Luna et al., 2017a) and therefore likely to be important in influencing their distribution. Trees are commonly found not only in woods and forests, but as isolated trees and in hedgerows in the countryside (Scholefield et al., 2016). For RRP trees supply food even when the tree is relatively young, but trees rarely supply nesting cavities until the tree reaches maturity. Mature trees tend to be larger, have more cavities and produce more food. The availability of trees mature enough to have nesting cavities is most likely to be a limiting factor for RRP distribution in those areas where they are scarce.

For many species, predation can be a factor influencing their distribution (Krebs, 2014). British RRP succumb to predation by Eurasian Sparrowhawks (*Accipiter nisus*) ( and in Europe to Long-eared Owl (*Asio otus*) ( Predation pressure on RRP in GB and mainland Europe is believed to be lower than that experienced by RRP in their native range (Shwartz et al., 2009), though there is little literature reporting predation of RRP. Therefore, within GB predation is unlikely to be a significant limiting factor on their distribution.

### 3.2.3 Abiotic factors and bird distributions

These are most likely to relate to weather variables because in their native sub-tropical range, sub-Saharan Africa and the Indian sub-continent (Juniper and Parr, 2003), RRP's are found in habitats ranging from hot and dry semi-desert to forests in monsoon areas (Cramp, 1985; Juniper and Parr, 2003; Khan et al., 2004). This wide range of habitat types in which birds occur suggests that rainfall will not influence their distribution in GB. Ambient temperature has been identified as one of the most pervasive factors determining animal distributions (McNab, 2012; Galván et al., 2018; Lembrechts et al., 2019). However, high temperatures are also unlikely to limit RRP distribution in GB where the mean maximum in July (for the period 1991-2020) is just 21.8°C for southern England (Met Office, 2022). On the other hand, lower temperatures may play a more fundamental role in determining where RRP's occur in GB, through energetic limitations during breeding attempts (Shwartz et al., 2009) or through reduced adult survival in winter (Newton, 1998).

Avian strategies for coping with cold weather can include: migration (moving away from colder areas before the colder period of the year, i.e. migration over long or short distances) the strategy of Barn Swallows (*Hirundo rustica*) (Rappole, 2013); cold weather movements (moving in response to cold weather, returning once climatic conditions allow), a strategy used by Common Pochards (*Aythya farina*; (Keller et al., 2009); or enduring cold weather by remaining sedentary as seen in Winter Wrens (*Troglodytes troglodytes*) (Peach et al., 1995).

To remain in an area through cold weather, birds respond by either using more energy to maintain a stable body temperature (i.e. increase their metabolic rate as seen in

Snow Buntings (*Plectrophenax nivalis*); (Scholander et al., 1950a), or by reducing energy expenditure enabling more energy to be used for thermogenesis, as seen in Dalmatian Pelicans (*Pelecanus crispus*) reducing movement-related energy expenditure on the wintering grounds (Efrat et al., 2019).

All homeothermic animals, including birds, have a range of temperatures known as the thermo-neutral zone (TNZ), within which they can maintain their body temperature by not changing their metabolic rate (McNab, 2012). Like all higher vertebrates, birds respond to temperatures outside the TNZ by employing behavioural and/or physiological mechanisms such as migration (Rappole, 2013), reduced energy expenditure (Efrat et al., 2019), increased metabolic rate (Scholander et al., 1950a) and raising the angle of body feathers (ptiloerection) (Dawson and Whittow, 2000).

When ambient temperature exceeds the upper limit of the TNZ (i.e. the upper critical temperature or UCT; (Nilsson et al., 2016), a bird must expend energy to reduce its core body temperature, often by gular fluttering (Talbot et al., 2018). When ambient temperature drops below the lower limit of the TNZ, i.e. the lower critical temperature or LCT, a bird must generate heat by expending energy through physiological mechanisms such as shivering (Milbergue et al., 2018). If cold weather is acute and prolonged, it is possible that birds will be unable to maintain sufficient energy reserves to maintain body temperature and death is likely. Prolonged periods of cold weather can cause marked reductions in the some populations of birds, such as Winter Wrens (*Troglodytes troglodytes*) (Peach et al., 1995) and alterations in bird communities (Cohen et al., 2021).

Heat generation is particularly important during both cold weather and during incubation of the eggs (Nord and Williams, 2015). Heat is required for embryo growth and is normally provided by its transfer from the brood patch of the incubating bird and the clutch (Deeming, 2008). Most birds incubate eggs in spring, during warmer weather when the energetic demand on the incubating bird can be maintained more easily (Wang and Beissinger, 2009). Earlier timing of breeding by RRP in GB compared with other breeding bird species has been proposed as a cause of their higher egg infertility than RRP nesting in Mediterranean areas (Shwartz et al., 2009).

In Britain, RRP are seen as a highly sedentary species. Cold weather movements do not appear to take place in this species. It may therefore be expected that the winter and breeding distributions would be the same. While no evidence could be found in literature that the distribution of RRP differs between winter and breeding season, neither could evidence be found that the distribution does not change between seasons. It is possible that RRP in GB may forage over slightly greater distances in search of food in one season compared to another, as food choices and availability change. For this reason, the distribution of RRP in both winter and the breeding season are examined in this thesis.

Elevation above sea level is another abiotic factor that can influence bird distributions, as increasing elevation leads to lower ambient temperatures (Dillon and Conway, 2021). The elevation above sea level has been shown to be a factor in the distribution of birds in the European Alps (Chamberlain et al., 2016) and to influence the number of species present along a vertical gradient in Taiwan (Lee et al., 2004). In the peninsular uplands of India, RRP are found up to 1,600 metres above sea level, but

only to 1,300 metres above sea level in the Himalayan foothills (Cramp, 1985). This would suggest that RRP's are most likely to be found only at lower elevations in GB.

#### **3.2.4 Habitat type and Rose-ringed Parakeet distribution**

British RRP's are usually found in areas of higher human population size and density (Balmer et al., 2013) (i.e. towns and cities). Such areas are not dominated by trees, but it is possible that RRP's require open space around trees, rather than being a true woodland species. This suggested by the reported avoidance of forests but common occurrence in lightly wooded areas in the native range (Cramp, 1985). This would suggest that open areas of land, such as grassland or arable fields, could be important to the species, possibly to allow clear flight paths between trees. Whilst young trees may supply food, RRP's require mature trees with cavities for the species to be able to nest. The maturity of trees is not represented in the 2007 Landcover Maps, nor is it represented in any available dataset found for this study.

Agricultural land (coupled with horticultural land in the 2007 Landcover Maps) is mainly a type of annual or perennial grassland, managed by humans. This habitat includes orchards, vineyards, fields of cereals, maize and peas, all of which may be sources of food for RRP's in GB as in Europe (Menchetti and Mori, 2014; White et al., 2019). Arable land may therefore be important both as a type of grassland and as a food source.

### **3.2.5 Human presence and Rose-ringed Parakeet distribution**

Another factor that may influence RRP distribution is the provision of food for birds by humans. The feeding of birds is popular in GB, as a means of maintaining connectedness with nature, helping birds to survive and for the pleasure of seeing birds (Clark et al., 2019; Brock et al., 2021). The ready availability of food to birds at feeders and the ability of RRP to dominate native species at bird feeders (Clergeau and Vergnes, 2011; Peck et al., 2014) enables RRP to ingest quantities of food without being displaced. This enables RRP to eat sufficient food, to counteract cold ambient temperatures, whilst minimising energy expenditure. This is made easier by the ability of RRP to dominate bird feeders and to deter native birds from feeding (Le Louarn et al., 2016). If RRP distribution is influenced by ambient temperature, anthropogenic heat in towns and cities, known as the urban heat island effect (UHI; REFs?), will likely influence their distribution with birds attracted to urban areas as a result, as occurs in Grey-headed Flying Foxes (*Pteropus poliocephalus*) in Melbourne, Australia (Parris and Hazell, 2005). Both the occurrence of bird feeding and the UHI are likely to have a greater influence where human populations are higher (i.e. in British towns and cities).

### **3.2.6 Study aims**

This study sets out to identify the key factors influencing the distribution of RRP in GB. Factors examined will include the availability of habitats to birds, measures of ambient temperature, elevation, and the number of humans per square kilometre. In the first step I source data collected for the BTO's *Bird Atlas 2007-2011* (Balmer et al.

2013) to create species distribution models (SDMs) using various environmental factors as predictor variables. In the second step I refine those initial models by dropping variables in turn to identify the SDMs that provide the strongest predictions of winter and breeding distributions of RRP. In the third step I use data from Chapter Two to compare models created in that chapter to those created in this one. In the final step I assess the relative importance of each variable in the SDMs in explaining where RRP are distributed in GB.

### **3.3 Methods**

#### **3.3.1 Datasets**

Distributional data on RRP were obtained by request from the BTO following their reporting in the BTO's *Bird Atlas 2007-2011* (Balmer et al., 2013). Volunteer observers were asked to identify a route around their designated tetrads that would enable the recording of all species normally found in that location. Each tetrad was a 2 × 2 km square of the Ordnance Survey (OS) British National Grid (BNG). The *Bird Atlas 2007-2011* survey method used Timed Tetrad Visits (TTVs) in which every bird seen actively using the tetrad surveyed within a period of 2 hours was recorded (actively using the tetrad excludes birds which are simply flying, but includes birds that are hunting prey whilst in flight). Two TTVs were made in each breeding season and two in each winter between November 2007 and July 2011 (inclusive). The *Bird Atlas 2007-2011* included roving records and casual records made outside of the TTVs (Balmer et al., 2013) which may have included records of birds that are passing through areas and, therefore, that may not have represented long-term occupants. Therefore, these were excluded from my analyses.

Following the TTV methodology (Balmer et al., 2013) should increase the probability of the recorded absence of a species from a tetrad being true, however, as highlighted by Butler et al. (2021) and Callaghan et al. (2022), a species occurring at low density could easily be missed, and a 'false' absence cannot be ruled out. A RRP was counted as present in a tetrad even if only counted in one visit in a given season. As the collection of records was by tetrads, a 2km x 2km resolution was used for all analysis in this chapter. The TTV records were assembled into two datasets that contained presence data for RRP in winter and breeding census periods.

As the sightings of RRP reported to the website were made by humans, it is likely that the distribution of these sightings was influenced by the distribution of humans, who made these reports: leading to a spatial bias towards areas commonly accessed by humans (Phillips et al., 2009; Kramer-Schadt et al., 2013; Meyer et al., 2015; Stolar and Nielsen, 2015). It is possible to correct for such a bias by including a sample bias file when carrying out species distribution modelling. In chapter two, the data of RRP sightings gathered through the website, may well be influenced by the distribution of the people making the sightings, however, the Bird Atlas data was derived from systematic surveys, of consistent effort and method, covering the whole of GB and is should be free from such a bias. It was therefore decided not to utilise a sample bias file in the analysis in this chapter, as such a bias should not exist in this data. Had a sample bias file been utilised in chapter two, it would have been necessary to either apply it just the website data, or to apply it both sets of data, which would have affected both the data and the reliability of the conclusions drawn.

Whilst data sources other than the TTV used for the Bird Atlas (Balmer et al., 2013), could have been used for this study, such as the BTO's Bird Track (British Trust for Ornithology et al., 2020), casual records submitted to the Bird Atlas team, eBird (Sullivan et al., 2009), GBIF (GBIF.org, 2020) and the website data collected for the last chapter, all of these records were excluded from the analysis for this chapter, precisely because all of those records depend on reporting by people, such as birdwatchers, who are not evenly distributed (fewer people watch birds in western Scotland than on the Norfolk coast, for example)(Stolar and Nielsen, 2015). The nature of the bias in such records may well be different for each particular dataset, requiring separate sample bias files. Utilising only TTV records for this chapter removes the need for a sample bias file.

The study derived habitat data from a 1 × 1 km raster dataset that expressed each habitat type as a percentage of cover of each 1-km square, aggregated from the 25 × 25 m dataset of the Land Cover Map (LCM) 2007, produced by the Centre for Ecology and Hydrology (CEH) (CEH, 2011). These data were used in raster form, each raster giving the percentage cover per 1 × 1 km square for the following habitat types, pertinent to the study species: (1) broad-leaved, mixed and yew (*Taxus bacatta*) woodland; (2) coniferous woodland; (3) arable and horticulture; (4) improved grassland; (5) rough grassland; (6) neutral grassland; (7) acid grassland; (8) calcareous grassland; (9) urban; and (10) suburban. The resolution of the LCM data was altered to 2 x 2km squares in ArcGIS v10.7 (ESRI, 2019) to match the resolution of the TTV dataset.

As the validation of models was to be carried out utilising data collected by the Feral Parakeet Sightings website in 2019-2021, it was decided to utilise habitat data from the Land Cover Map (2015) (Rowland et al., 2017c) to model the most recent RRP observations detailed in Chapter Two. The Land Cover Map 2007, had some inconsistencies in the classification of grassland, for this reason the final 2015 Land Cover Map did not include rough grassland as a habitat type (Rowland et al., 2017a). For this reason, all grassland habitat types were consolidated into one grassland category, enabling interchangeability between the 2007 and 2015 Land Cover Maps in later analysis. Therefore, all grassland subcategories were summed to create an amalgamated raster giving a total percentage of each 2-km square covered by grassland for the LCM (2007) and for the LCM (2015).

Woodland area was derived from the National Forest Inventory 2011 dataset produced by the Forestry Commission (Forestry Commission, 2020). This dataset was obtained as a shapefile of woodlands and was manipulated in ArcGIS v10.7 (ESRI, 2019) to yield a raster showing the area of each 2-km square occupied by woodland, with no distinction between coniferous and broad-leaved woodland. This provided an indication of the amount of woodland present, as opposed to the extent of tree cover provided by LCM (2007) and LCM (2015). While the distinction is subtle, the original woodland area raster gave the area of woods within each  $1 \times 1$  km square, while the two woodland habitat types included the area covered by trees of either broad-leaved, mixed and Yew woodland or coniferous woodland (excluding Yew) which in suburban areas could be extensive without any actual woodland being present. As the 2011 National Forest Inventory was released in 2020, the same raster was used for both the BTO-derived SDMs and those generated from independent RPP observations in

Chapter Two. No dataset was found to be available that both gave an indication as to the size or maturity of trees and covered the whole of GB.

Human population density was extracted from a dataset produced by the CEH and the Census Office (Reis et al., 2017), providing a raster derived from census and land cover data giving the number of people occupying each 1-km square of the BNG during the National Census of 2011. The same raster was used for both BTO-derived SDMs and those generated from independent RRP observations in Chapter Two. This data was also manipulated in ArcGIS v10.7 (ESRI, 2019) to give a 2-km resolution for the analysis carried out in this chapter.

A dataset of the length of roads per  $1 \times 1$  km square of the BNG (Ordnance Survey, 2021) was obtained from the Ordnance Survey (OS) website (<https://osdatahub.os.uk/>). The same website also provided data on elevation to a resolution of 50 m (Ordnance Survey, 2020). The elevation dataset was manipulated in ArcGIS to give a  $2 \times 2$  km resolution raster of mean elevation per  $2 \times 2$  km square. As RRP were absent from all tetrads where mean elevation exceeded 140 m, all  $2 \times 2$  km squares with an elevation  $>145$  m were excluded from the analysis.

As the TTVs finished in 2011, the ambient temperature measures used covered the period of 1<sup>st</sup> December 2010 to May 31<sup>st</sup> 2011 (inclusive) because RRP in GB are sedentary (Pithon and Dytham, 2002; Butler, 2003) and increasing in number (Butler, 2003; Arnold et al., 2017; Woodward et al., 2018, 2020) and therefore it would be unlikely that areas containing RRP in 2007 would not still contain them in 2011. Ambient temperatures were obtained for December to February (inclusive) for the winter distribution and December to May (inclusive) for the breeding seasons of RRP.

The breeding season was taken as starting from 1<sup>st</sup> December, because nest sites selection starts well before the first egg is laid, and laying can start in January in GB (Ferguson-Lees et al., 2011), so the breeding season distribution is effectively set in December. Data were obtained from the Meteorological Office HAD UK 1 × 1 km square temperature NetCDF files (Met Office; Hollis et al., 2021, 2019).

The NetCDF files were imported into ArcGIS and converted into rasters for analyses of ambient temperature at a 2 x 2km resolution that included: (1) the number of days of ground frost; (2) mean monthly minimum temperature; and (3) heating degree days (HDD). While days of ground frost and mean monthly minimum temperatures are simple measures of cold temperatures, HDD was also included because it combines the degree of cold temperatures with a measure of their duration.

The HDD measure is similar to ‘warmth sum’ (i.e. sum of mean daily temperatures) used by van Balen (1973) and Perrins and McCleery (1989), but instead of summing temperatures over a given period, HDD is a metric that sums the positive differences between mean daily temperatures and a base temperature ( $T_{\text{base}}$ ) over a set period of time (Sivak, 2008; Azevedo et al., 2016). HDD was originally created to aid in predicting demand for fuel (coal and gas) in the USA, enabling utility companies to anticipate the need for fuel. A negative value on any one day would indicate that heating was not required, so negative values are counted as zero.

The calculation of HDD can be stated as:

$$T_{\text{mean}} = (T_{\text{max}} + T_{\text{min}})/2$$

$$X = T_{\text{base}} - T_{\text{mean}}$$

$$HDD = \sum(x \geq 0) \quad (\text{Eqn 2.1})$$

where  $T_{\text{mean}}$  = mean daily temperature,  $T_{\text{max}}$  = maximum daily temperature,  $T_{\text{min}}$  = minimum daily temperature, and HDD = Heating Degree Days.

Mean temperatures are used as the best representation of the temperature over the course of the day. Other more precise ways of calculating a day's mean temperature do exist, such as kinetic mean temperature, but such precision is not needed in this study and the data required to calculate a mean kinetic temperature is not available for the whole of GB. The base temperature ( $T_{\text{base}}$ ) is the most critical temperature to get right. When used to calculate HDD for fuel consumption, one criticism of the  $T_{\text{base}}$  is that it is based on outdoor temperatures, rather than temperatures inside the houses being heated (Azevedo et al., 2015). That issue does not apply here, as the RRP live outdoors.

The value of  $T_{\text{base}}$  was defined as the LCT below which RRP need to increase their metabolic rate to maintain homeothermy. In captive RRP in Pietermaritzberg, South Africa, Thabethe et al. (2013) found that this was 15°C. This value for the LCT was supported by Professors Wes Weathers and Joe Williams in personal communications and therefore this value was selected as the  $T_{\text{base}}$  for temperature-related analyses of RRP distribution in GB. The mean minimum temperature at the coldest time of the year (June and July) in Pietermaritzberg, is 8°C (Zoomash Ltd, 2022c), compared to 3°C in January and February in London (Zoomash Ltd, 2022a).

For the HDD data rasters of minimum ( $T_{\text{min}}$ ) and maximum daily temperatures ( $T_{\text{max}}$ ) were extracted from NetCDF rasters for each day. These rasters were then averaged

to derive a mean daily temperature for each grid square. Each value was then subtracted from  $T_{\text{base}}$  (15°C) and resulting values  $\geq 0$  were retained, creating a new raster of daily heating degrees which were then summed to provide HDD for the winter and breeding periods. HDD rasters were also produced for the winter and breeding seasons of 2021, to use for validation of the models using data collected by the website described in chapter 2.

### 3.3.2 Preparation of rasters for species distribution modelling

To prepare the files for analysis using the *sdm* package (Naimi and Araujo, 2016) in *R* (R Core Team, 2020), all the rasters of environmental factors (i.e. habitat types, temperatures, elevation, woodland area, road length and human population density) were given a common size, origin and projection. All the rasters were imported to *R* and cropped to the area of the smallest raster defined as the following BNG points: (1) 65000, 10000 (minimum *x*, minimum *y*); and (2) 655000, 1209000 (maximum *x*, maximum *y*). Raster resolutions were 1000 m on both *x* and *y* axes. The origin of each raster was set to (0, 0) on the BNG. The projection of all rasters was: "+proj=tmerc +lat\_0=49 +lon\_0=-2 +k=0.9996012717 +x\_0=400000 +y\_0=-100000 +ellps=airy +units=m +no\_defs", and was the projection of the BNG (OSGB 1936). All the rasters were aligned with common resolution, origin, projection and size, thereby making them comparable.

To enable modelling based on the actual distribution of RRP in GB, each raster was also cropped to give it the same origin and projection, but to reduce it in size to the following BNG points: (1) 320000, 120000 (minimum *x* and minimum *y*); and (2)

650000, 545000 (maximum x and maximum y). The rasters were labelled as S (small; Fig. 3.2) or L (large; Fig. 3.3) to indicate their extents. This was done because the realised niche of RRP in GB may be far smaller than their fundamental niche, as the species may be expanding its distribution. Creating models based on the minimum area within which RRP occur, avoids possible bias due to including large areas of GB which RRP could possibly occupy, but have yet to reach.

### **3.3.3 The *sdm* package in *R***

Species distribution modelling has become more accessible due to the availability of R packages such as *sdm* (Naimi and Araujo, 2016) utilised here because of its ability to run multiple modelling methods, using consistent methods for training the models, and its capability of assessing Variance Inflation Factors (VIFs) and outputting model metrics. As a 'click and run' package, *sdm* enables a uniformity of pre-processing and processing data, and easy comparison of models. The *sdm* package was run using *RStudio*, v.1.3.1056 *Water Lily* (RStudio Team, 2019) and *R* v.4.0.2 '*Taking Off Again*' (R Core Team, 2020).

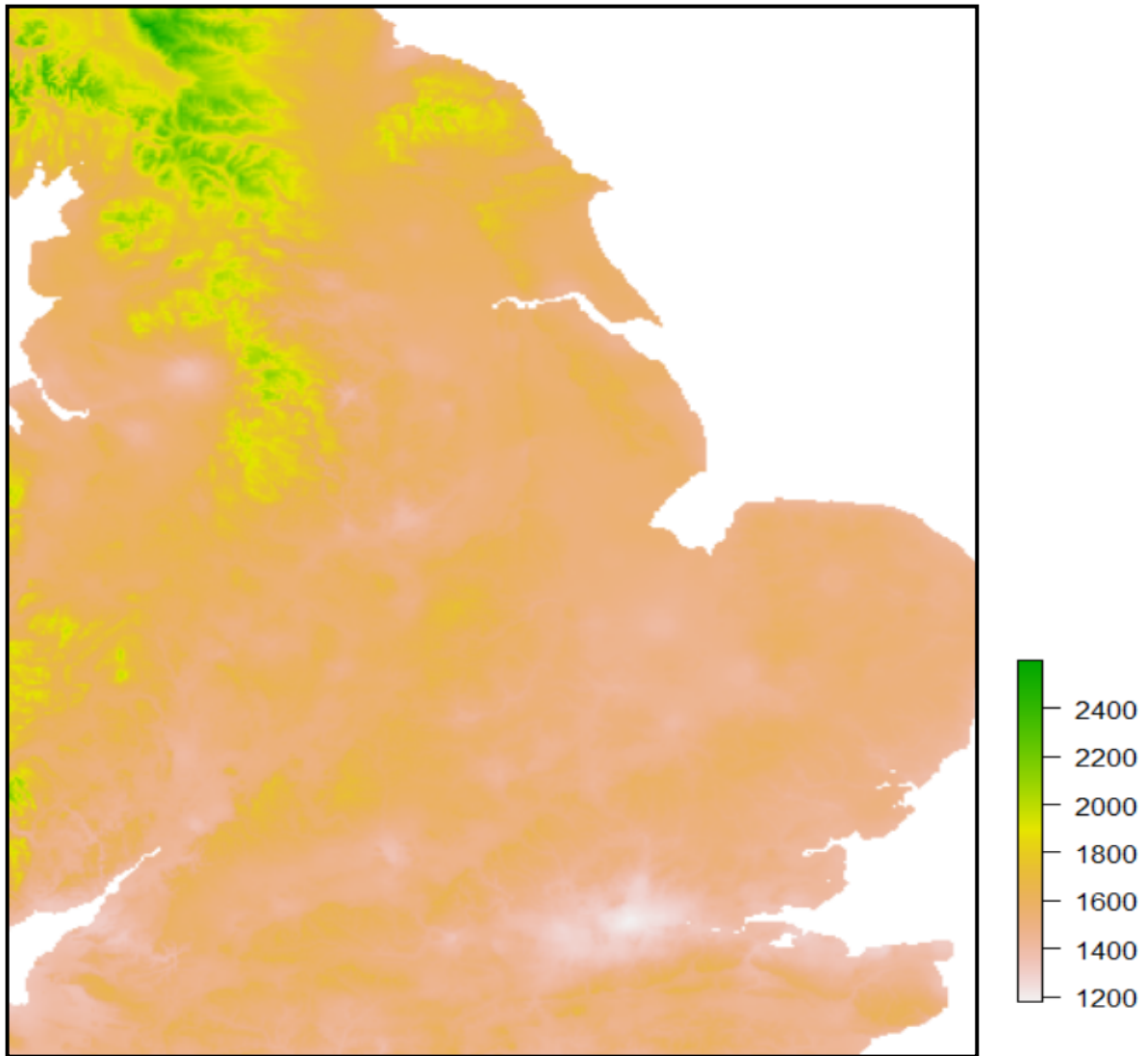


Figure 3.2 Plot of the extent of the small (S) rasters of HDD from December 1st 2010 to May 31st 2011 (inclusive), covering the minimum area within which Rose-ringed Parakeets (*Psittacula krameri*) were recorded in TTVs for the BTO's Bird Atlas 2007-2011 (Balmer et al., 2013). The legend shows range of HDD by colour.

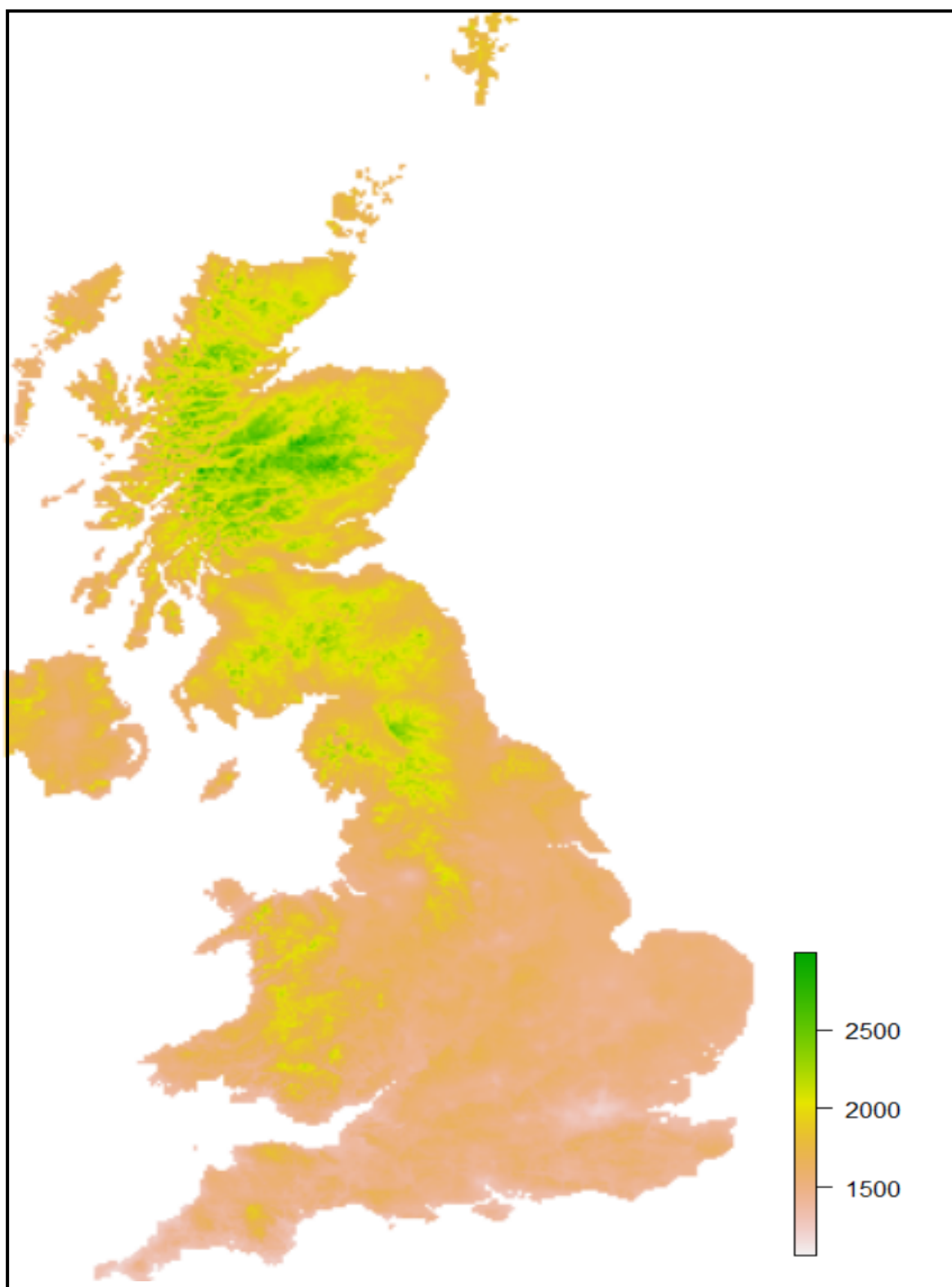


Figure 3.3 Plot of the extent of the large (L) rasters of HDDs from December 1st 2010 to May 31st 2011 (inclusive). The legend shows range of HDD by colour.

### 3.3.4 Modelling methods

The TTVs were carried out in a systematic way and across GB. Although it is unlikely that a bird the size and colour of a RRP, and with its overt behaviours such as loud vocalisations (Mullarney et al., 1999; Juniper and Parr, 2003) would be missed by an experienced bird surveyor, it cannot be assumed that the absence of a record of a RRP was a true absence. Therefore, the modelling used techniques that accommodate presence-only data. These were maximum entropy modelling (commonly known as 'MaxEnt'; (Phillips et al., 2017b), Maxlike (Royle et al., 2012) (like MaxEnt, with a similar performance but developed more recently; (Merow and Silander, 2014), and generalised linear models (GLMs; (Nelder et al., 1972).

### 3.3.5 Variance Inflation Factors (VIFs)

The environmental variables were all assessed for covariance using the *vifstep* function in the *sdm* package. This function calculated the VIFs for all variables, the variable with the highest VIF >10 was then removed, and the process was repeated until all variables had VIFs <10. A VIF greater than 10 is generally accepted as indicating severe collinearity (Salmerón Gómez et al., 2016).

It was found that two habitat variables showed collinearity. These were areas of broad-leaved woodland and suburban habitat. As trees are ecologically fundamental for RRP, it was decided to retain the broad-leaved woodland habitat. This decision to exclude suburban habitat coverage was supported by the presence of both human density and road length in the predictor variables being retained at this point. The measures of temperature all showed collinearity. Due to this collinearity, it was decided

to identify the best performing measure of temperature, and to then use that measure for subsequent analyses.

### **3.3.6 Setting up the species distribution models (SDMs)**

When setting up the species distribution model in the *sdm* package, the first step is to select the predictor variables (in this study a list of rasters). Next the species distribution model data is set up: the species data to be used is identified, as are the predictor variables and the 'background' or pseudo-absence data: in this case the *gRandom* method was chosen to select 2000 points from the predictor variables to use as pseudo absence data. For the species distribution model itself, the data to be used as presence data is identified, the species distribution model data is specified and the modelling methods are specified (in this case '*glm*', '*maxlike*', *maxent*'), the replications are set (using the data partitioning methods *subsampling* and *bootstrapping*, 70% of data was used to train the model and 30% to test the model, and the number of replications of each method (3 replications each), the *parallelSettings* were set as *ncore* = 4 and *method* = *parallel* as recommended.

For each model method (i.e. '*glm*', '*maxlike*' and '*maxent*'), three sets of training data were created using bootstrapping and three using sub-sampling, giving six replicate models per modelling method with a total of 18 models produced. This made the resulting models more reliable than models using a one-time data split, which could introduce spatial bias into the model (Araújo et al., 2005).

### 3.3.7 Model performance and refinements

The *sdm* package produces a mean score, based on the six replicates for each modelling method. The mean scores are for Area Under the Curve/Receiver Operating Characteristic curve (AUC/ROC) (Wisz et al., 2008), Correlation (Cor) (Demirtas and Hedeker, 2016), True Skill Statistic (TSS) (Allouche et al., 2006) and Deviance (Dev) (Hastie, 2009). For assessing AUC/ROC, Araújo et al. (2005) proposed that AUC/ROC scores can be used to assess the quality of outputs as: > 0.9 – ‘excellent’; 0.8 to 0.9 – ‘good’; , 0.7 to 0.8 – ‘fair’, 0.6 to 0.7 – ‘poor’; 0.5 to 0.6 – ‘fail’; < 0.50 – yields counter predictions. When assessing Correlation, the closer the value is to 1, the stronger the relationship and the better the SDM is performing (Demirtas and Hedeker, 2016). With TSS, again the closer the value is to 1, the better the performance of the SDM (Allouche et al., 2006). The value for Dev is relative to other models, with better performing models having less deviance and hence a lower value for Dev (Hastie, 2009). For all outputs and tests, the  $\alpha$ -threshold used was 0.05.

While AUC has been found to be misleading when comparing models made with different data, it remains acceptable as a means of comparing models created with the same data (Lobo et al., 2008). Models were run in the *ENMeval* package (Kass et al., 2021) in R Studio, using jack-knife data-partitioning and *Maxent* (Phillips et al., 2017a) modelling method, allowing model validation using a different method.

Each model was run in *ENMeval* using the maxnet algorithm as the Maxent algorithm could not be made to run and the *ENMeval* package does not allow the use of glm or maxlike. The background points were standardised at 10,000 points, used in every

model run in *ENMeval*. Data-partitioning was performed using the jack-knife method as neither sub-sampling nor bootstrapping can be used in *ENMeval*.

The values of the rasters of days of ground frost, mean monthly minimum temperatures and HDD covaried with each other, due to the similarity of the distributions of ground frost, mean minimum temperatures and HDD, as already stated. As all three measure ambient temperatures, the ambient temperature measure that produced the best performing model was used for all subsequent analyses.

The first set of models were checked to see if dropping any one variable from the model would improve the model. The best performing model with a single dropped variable was then selected based on the mean scores for AUC/ROC, Cor, TSS and Dev. This drop variable process was repeated until no further improvement to the model was achieved by dropping a variable.

The *sdm* package calculates the relative importance of each variable in the performance of the model. It gives the mean percentage contribution of the variable to the performance of the 18 replicates of the model, calculated using AUC/ROC and calculated by COR, giving two values of importance for each variable. The statistical significance of these contributions is also calculated.

### **3.3.8 Ensemble prediction of probability of habitat suitability**

Once the final models were obtained, an ensemble prediction of the distribution of RRP in GB was produced for the winter and breeding seasons (Naimi and Araújo, 2016) This produced a raster giving the probability of habitat suitability of RRP in each

1 × 1 km square. For the ensemble predictions, the model and predictor variables covering the whole of GB to be used were specified, the ensemble was weighted according to the TSS of each replicate. The threshold used to calculate TSS was optimised with the setting option 2, max(se+sp): sen = sensitivity (true positive rate) and sp = specificity (true negative rate).

### **3.3.9 Validation of the models using website data.**

Ensemble predicted maximum distributions for RRP in the winter and breeding seasons were also produced, based on the website data from Chapter Two, ambient temperature data for 2021 (the end of the period of data collection via the website) and the Land Cover Map 2015 ) (the most appropriate habitat data available). This enabled the probabilities of habitat suitability at locations where RRP were recorded in each set of data to be extracted for the purposes of comparison.

### **3.3.10 Statistical analysis of Rose-ringed Parakeet distribution in relation to HDD**

HDD values for one 1-km square per tetrad where RRP were present were extracted from the HDD rasters for the winter and breeding season. A random selection of approximately one tenth of 1-km squares where RRP were absent within the area of the small (S) HDD rasters were used to extract values of HDD. These distribution of HDD values where RRP were tested for normality using a Shapiro test and found to be significantly non-normal (winter:  $w = 0.99$ ,  $p < 0.00001$ ; breeding season:  $w = 0.99$ ,

$p < 0.00001$ ). Therefore, Wilcoxon rank sum tests were run in *R* to examine whether RRP's favoured areas with higher ambient temperatures (lower values of HDD).

#### **3.4.1 Distribution of Rose-ringed Parakeets in 2011 from the BTO's *Bird Atlas 2007-2011***

The winter and breeding distributions of RRP's were similar with birds occupying 599 and 382 tetrads, respectively (Fig. 3.4). In both seasons, RRP were located mainly in London, with some presence in other cities, such as Birmingham and Manchester.

#### **3.4.2 Variance Inflation Factor assessment.**

The VIFs for both seasons were calculated using the *vifstep* process in the *sdm* package in *R*, the results are shown in Appendix 3.1. Dropping the suburban habitat brought the VIF for broad-leaved, mixed and Yew woodland down to 3.074222 in winter and 3.270920 in the breeding season: VIF values should be below 10, and ideally below 5 (Guisan et al., 2017). Due to the measures of ambient temperatures showing some collinearity, models were produced to find the best performing ambient temperature measure, before moving to the drop variable process of model improvement.

Once the final models had been produced, the VIFs were checked again and the results are shown in Appendix 3.2.

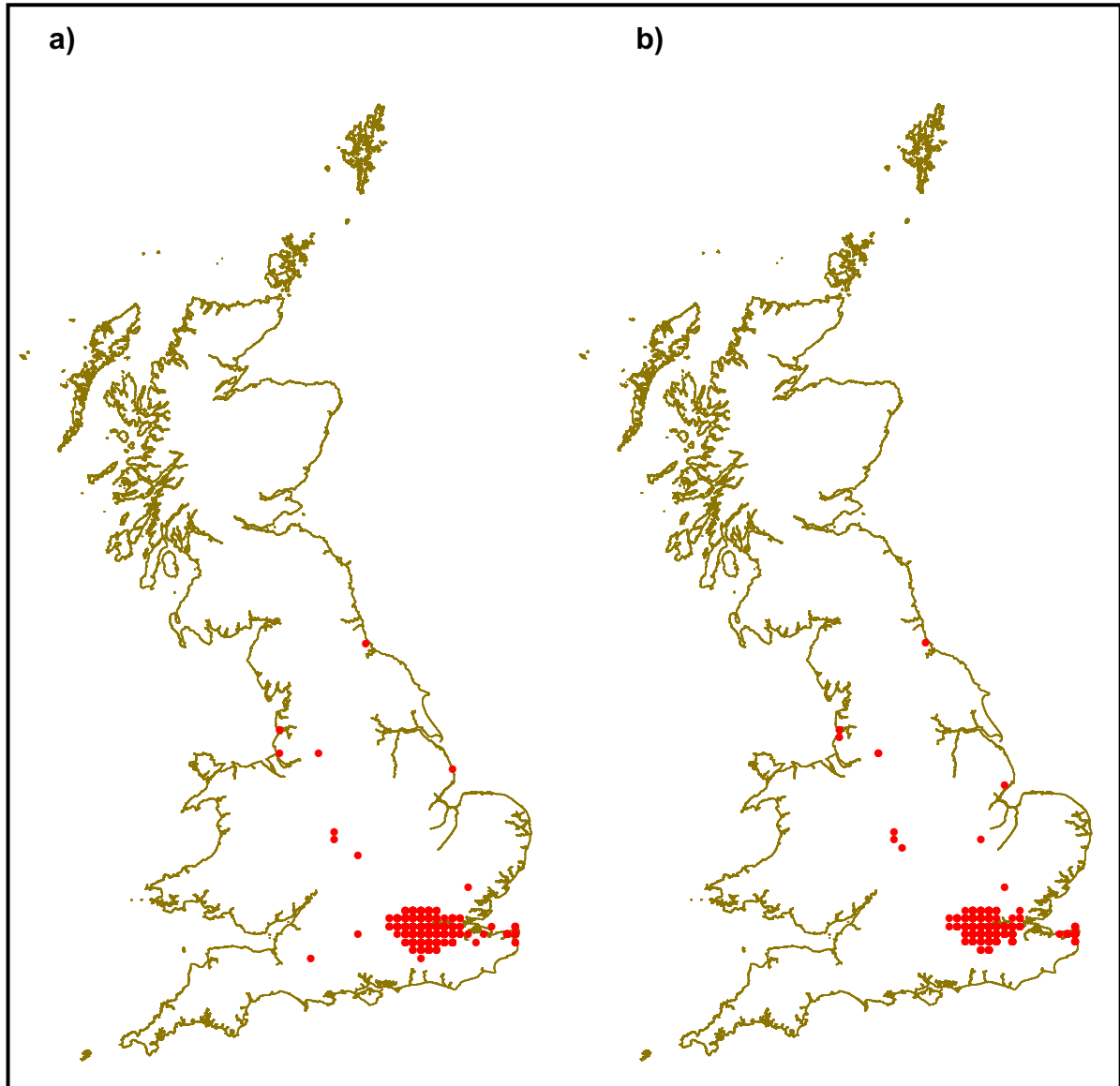


Figure 3.4 The (a) winter and (b) breeding distributions of Rose-ringed Parakeets (*Psittacula krameri*) in GB as found during TTVs for the BTO's Bird Atlas 2007-2011 (Balmer et al., 2013).

### 3.4.3 Model performance and model refinement

As described in the methods (section 3.3.6) there was collinearity between Broad-leaved, mixed and Yew woodland and Suburban habitats. Both habitats were initially removed by the *vifstep* process, but as RRP utilise broad-leaved trees extensively, this habitat was retained and rerunning the *vifstep* process without suburban habitat

resulted in the retention of broad-leaved woodland. The initial values of VIFs are shown in Appendix 3.1 The same variables were retained following the vifstep process, in both seasons and with both sizes of raster. There was also collinearity between measures of ambient temperatures. As it makes ecological sense to include one measure of ambient temperature, the first stage in modelling was to identify the best performing measure, see Table 3.1

Table 3.1 Model outputs for the initial models to find the best performing measure of ambient temperatures. Models are: GLM – generalized linear model; maxlike – formal likelihood model; and maxent – maximum entropy model. Model outputs are: AUC/ROC – area under the curve/receiver operating characteristic curve; COR – correlation; TSS – true skills statistic; and Dev – Deviance.

| Winter Season                    |         |      |      |      |
|----------------------------------|---------|------|------|------|
|                                  | AUC/ROC | COR  | TSS  | Dev  |
| Ground Frost                     |         |      |      |      |
| GLM                              | 0.87    | 0.64 | 0.56 | 0.93 |
| maxlike                          | 0.85    | 0.62 | 0.58 | 1.02 |
| maxent                           | 0.87    | 0.67 | 0.63 | 0.94 |
| Mean Monthly Minimum Temperature |         |      |      |      |
| GLM                              | 0.89    | 0.69 | 0.62 | 0.86 |
| maxlike                          | 0.86    | 0.66 | 0.64 | 0.85 |
| maxent                           | 0.89    | 0.69 | 0.63 | 0.92 |
| Heating Degree Days              |         |      |      |      |
| GLM                              | 0.92    | 0.74 | 0.68 | 0.71 |
| maxlike                          | 0.91    | 0.73 | 0.67 | 0.84 |
| maxent                           | 0.92    | 0.75 | 0.69 | 0.85 |
| Breeding Season                  |         |      |      |      |
|                                  | AUC/ROC | COR  | TSS  | Dev  |
| Ground Frost                     |         |      |      |      |
| GLM                              | 0.85    | 0.63 | 0.58 | 0.91 |
| maxlike                          | 0.84    | 0.62 | 0.54 | 1.07 |
| maxent                           | 0.88    | 0.66 | 0.63 | 0.88 |
| Mean Monthly Minimum Temperature |         |      |      |      |
| GLM                              | 0.88    | 0.68 | 0.64 | 0.82 |
| maxlike                          | 0.90    | 0.71 | 0.65 | 0.85 |
| maxent                           | 0.91    | 0.70 | 0.67 | 0.82 |
| Heating Degree Days              |         |      |      |      |
| GLM                              | 0.93    | 0.76 | 0.69 | 0.68 |
| maxlike                          | 0.90    | 0.72 | 0.70 | 0.81 |
| maxent                           | 0.93    | 0.74 | 0.70 | 0.77 |

The final variables retained in the models are shown in Table 3.2 (two variables were dropped from the initial breeding season model and one variable was dropped from the initial winter season model. The model outputs for the final models are shown in Table 3.3.

Table 3.2 Environmental variables retained in the final model.

| Winter Season                        | Breeding Season                      |
|--------------------------------------|--------------------------------------|
| Broad-leaved, mixed and Yew woodland | Broad-leaved, mixed and Yew woodland |
| Arable and Horticultural Land        | Coniferous Woodland                  |
| Grassland                            | Arable and Horticultural Land        |
| Urban                                | Grassland                            |
| Human population density             | Urban                                |
| Elevation                            | Human population density             |
| Road Length km <sup>-2</sup>         | Elevation                            |
| Heating Degree Days                  | Road Length km <sup>-2</sup>         |
|                                      | Heating Degree Days                  |

Table 3.3 Mean performance scores for SDMs of wintering and breeding distributions of Rose-ringed Parakeets (*Psittacula krameri*) in 2011 in GB. Models are: GLM – generalized linear model; maxlike – formal likelihood model; and maxent – maximum entropy model. Model outputs are: AUC/ROC – area under the curve/receiver operating characteristic curve; COR – correlation; TSS – true skills statistic; and Deviance.

| Models          | Mean performance scores |      |      |          |
|-----------------|-------------------------|------|------|----------|
|                 | AUC/ROC                 | COR  | TSS  | Deviance |
| <b>Winter</b>   |                         |      |      |          |
| GLM             | 0.91                    | 0.76 | 0.74 | 0.71     |
| maxlike         | 0.93                    | 0.73 | 0.68 | 0.78     |
| maxent          | 0.92                    | 0.76 | 0.74 | 0.74     |
| <b>Breeding</b> |                         |      |      |          |
| GLM             | 0.93                    | 0.77 | 0.72 | 0.71     |
| maxlike         | 0.91                    | 0.74 | 0.72 | 0.72     |
| maxent          | 0.93                    | 0.76 | 0.75 | 0.74     |

For both winter and breeding seasons, the mean AUC/ROC scores for all models show excellent discrimination (Araújo et al., 2005), strong correlation and a high value for the TSS.

The results of the model runs in *ENMeval* are shown in Table 3.4 (below). These show that AICc scores back up the choice of measure of cold for both seasons, though there is less support in the Log-likelihood, wAICc and meanAUC scores. In all models the regularisation parameter of 1 produced better performing models. The use of only one algorithm and a different method of data-partitioning may explain the slightly different levels of support for the cold measure used in the models.

Table 3.4: Model Performance scores from Maxnet models run in ENMeval in R, for winter and breeding season. AICc is Aikaike Information criteria, wAICc is weighted AICc and RM is the regularisation parameter.

| Model               | Log-likelihood | AICc     | delta AICc | wAICc     | meanAUC   | RM |
|---------------------|----------------|----------|------------|-----------|-----------|----|
| Winter Season       |                |          |            |           |           |    |
| Ground Frost        | -1887.561      | 5090.820 | 187.128    | 0.9507066 | 0.8647671 | 1  |
| Mean Temperature    | -1796.857      | 4909.413 | 5.721      | 0.9267316 | 0.9000142 | 1  |
| Heating Degree Days | -1793.997      | 4903.692 | 0          | 0.9419928 | 0.9044622 | 1  |
| Breeding Season     |                |          |            |           |           |    |
| Ground Frost        | -1120.653      | 2934.381 | 152.755    | 0.7508578 | 0.8603319 | 1  |
| Mean Temperature    | -1049.540      | 2799.505 | 17.879     | 0.7324488 | 0.9160838 | 1  |
| Heating Degree Days | -1040.601      | 2781.626 | 0          | 0.5593534 | 0.9094333 | 1  |

#### 3.4.4 Variable importance

The dominant explanatory variable in both winter and breeding season models was HDD (Table 3.5). The mean importance of HDD to the winter distribution model was 70.00%, and for the breeding season was 76.75%. The second most influential explanatory variable in both seasons was human density (mean importance: winter 7.10%; breeding season 6.30%) followed by broad-leaved woodlands (mean importance: winter 5.25%; breeding season 6.25%) and elevation (mean importance: winter 4.85%; breeding season 6.4%). The *sdm* package tool *getVarImp* gives the exact percentage of the importance of each variable, but only indicates the range of the *p*-value (i.e.  $0.05 > p > 0.01$ ). The extraction of exact *p* values for each variable is not supported.

Table 3.5 Percentage contribution for each predictor variable in the final distribution models by correlation and AUC/ROC curve. %: percentage contribution to the model. p: level of statistical significance. Bold p values are statistically significant.

| Explanatory variable      | Season      |               |         |               |             |               |         |               |
|---------------------------|-------------|---------------|---------|---------------|-------------|---------------|---------|---------------|
|                           | Winter      |               |         |               | Breeding    |               |         |               |
|                           | Correlation |               | AUC/ROC |               | Correlation |               | AUC/ROC |               |
|                           | %           | <i>p</i>      | %       | <i>p</i>      | %           | <i>p</i>      | %       | <i>p</i>      |
| Heating degree days (HDD) | 77.2        | <b>0.0001</b> | 62.8    | <b>0.0001</b> | 83.6        | <b>0.0001</b> | 69.9    | <b>0.0001</b> |
| Human density             | 8.8         | <b>0.01</b>   | 5.4     | <b>0.05</b>   | 8.8         | <b>0.001</b>  | 3.8     | <b>0.01</b>   |
| Broad-leaved woodland     | 7.1         | <b>0.05</b>   | 3.4     | <i>ns</i>     | 8.2         | <b>0.001</b>  | 4.3     | <i>ns</i>     |
| Elevation                 | 6.1         | <b>0.05</b>   | 3.6     | <i>ns</i>     | 8.0         | <b>0.01</b>   | 4.8     | <b>0.05</b>   |
| Arable                    | 3.9         | <i>ns</i>     | 2.3     | <i>ns</i>     | 4.2         | <i>ns</i>     | 2.3     | <i>ns</i>     |
| Grassland                 | 1.6         | <i>ns</i>     | 0.9     | <i>ns</i>     | 1.7         | <i>ns</i>     | 1.0     | <i>ns</i>     |
| Urban                     | 1.2         | <i>ns</i>     | 0.7     | <i>ns</i>     | 2.0         | <i>ns</i>     | 0.6     | <i>ns</i>     |
| Road length               | 0.8         | <i>ns</i>     | 0.7     | <i>ns</i>     | 0.9         | <i>ns</i>     | 0.6     | <i>ns</i>     |
| Coniferous woodland       | -           | -             | -       | -             | 1.7         | <i>ns</i>     | 1.2     | <i>ns</i>     |

### 3.4.5 Ensemble predictions

The weighted predictions of the distributions of RRP<sub>s</sub> in the winter and breeding seasons are shown in Figure 3.5a and b, respectively.

The predicted maximum winter distribution of RRP<sub>s</sub> appears to mirror the spatial distribution of the inverse of the HDD from December 2010 to February 2011 (Fig. 3.6). This is also true of the predicted maximum breeding season distribution of RRP<sub>s</sub>, and its relationship with the spatial distribution of the inverse of HDD from December 2010 to May 2011 (Fig. 3.7).

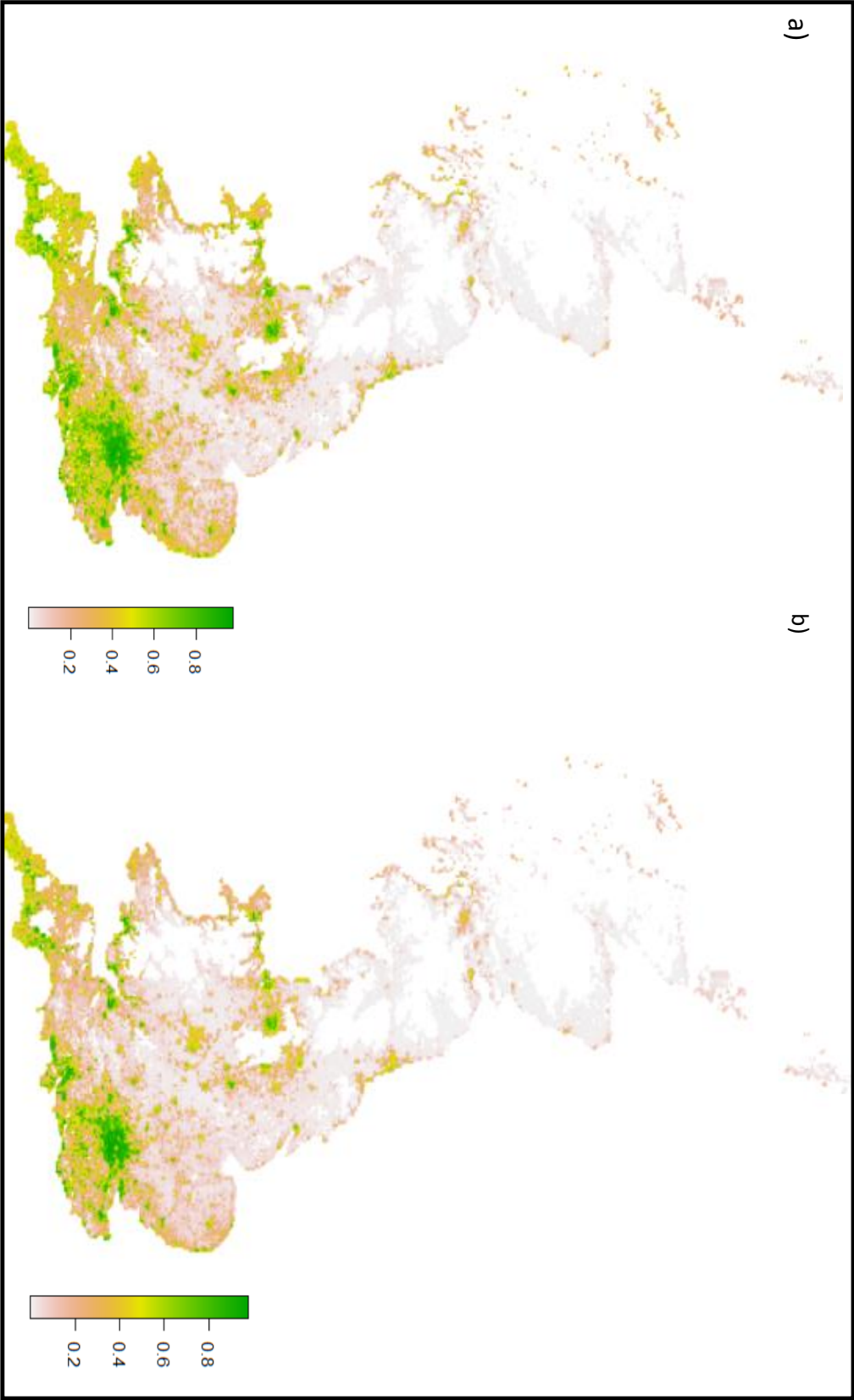


**Figure 3.5** Weighted ensemble model predictions of the probability of habitat suitability of Rose-ringed Parakeets (*Psittacula krameri*) in Great Britain in a) winter and b) breeding season. Based on Timed Tetrad Visit data from the Bird Atlas 2007-2011 (Balmer et al., 2013)

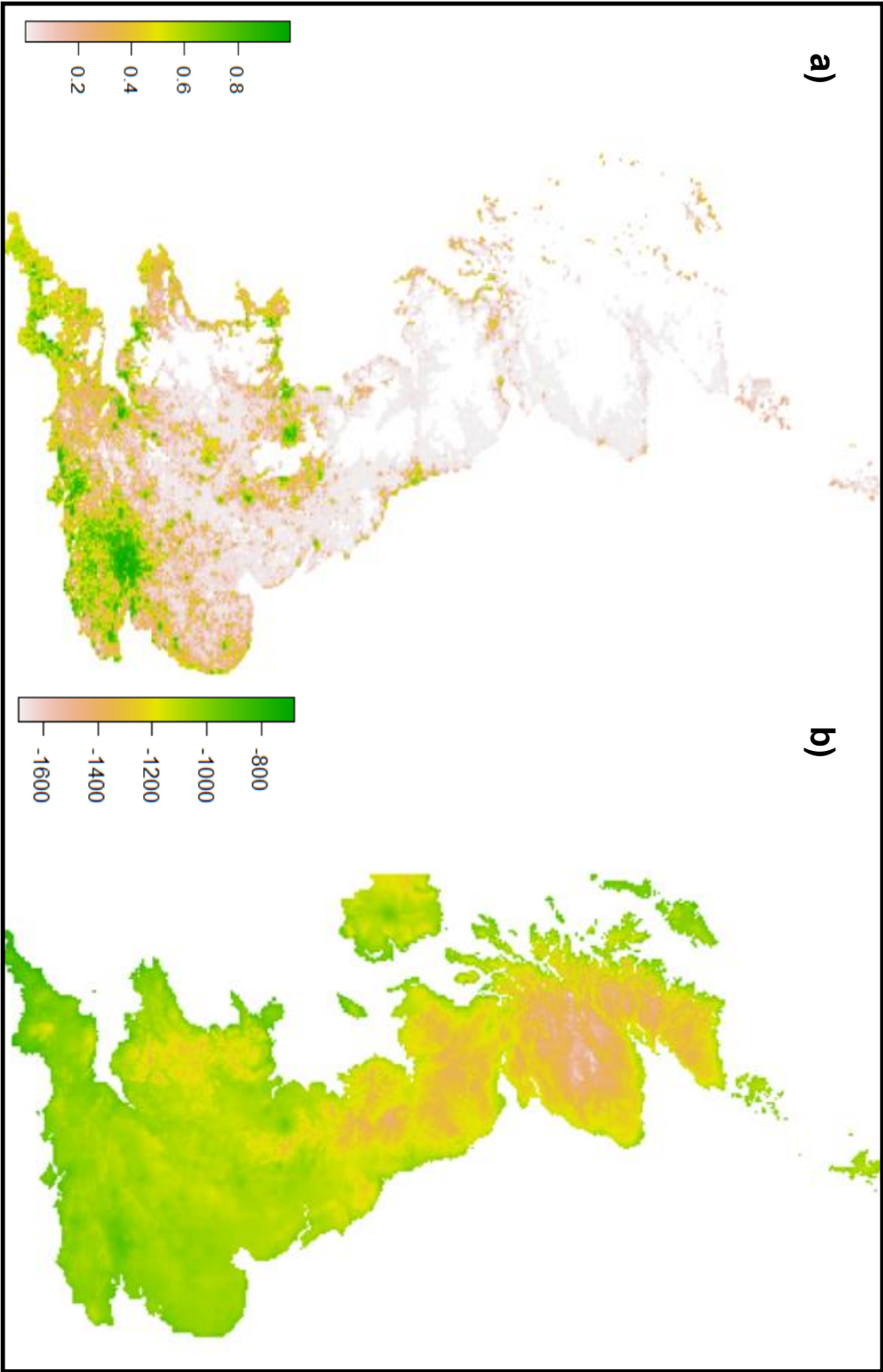


**Figure 3.6** a) Predicted maximum winter distribution of Rose-ringed Parakeets (*Psittacula krameri*) in Great Britain, 2011, and b) Heating Degree Days (HDD) from December 1<sup>st</sup>, 2010 to February 28<sup>th</sup>, 2011. Legends represent a) probability of habitat suitability, and b) the sum of HDD multiplied by 1.

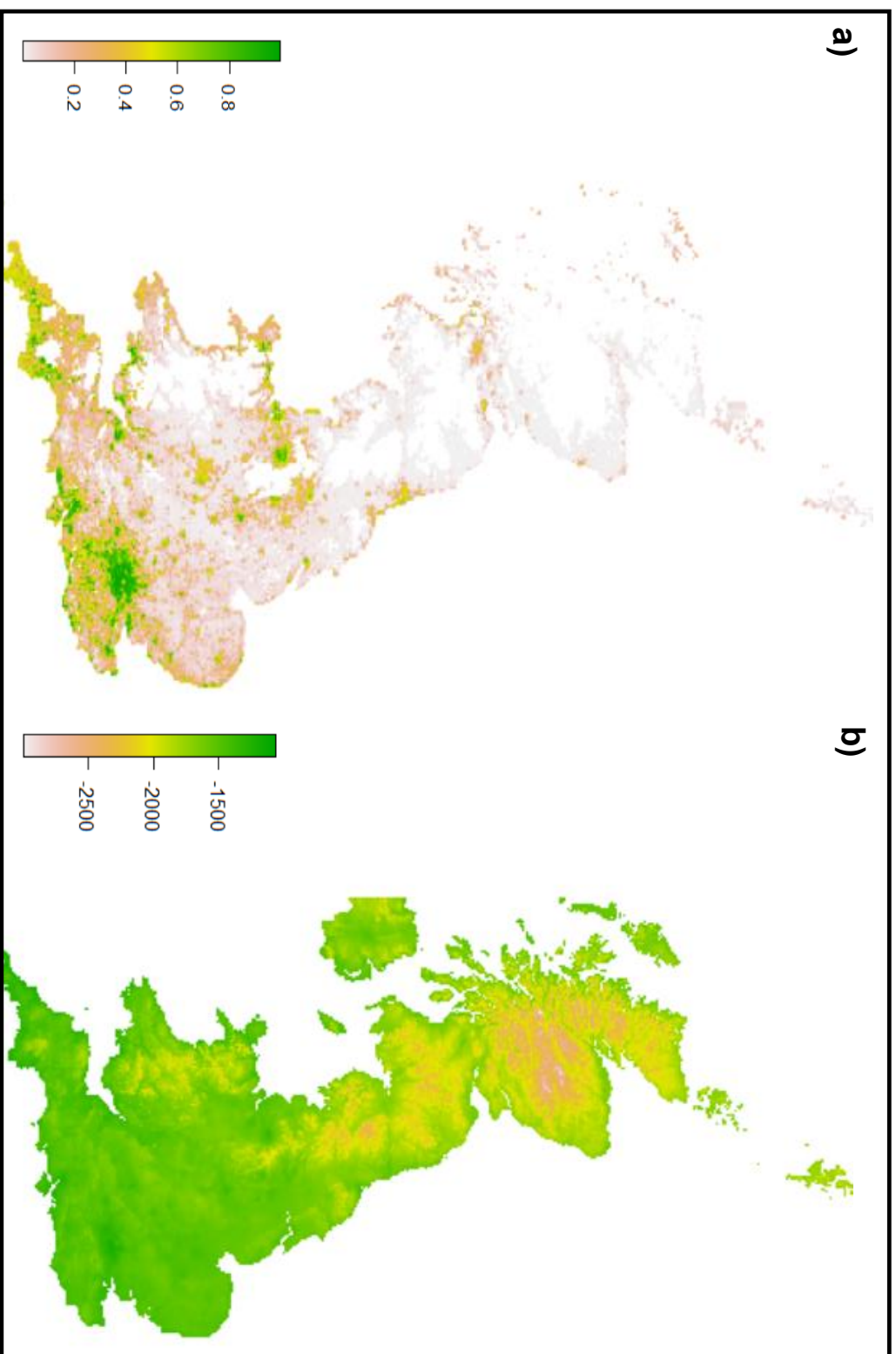


**Figure 3.7** a) Predicted maximum breeding season distribution of Rose-ringed Parakeets (*Psittacula krameri*) in Great Britain, 2011, and b) Heating Degree Days (HDD) from 1<sup>st</sup> December 2010 to 31<sup>st</sup> May 2011. Legends represent a) probability of habitat suitability, and b) HDD multiplied by -1.

### 3.4.6 Validation of the models from Chapter Two data

The results from extraction of probabilities of habitat suitability for models based on TTV data, and models based on website data are shown below, contrasting points where RRP were found in TTVs with points where RRPs were reported to the website.

The results are shown in Table 3.6

Table 3.6 Mean probability of habitat suitability (Mean PO), 95% confidence intervals (CI) and standard deviation (SD) of Rose-ringed Parakeets (*Psittacula krameri*) in Great Britain from ensemble predictions of Species Distribution Models based on Timed Tetrad Visits (TTVs) for the BTO's Bird Atlas 2007-2011 (Balmer et al., 2013) and website data, 2019-2021.

| Ensemble prediction | Data source         |        |      |                   |        |      |
|---------------------|---------------------|--------|------|-------------------|--------|------|
|                     | BTO Atlas Locations |        |      | Website Locations |        |      |
|                     | Mean PO             | 95% CI | SD   | Mean PO           | 95% CI | SD   |
| TTV winter          | 0.81                | 0.01   | 0.16 | 0.62              | 0.02   | 0.25 |
| TTV breeding        | 0.78                | 0.01   | 0.18 | 0.57              | 0.01   | 0.18 |
| Website winter      | 0.55                | 0.01   | 0.28 | 0.66              | 0.02   | 0.22 |
| Website breeding    | 0.53                | 0.02   | 0.31 | 0.64              | 0.02   | 0.26 |

Table 3.4 shows that the surveying of TTVs where absence of RRPs is likely to be a true absence (but not certain) produced a better model than the website data. The website data relied on both RRPs being observed, and that RRP sighting being reported to the website, and the SDMs are therefore more likely to generate a background point for absence, where RRPs are actually present. This seems to

demonstrate that in this case, use of systematic methodology in locating RRP produces a better result than using *ad hoc* sighting data reported to a website.

### 3.4.7 Rose-ringed Parakeets and HDD

As the predicted maximum distributions of RRP in both winter and breeding seasons are clearly related to the spatial distribution of HDD (Figures 3.8 and 3.9), RRP should be found in areas with lower values of HDD (i.e. at temperatures closer to 15°C). On examining the values for HDD in locations with RRP and a random selection of locations within the area of the small rasters where RRP were not reported, the mean sum of HDD for areas where RRP were present in winter was  $997.65 \pm 4.08$  (1 SD) *versus*  $1,074.32 \pm 4.60$  where they were absent. This difference was highly statistically significant (Wilcoxon test:  $W = 1,299,823$ ,  $N_{\text{absent}} = 2,435$ ,  $N_{\text{present}} = 597$ ,  $p < 0.00001$ ). The comparative results for the breeding season were  $1,394.90 \pm 8.55$  where birds were present *versus*  $1,552.24 \pm 9.12$  where they were absent with the same statistical significance (Wilcoxon test:  $W = 825,334$ ,  $N_{\text{absent}} = 2,435$ ,  $N_{\text{present}} = 379$ ,  $p < 0.00001$ ).

## 3.5 Discussion

Having established that the distribution of RRP in GB, as shown in the BTO's *Atlas 2007-2011* (Balmer et al., 2013) was almost entirely in towns and cities (Fig. 3.1a), the SDM based ensemble predictions demonstrate that the fundamental niches of RRP in GB, in both the winter and breeding seasons, are considerably larger than the currently realised niche. This finding suggests that RRP could continue to expand their range on GB, in both seasons.

### **3.5.1 Influences on Rose-ringed Parakeet distribution**

The results show that the biggest influence on RRP distribution is ambient temperatures, with RRP favouring areas with warmer temperatures, particularly in the breeding season. Ambient temperature is a stronger influence on the model of RRP distribution in the breeding season than in the winter. This is likely to reflect the influence of cold on eggs during incubation, with RRP in GB having a much higher rate of egg failure to hatch than in warmer climes (Shwartz et al., 2009). In the winter season, ambient temperatures will influence distributions as RRP will favour warmer areas, where the energy requirements of maintaining homeothermy are lower as the ambient temperatures near the LCT (Scholander et al., 1950a; McNab, 2012; Thabethe et al., 2013).

As RRP have a sub-tropical and tropical native range (Cramp, 1985; Forshaw, 1989; Juniper and Parr, 2003), it is not surprising that they are sensitive to ambient temperature in GB (Shwartz et al., 2009; Border et al., 2018). In London, the mean minimum temperature in January (the coldest month) is 4°C (Zoomash Ltd, 2022a), but in New Delhi, in the native range, the mean minimum temperature in January (the coldest month) is 12 °C (Zoomash Ltd, 2022b). In terms of explanatory power in SDMs created in this study, HDD was a more powerful variable than mean monthly minimum temperatures or days of ground frost, probably because it assessed duration of exposure to ambient temperature as opposed to a temperature measure that is a snapshot. At lower temperatures RRP reduce energy expenditure to liberate more energy from energy budgets for thermoregulation (Thabethe et al., 2013). The LCT of

RRPs of 15°C used in this study in calculating HDD is higher than the mean monthly minimum temperature in the south of England throughout the year (Met Office, 2022).

The importance of HDD in the models compared to the distribution of trees can be seen in the (albeit low) predicted probability of habitat suitability of RRP in the islands of the Outer Hebrides, Orkney and Shetland (Figs 3.8 and 3.9), where trees are scarce, particularly those large enough to support breeding RRP.

Elevation relates to temperatures, as temperature falls with elevation (Lute and Abatzoglou, 2021; Minder et al., 2010; McCutchan, 1983). Elevation is known to influence bird communities (Lee et al., 2004; Chamberlain et al., 2016). RRP are known to occur at altitudes of 1,600 metres in the Indian peninsular uplands, and 1,300 metres in the Himalayan foothills, it is to be expected that the upper elevation limit on RRP in GB would be considerably lower than in the native range (Auer and King, 2014; Burner et al., 2020).

The importance of broad-leaved, mixed and Yew woodland to RRP makes ecological sense. Trees are sources of food for RRP (Cramp, 1985; Clergeau and Vergnes, 2011; Shivambu et al., 2021) and of nesting sites that are cavities in more mature trees with RRP being obligate cavity nesters (Newson et al., 2011; Le Louarn et al., 2017; Butler, 2021). In addition, RRP also roost in trees (Pithon and Dytham, 1999; Butler, 2003; Peck, 2013). and this may add to the importance of particularly broad-leaved woodland to the birds.

The distribution of RRP has changed between 2011 (when the TTVs were carried out) and 2021 (the year used for validating the model with the website data). There appears to have been a spread to the south-west (Plymouth) and to the north

(Newcastle and Glasgow). As temperatures are known to be rising in GB (Kendon et al., 2019, 2021) it appears that ambient temperatures may have risen sufficiently to enable further colonisation of GB by RRP. Colonisation of new areas of GB by RRP is slow. This is probably due to the short dispersal distance of RRP, possibly as little as 400 m a year (Butler, 2003). Butler (2003) also identified that new colonies of RRP could arise up to 13km from established colonies (though usually closer). It is clear that colonisation of GB by RRP is probably not complete and that further range expansion is possible in GB.

It is also clear that RRP make extensive use of bird feeders in towns and cities (Clergeau and Vergnes, 2011; Peck, 2013; Le Louarn et al., 2016; Deguines et al., 2020). It is possible that the presence of bird feeders may also make life in towns and cities more attractive to RRP. Human population density can be seen as being an indication of the provision of supplementary foods by humans. This may be complicated by affluence and housing type. People living in tower blocks will have a high density per unit of area, but very little chance to feed birds in the absence of gardens. The importance of human density in the final models suggests that RRP may require human presence in some way. This human presence requirement may relate to the presence of supplementary feeding, though it may also relate to a reduced predation pressure in the native range that has lead RRP to become synanthropic. The relationship between RRP, bird feeders and humans is an area that would reward further investigation.

None of the other retained variables in the models were statistically significant. This may reflect the over-whelming influence of ambient temperatures, rather than the lack of importance of other variables. Of the retained variables, the combination of human population density, road length per km<sup>2</sup> and urban habitat, may all reflect the influence of urban areas (where the road network is most dense, human population density is higher and urban habitats are more common) on temperatures. The Urban Heat Island (UHI) effect provides a link between RRP distribution and thermal conditions in urban centres. Many recent studies have investigated the UHI phenomenon (e.g. Magli et al., 2015; Azevedo et al., 2016; Warren et al., 2016; Palme et al., 2017; Sobstyl et al., 2017), not least because while cities cover just 2% of the surface of the Earth, their human inhabitants consume 75% of world's energy (Gago et al., 2013), 69% of the global human population being forecast to live in cities by 2050 (Bassett et al., 2016). The UHI phenomenon has a number of adverse impacts on human health through temperature related health impacts (Tomlinson et al., 2011; Vargo et al., 2016), mortality in heat waves (Heaviside et al., 2016), tick associated Lyme disease (Buczek et al., 2014) and air quality (Leung et al., 2011). In addition, urbanisation also influences the phenology of birds (Vaugoyeau et al., 2016; Gryz and Krauze-gryz, 2018) and the distribution of organisms (Parris and Hazell, 2005; Valle-Díaz et al., 2009; Brans et al., 2018).

### **3.5.2 Comparing winter and breeding season distributions**

The predicted maximum potential distributions of RRP in winter and the breeding season are similar (Figs 3.8 and 3.9). It can be seen, however, that the breeding season distribution is more limited than that of the winter. This probably indicates that

the breeding distribution is more strictly limited by ambient temperatures than the winter distribution. This is potentially due to low ambient temperatures reducing the number of eggs that hatch (Shwartz et al., 2009). It is possible that foraging distances are greater in winter than in summer, however, there is no evidence to support this in this study.

### **3.5.3 Model performance**

It is clear that the models produced both performed excellently by the AUC/ROC measurement. Both of the models were clearly good when assessed by both COR and TSS (the DEV metric is essentially a comparative measure, enabling comparison between model replicates, but less useful for comparing one overall model against another. These all suggest that the models produced are good models that explain the distribution of RRP in GB in 2011 (Dormann et al., 2012; Shabani et al., 2016; Graham et al., 2017).

### **3.5.4 Model validation**

The extraction of the probabilities of habitat suitability from the ensemble predictions of winter and breeding distributions of RRP in GB created from both TTV and Chapter Two data, suggests that the BTO Atlas-based models are valid and sufficiently robust to be used for further forecasting of RRP distributions in GB. The predicted distributions are based on weighted averages across all 18 replicates of each model and based on optimisation of true positive and true negative predictions. In addition, the predicted

probabilities of habitat suitability derived from the BTO Atlas-based models and applied to more recent observations of RRP in Chapter Two, returned similar probabilities of habitat suitability.

The models run in *ENMeval* produced the same support for HDD as a measure of cold as the models run in *SDM* but only in the AICc scores (see Table 3.4 above). The differing support for the models is similar to that seen between the different modelling algorithms in SDM, and demonstrates a benefit of using an ensemble modelling approach, where several modelling algorithms are judged over the whole variety of models, rather than over single replications with only one modelling algorithm used. The different validation values in *SDM* and *ENMeval* demonstrate that there is still some disagreement over the best measures of model performance.

### **3.6 Extrapolation of prediction**

In this chapter, the distribution modelled was based on a minimum area within which all of the records of RRP found in TTVs for the Bird Atlas 2007-2011 were found. The predicted distributions of RRP in both the winter and breeding season were produced for the whole of GB. While this is a limited expansion from the realised range in GB, some inaccuracies may have occurred. This is particularly true in the Scottish Islands, where RRP have a low predicted likelihood of occurrence, despite the fact that there are few trees in those areas. This is probably due to the dominance of HDD in the model compared to the presence of trees.

Expanding the prediction to any area wider than GB would be likely to introduce far more inaccuracies. This would be due to a different range of habitats and

temperatures, with widely varying values of HDD. In a similar vein, producing models based on the predicted distribution of RRP in GB, will not reflect conditions found elsewhere in the world. Predicting the likelihood of RRP presence around the world based on a model derived from data for GB only, is likely to produce a model showing presence of RRP only being likely in temperate regions of the world and excluding tropical and sub-tropical areas. Conversely, creating a model of RRP distribution world-wide based only on records from the native range would be likely to produce a predicted distribution that excludes temperate areas. This difference arises due to the assessment of only one extreme of temperature: in this chapter cold temperatures are assessed, but not hot temperatures.

It is possible that natural selection produced a population of RRP in GB that is better able to survive cold weather. This may be supported by the prevalence of genes from the Northern Indian sub-species of RRP in the GB population (Pithon et al., 2001), though this may reflect the origin of introduced birds, rather than true natural selection of those birds in British conditions.

### **3.7 Future work**

In both the winter and the breeding season models, distributions of RRP were mostly explained by ambient temperatures, followed by elevation and the presence of broad-leaved, mixed and Yew woodland. The influence of ambient temperature was greatest in the breeding season, suggesting that the colder temperatures of GB are responsible for the higher levels of eggs failing to hatch experienced by RRP in GB (Shwartz et

al., 2009). Elevation probably acts in a similar way to ambient temperatures in influencing RRP distribution.

For a sub-tropical bird species such as RRP, a preference for warmer areas in GB is to be expected. The UHI influences the temperatures found in towns and cities, and it is probable that the UHI is one of the major factors that has enabled the colonisation of some cities and towns in GB. The UHI phenomenon is strongest in large cities and, therefore, it is unsurprising that RRP are found mainly in and around large conurbations in GB.

The models developed in this chapter, and validated by extracting probabilities of habitat suitability from the ensemble model predictions, are sufficiently robust to use for predicting the potential maximum winter and breeding distributions of RRP in GB in the future. It is possible that the major limit to the distribution of RRP within the maximum potential distributions (fundamental niches) in GB shown in this chapter, is the time taken by RRP to increase their range.

It would be beneficial to species distribution modelling and ecological niche modelling if the statistical packages were developed further to enable the use of both sets of model performance measures in both statistical packages. Such a development in statistical modelling is beyond the scope of this study, but would certainly benefit future researchers seeking to use the ensemble modelling approach.

The ensemble predictions of winter (Fig. 3.6a) and breeding distributions (Fig. 3.6b) of RRP in GB suggest that birds will occupy a greater area of GB in the future. The ensemble predictions suggest that these areas will continue to be mainly within towns and cities, but with some spread into more rural areas, particularly along the south

coast of England and Wales, with some birds potentially occupying areas inland in the south-west peninsula. All of these areas share one obvious feature: warmer temperatures.

One of the features of the climate in GB is the warming of temperatures in recent years, due to anthropogenic climate change. Having developed models of winter and breeding season distributions of RRP in 2011 under the predictor variables relevant to that time, the models could be used to predict changes in RRP distribution in GB, if those predictor variables change. The Met Office has carried out extensive modelling of weather patterns, under a range of climate change scenarios. The outputs of that modelling can be obtained from the Met Office website (<https://archive.ceda.ac.uk/>). While the future availability and coverage of habitats is less easy to predict, particularly as the GB government sets the overall vision for development, which is then implemented at more local levels of government: Parish, District and County Councils.

It is therefore possible to utilise the models of weather patterns produced by the Met Office to create rasters of the predicted distribution and HDD in future years. Those rasters can then be used to create new ensemble predictions of maximum potential distributions of RRP in GB during the winter and breeding periods. Furthermore, as the UK Government has made a commitment to increase tree planting to assist the UK in becoming carbon neutral (Ares et al., 2021), it may be possible to make some predictions of the degree of tree cover in the future. This increase in tree cover can also be incorporated into the models developed in this chapter.

The next chapter in this thesis will therefore utilise the models developed here, the weather patterns predicted by the Met Office for future years and possible scenarios

for the future distribution of tree cover to examine how climate change and the planting of trees, to aid in achieving carbon neutrality, may influence the distribution of RRP in GB.

## CHAPTER 4: THE FUTURE DISTRIBUTION OF ROSE-RINGED PARAKEETS (*PSITTACULA KRAMERI*) IN GREAT BRITAIN

### 4.1 ABSTRACT

Future climate change will bring increased temperatures to Great Britain (GB), influencing the distributions of organisms sensitive to temperature. Using the species distribution model (SDM) developed in Chapter 3 and based upon Timed Tetrad Visit data from the British Trust for Ornithology's (BTO) *Bird Atlas 2007-2011* (Balmer et al., 2013) and one of the Met Office climate change predictions (UKCP18 RCP8.5, outcome 01) for the periods December 2020 to December 2040 and December 2060 to 2080, distributions of Rose-ringed Parakeets (RRPs) in GB were predicted for 2021, 2031, 2061 and 2071. As changes in habitat are unpredictable, the latest Land Cover Maps 2015 (LCM2015) were used across all time periods, although an attempt was made to refine the predicted distribution of birds in 2071 by increasing tree cover by 3%, 5% and 7%, reflecting planned tree planting to act as carbon sinks to achieve the United Kingdom (UK) government's aim of carbon neutrality by 2050. These changes produced no significant variation in the probability of habitat suitability of RRP. The overwhelming impact of climate change on future distributions of RRP resulted in a SDM that predicted birds would expand in range in response to the predicted markedly milder winters and only marginally warmer summers. Birds were predicted to colonise more rural areas of south-west GB and more towns and cities in the north of England and Scotland south of the Highlands in future. Future expansion of range will likely be seen more often in the winter than in the spring/summer when birds breed. Colonisation of rural areas in the south-west and south of GB will continue while RRP

distribution will increase in the cities of central GB. Urban Heat Islands in towns and cities may act as sources of RRP populations that move out into the countryside. The mitigating impacts of future tree planting towards carbon neutrality by 2050 appear unlikely to contribute markedly to further expansion of range of RRP in GB.

**Keywords:** global warming; heating degree days (HDD); range expansion; tree cover; urban heat island (UHI).

## **4.2 INTRODUCTION**

### **4.2.1 Climate change and future distributions of organisms**

Anthropogenic climate change is already driving temperature rises in Great Britain (GB) (Stainforth et al., 2013; Kendon et al., 2019, 2021). Climate change is known to change the distribution of birds, with most in the Northern Hemisphere shifting their distributions northwards (Virkkala et al., 2008, 2013; Scridel et al., 2018; Pettorelli et al., 2019; Soultan et al., 2022). Many bird species will shift northwards with high species turnover in many locations (Virkkala and Lehikoinen, 2017), although it is unlikely that the number of species leaving an area will be matched by those arriving (Virkkala et al., 2013) as many species experience range contractions as they shift poleward (Virkkala et al., 2008). As climate change causes rising temperatures in GB, birds on the northern edge of their range that are limited by cold, are expected to shift their range northwards. One such species in GB, is the Rose-ringed Parakeet.

#### **4.2.2 Ambient temperatures and Rose-ringed Parakeets in Great Britain**

One effect of climate change is a rise in the mean ambient temperatures experienced in GB, as described in the “State of the UK Climate, 2020” (Kendon et al., 2021). British ambient temperatures are generally higher in the south than the north and in the west than the east (Hennessy, 1888; Lennon and Turner, 1995; Hall and Hanna, 2018). This general trend is illustrated in Figure 4.1 that shows higher mean temperatures in the south and west of GB compared with the accumulated temperature difference over time between the Lower Critical Temperature of RRP of 15°C between the start of December 2010 and the end of February 2011, which is highest in the mountains of Scotland, Wales and England, and lowest in the south and west of GB (the opposite distribution to mean minimum temperatures).

Figure 4.1 shows some areas in GB are warmer than others and this is particularly true of urban areas (e.g. Greater Manchester, London) that constitute Urban Heat Islands (UHI), the phenomenon of temperatures in towns and cities being higher than the surrounding rural areas, first described by Howard (1818). These heat islands are created through the absorption, and later release, of solar energy by buildings and man-made surfaces, and heat generated by human activities, such as heating, cooling and transport (Magli et al., 2015; Azevedo et al., 2016).

The higher ambient temperatures in UHIs make towns and cities more suitable for RRP than the surrounding, cooler, rural areas, as demonstrated by the predicted maximum distributions of RRP in the winter and breeding seasons of 2011 described

in Chapter 3. It appears that areas of UHI in 2011 were vital for RRP, as the potential distributions of RRP away from the south-west of GB were mainly limited to towns and cities where ambient temperatures are higher.

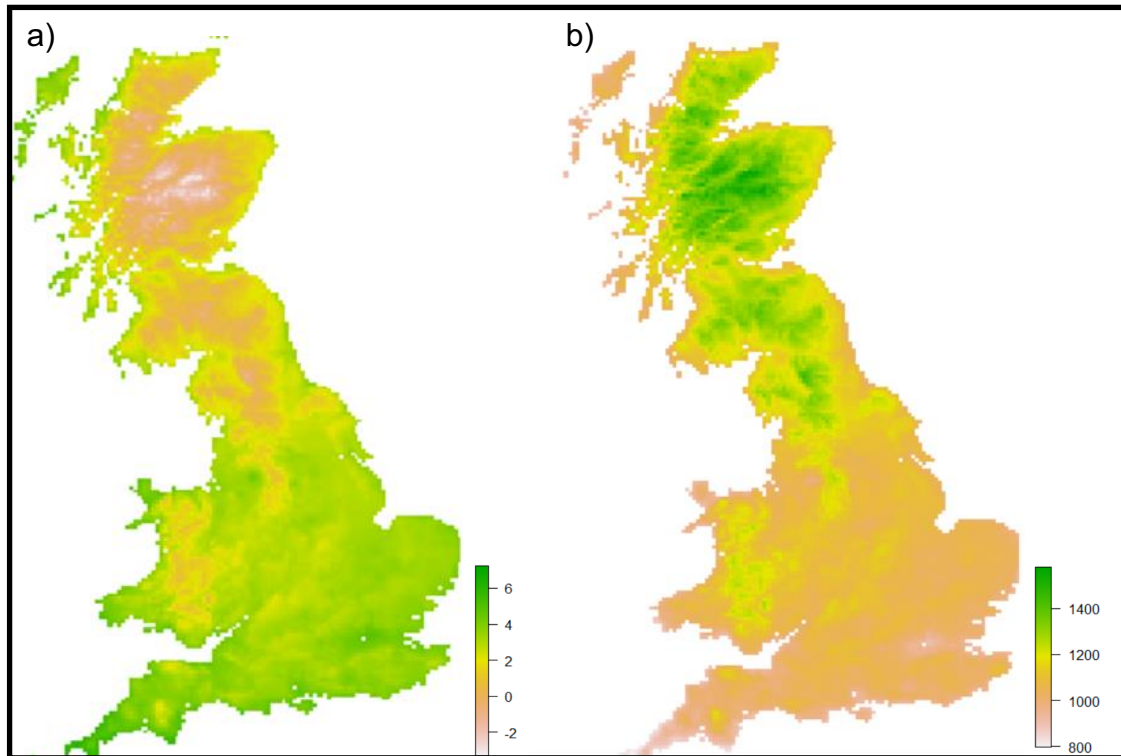


**Figure 4.1** The distribution in Great Britain (GB) of a) mean temperature for the period 1<sup>st</sup> December 2010 to 28<sup>th</sup> February 2011; and b) Heating Degree Days (HDD) for the period 1<sup>st</sup> December 2010 to 28<sup>th</sup> February 2011. HDD was derived from the Lower Critical Temperature for Rose-ringed Parakeets (*Pasittacula krameri*), as stated by (Thabethe et al., 2013), at 15 °C. Legend shows a) temperature in °C; and b) value of HDD.

The winter and the breeding predicted distributions of RRP in 2011 (see Fig. 3.7) appeared to follow two major patterns: in the south-west of GB, the predicted distributions suggested that many rural areas were suitable for RRP, while away from the milder south-west, RRP were more limited in potential distribution to mainly towns

and cities. As ambient temperatures are by far the strongest limiting predictor variable on the distribution of RRP (see Table 3.4), in both seasons, the predictions suggested that it was unlikely that RRP would be able to occupy most rural areas in GB due to low ambient temperatures.

Climate change is already causing rising temperatures in GB (Kendon et al., 2021), and it is possible that as ambient temperatures rise RRP potential distributions will also change. Predicting future ambient temperatures requires the modelling of changing climate and weather patterns across GB. Fortunately, the Met Office has already carried out such modelling and the resulting datasets are available to researchers in the form of the UKCP18, RCP8.5 (Met Office Hadley Centre, 2019). The UKCP19 RCP8.5 predictions give realistic predictions of weather and temperature patterns across GB for the periods 1980-2000, 2020-2040 and 2060 to 2080.

RCP8.5 is the most extreme scenario of emissions of greenhouse gases leading to higher levels of climate change. Whilst this may be extreme in the time period covered by RCP8.5, if human behaviour remains harmful to the environment beyond 2080, the emission levels necessary to cause RCP8.5 may well happen, albeit not in the time frame of RCP8.5. Thus RCP8.5 is a possible scenario for the future, even though it may take longer to reach the full extent of climate change suggested in this scenario.

#### **4.2.3 Trees and Rose-ringed Parakeets in Great Britain**

Trees provide fundamental habitats for RRP. RRP nest in tree cavities and feed on tree seeds, buds, flowers, nectar and young leaves (Cramp, 1985; Juniper and Parr,

2003; Clergeau and Vergnes, 2011). The distribution of broad-leaved, mixed and yew woodland habitats was one of the statistically significant predictor variables in both the winter and breeding season SDMs for the species in Chapter 3 (see Table 3.4). Coniferous tree distribution was a statistically non-significant predictor variable, demonstrating that conifers have less importance to the SDMs than broad-leaved trees. In GB, RRP's may feed on one species of pine (*Pinus* sp.; Cramp, 1985), whilst in France, RRP's were recorded as feeding on Yew (*Taxus baccata*) berries (Clergeau and Vergnes, 2011).

Apart from feeding and nesting, RRP's use trees for roosting communally when they gather each evening at regular sites, often flying several miles to reach the roost site (Pithon and Dytham, 1999; Peck, 2013). Whilst the number of birds coming to roost sites has been counted to enable calculation of population size (Pithon and Dytham, 1999; Peck, 2013), there is little information available on the trees in which RRP's roost. It is feasible that some large coniferous trees with an open structure may be used, but it appears more likely that RRP's would be roosting in broad-leaved trees, particularly as most coniferous woodlands in GB are found away from areas occupied by RRP's, which are predominantly located in the south-east of GB, where broad-leaved, mixed and Yew woodlands are more common (see Fig. 4.2).

The future distribution of trees in GB is difficult to predict. One means of combatting climate change is to sequester carbon in increased numbers of trees in both forests (van der Gaast et al., 2018) and cities (McHugh et al., 2015), "The England Trees Action Plan 2021-2024" (UK Government, 2021) set short-term targets for tree

planting, and a briefing paper of June 2021 (Ares et al., 2021) gave a target of 30,000 hectares (ha) of trees to be planted each year to aid in the UK target of carbon neutrality (storing at least as much carbon as is released into the atmosphere) by 2050. Current tree planting is well below the targets set by the UK Government (Reid et al., 2021). Planting 30,000 ha of trees until 2050, would produce an increase in the extent of tree cover in GB of approximately 7%, if that rate of planting is achieved and maintained.

The main mechanism for this tree planting is the payment of incentives to UK landowners for planting trees (UK Government, 2021). Extensive tree planting has been taking place already in a number of projects, such as the Heart of England Forest and the National Forest (both in the Midlands of England), but incentivising landowners will tend to produce an increase in tree planting that is widely distributed and with no central plan. Most tree planting will take place on either arable land, grassland or in land being developed for housing (often on arable land or grassland). This may produce a distribution of trees that is widely and relatively evenly spread, although it is currently impossible to predict precisely.

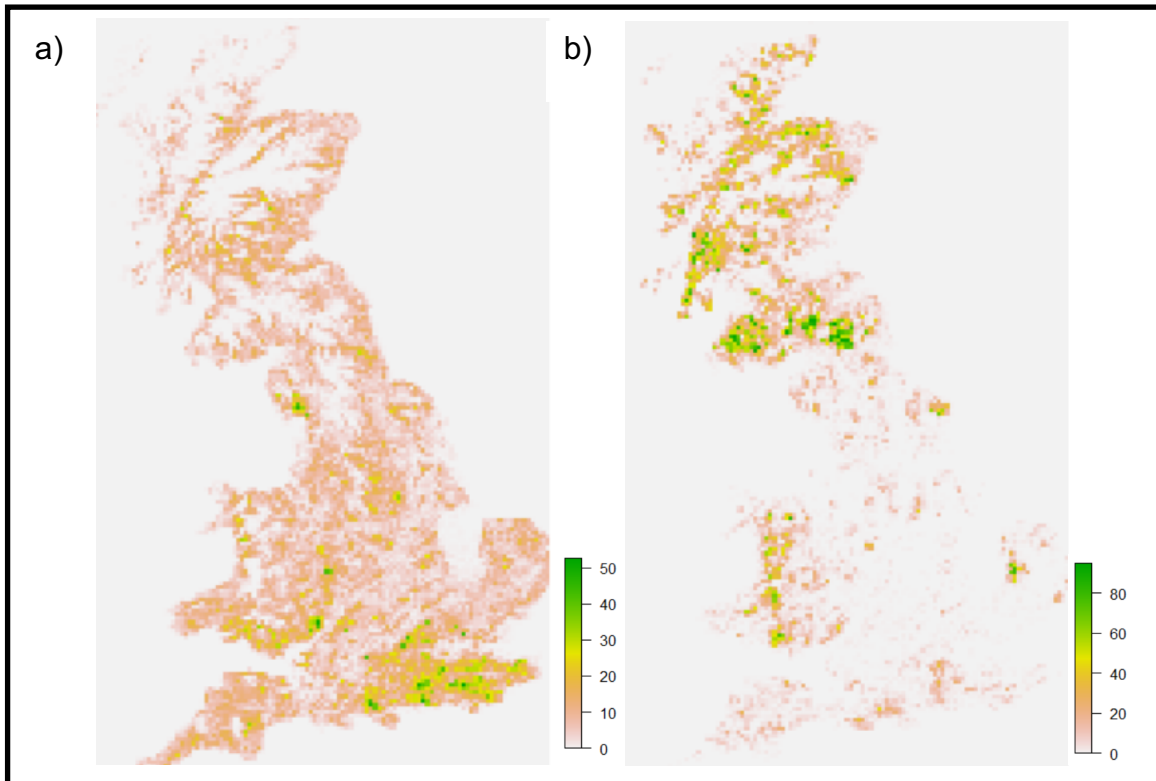


**Figure 4.2** The distribution of (a) broad-leaved, mixed and yew woodland, and (b) coniferous woodland in GB. (Source: Rowland et al., 2017b). Based upon Land Cover Map 2015 ©.UKCEH, 2017. Contains Ordnance Survey data © Crown Copyright, 2007. Licence number 100017572.

The rising ambient temperatures in GB and the drive to increase the extent of trees across GB will alter two of the main influencing factors on the distribution of RRP in GB. This is likely to influence RRP distribution in the future. This raises the question of what the future distributions of RRP in GB will be?

#### 4.2.4 Why do future Rose-ringed Parakeet distributions in Great Britain matter?

Native ecosystems around the world can be threatened by alien invasive species (Myers et al., 2000), with establishment of alien invasive species being enabled by declines in native species (Manchester and Bullock, 2000). In this context, an alien

species is one that has been introduced, while an invasive species is one that can do harm to native species and ecosystems, damage economic interests or cause harm to human health. Alien invasive species can outcompete even dominant native species (Colléony and Shwartz, 2020). RRP's have established populations in many countries around the world and are well known as an alien invasive species (Keller et al., 2011; Menchetti and Mori, 2014; Shiels and Kalodimos, 2019; Pyšek et al., 2020). Given that RRP's are an introduced species in GB, do they meet the criteria for being classed as invasive in GB?

There is certainly potential for RRP's to impact on native cavity-nesting bird species in GB. This may be through their early occupation and subsequent defence of nest sites (Butler, 2003). Though experimental evidence of RRP's impacting on Eurasian Nuthatches (*Sitta europaea*) has been identified in Belgium (Strubbe and Matthysen, 2009b). Newson et al. (2011) were, however, unable to identify impacts of RRP's on native cavity nesting birds in GB but could not rule out impacts where the supply of nesting cavities is limited.

Another possible impact of RRP's on native birds is through access to food. Parakeets are known to impact on feeding behaviours of native birds in GB (Peck et al., 2014) and in France (Deguines et al., 2020). The mechanism of the impact is simple domination of bird feeders by RRP's, which are larger than most birds attending bird feeders and forage in flocks, so when one RRP moves away, another takes over. In GB, the species most impacted by the monopolisation of bird feeders by RRP's are Blue Tits (*Cyanistes caeruleus*) and Great Tits (*Parus major*) (.

With regard to economic interests, RRP's are known as an agricultural pest species in the native range (Ahmad et al., 2011, 2012) and the introduced range (Shiels et al., 2018; Shiels and Kalodimos, 2019). In GB the city based distributions of RRP have so far meant that, on the whole, the species remains mostly a potential agricultural pest (Pithon and Dytham, 2002; Marchant, 2019), though there are reports of damage to fruit crops and vineyards in south-east GB (FERA, 2009). Expanding RRP distribution is likely to bring higher numbers of RRP within easy reach of both arable and orchard crops.

Could RRP have a detrimental impact on human health in GB? Many species of bird carry organisms that can be harmful to humans, such as bird flu in poultry, ducks and geese (Matchett et al., 2013; Xu et al., 2016), and West Nile virus (causative agent of West Nile Fever) in many resident birds in GB (Brugman et al., 2013). The human disease psittacosis is caused by *Chlamydophila psittaci*, which has been identified in many species of parrot (including RRP's) kept as cage-birds in Poland (Piasecki et al., 2012). The risk of catching psittacosis from RRP's is highest among people who keep the birds and are in close contact with them. This link to psittacosis was identified by Heald et al. (2020) as one of the motivations for releases of RRP's in GB.

As a species that could impact on native birds, could become an agricultural pest and that may pose a risk to human health, RRP's are a prime candidate to be identified as an invasive species in GB. The potential for RRP's to have detrimental effects on biodiversity, agriculture and horticulture, and human health makes awareness of the potential future distributions of RRP's of paramount importance to economists, farmers, horticulturalists, conservationists and epidemiologists in planning their future activities.

For any species with a distribution that is limited by ambient temperatures, such as RRP in GB, rising temperatures may enable the species to expand its range. Range expansion of RRP in GB, will increase the likelihood of interactions with native species, biodiversity as a whole and potentially humans. Knowledge of bird distributions is therefore an important part of planning and policy for government, conservation organisations, farmers, fruit growers and the National Health Service.

#### **4.2.5 Chapter aims**

The main aim of the study is to predict the future potential distributions of RRP in GB. To do this, the weather predictions of UKCP18, RCP8.5 will be used to create a Species Distribution Model (SDM), based on the predictor variables of 2011, using 5-km resolution rasters. Ensemble predictions will be created for the potential distributions of RRP for the winter and breeding seasons of 2021, 2031, 2061 and 2071 (10, 20, 50 and 60 years from the 2011 potential distributions produced in Chapter 3). By varying the rasters of tree cover within sensible limits to reflect potential increases in tree planting, a sensitivity analysis of the potential distribution of RRP responding to increased availability of trees will be carried out.

### **4.3 METHODS**

#### **4.3.1 Data sources**

In order to be able to understand how weather patterns in GB will change in the future, the Met Office Hadley Centre (2019) modelled weather patterns, based on historic

weather data, that illustrate how the warmth due to climate change will influence the weather of GB. This modelling is known as UKCP18 and is based on the high emissions scenario RCP8.5, with 12 different modelling outcomes. For this chapter the outcome numbered 01 (Met Office Hadley Centre, 2019) was used.

The years chosen for the future distribution work were 2021, 2031, 2061 and 2071. These years are 10, 20, 50 and 60 years after the surveys for the Bird Atlas 2007-2011 (Balmer et al., 2013), and give a short and medium-term view on the potential future for RRP in GB. The years 2041 and 2051 could not be studied, as these years are not covered by UKCP18 RCP8.5.

For the years 2021, 2031, 2061 and 2071, the UKCP18 provided monthly mean temperatures. These were calculated by the Met Office from the daily mean temperatures. The relevant rasters of monthly mean temperatures were then imported into ArcGIS v.10.7 (ESRI, 2019), and a raster of the mean temperature for each of the winter and breeding seasons was calculated using the raster calculator and the following equations:

$$\text{winter } MT = [(MT_{\text{DEC}} \times 31) + (MT_{\text{JAN}} \times 31) + (MT_{\text{FEB}} \times 28)/90] \quad (\text{Eqn 4.1})$$

and

$$\begin{aligned} \text{breeding season } MT = & [(MT_{\text{DEC}} \times 31) + (MT_{\text{JAN}} \times 31) + (MT_{\text{FEB}} \times 28) + (MT_{\text{MAR}} \times 31) + \\ & (MT_{\text{APR}} \times 30) + (MT_{\text{MAY}} \times 31)/192] \end{aligned} \quad (\text{Eqn 4.2})$$

where  $MT$  = mean temperature for the month and subscript months correspond to months between December and May (inclusive).

Rasters were then imported into *RStudio* (RStudio Team, 2019), cropped using a polygon feature of the GB coastline, and all values were extracted and summarised, providing the mean temperature across the whole of GB for that season.

#### **4.3.2 Creating rasters of Heating Degree Days (HDD) for future years**

Data were taken from a gridded dataset at a 5-km resolution, allowing relatively straightforward conversion of habitat rasters from a 1-km resolution. The UKCP18 models provided maximum, minimum and mean temperatures for each day. The mean daily temperature NetCDF files were downloaded and HDD rasters created, using ArcGIS 10.7 (ESRI, 2019), for the winter (from 1<sup>st</sup> December to 28<sup>th</sup> February, inclusive) and the breeding (from 1<sup>st</sup> December to 31<sup>st</sup> May, inclusive) seasons of 2021, 2031, 2061 and 2071 (as described in section 3.3.1). Rasters of HDD for 2011 were aggregated at a 5-km resolution from the 1-km resolution raster used in Chapter 3, calculating the mean value from all  $1 \times 1$  km cells for each  $5 \times 5$  km cell. Similar aggregations were applied to rasters for habitat taken from the Land Cover Map 2015 (LCM2015; Rowland et al., 2017a), and for elevation, housing density, and road length per 1-km square (see section 3.3.1).

In this way all rasters were produced with the same 5-km resolution, and the same origin, projection and size (as described in Section 3.3.2). While it is expected that habitats will change in the future, it is not possible to predict future habitat changes

accurately. For this reason, habitat rasters used were maintained at the 2015 distribution, until the analysis of RRP distribution sensitivity to changes to woodland. This was carried out based on 2071 ambient temperatures, with increases of 3%, 5% and 7% in tree cover, applied to both broad-leaved, mixed and Yew woodland and coniferous woodland in proportion to the ratios of current cover of each habitat type (and equivalent reductions in land cover of both grassland and arable and horticultural land) This represents three levels of increase in tree cover, that may result from the UK Government's plan to aid in carbon neutrality by 2050 through carbon sequestration in trees.

#### **4.3.3 Creation of a SDM for Rose-ringed Parakeet distribution in 2011**

Having created the 5-km rasters for the different variables, a new SDM was created based upon bird census from the British Trust Ornithology's (BTO) *Bird Atlas 2007-2011* (Balmer et al., 2013) and the 5-km resolution rasters of the same predictor variables for winter and breeding season habitat suitability of RRP as in Chapter 3 (see Table 4.1). The same settings were used for 'background' (pseudo-absence points), modelling methods, data partitioning methods, replications and *parallelsettings* as for the modelling in the last chapter, as detailed in Section 3.3.6.

Table 4.1 Environmental variables used for the Species Distribution Modelling and ensemble predictions of future distributions of Rose-ringed Parakeets (*Psittacula krameri*) in Great Britain in 2021, 2031, 2061 and 2071.

| Winter Season                        | Breeding Season                      |
|--------------------------------------|--------------------------------------|
| Broad-leaved, mixed and Yew woodland | Broad-leaved, mixed and Yew woodland |
| Coniferous Woodland                  | Coniferous Woodland                  |
| Arable and Horticultural Land        | Not Retained                         |
| Grassland                            | Grassland                            |
| Urban                                | Urban                                |
| Human population density             | Human population density             |
| Elevation                            | Elevation                            |
| Road Length km <sup>-2</sup>         | Road Length km <sup>-2</sup>         |
| Heating Degree Days                  | Heating Degree Days                  |

#### 4.3.4 Ensemble predictions of Rose-ringed Parakeet distributions in winter and breeding seasons in 2021, 2031, 2061 and 2071

Initially SDMs were created for the distributions of RRP in winter and the breeding season in 2011 at a 5km resolution. This was done using the *sdm* (Naimi and Araújo, 2016) *R* package. From these SMDs it was possible to predict future potential distributions in response to changes in ambient temperatures, by swapping one raster of ambient temperature for another. In this case the HDD raster for the seasons of 2011, were replaced with HDD rasters for the seasons of 2021, 2031, 2061 and 2071, derived from UKCP18 RCP8.5, outcome 01 (Met Office Hadley Centre, 2019). In each case, the new raster was allocated the same name as the original raster to enable its use in the SDMs. Weighted average ensemble predictions of the distribution of RRP

in the winter and breeding seasons of 2021, 2031, 2061 and 2071 were produced. These ensemble predictions used the same method of weighting described in Section 3.3.8, to produce each ensemble prediction based on all 18 replicates within the overall SDM.

#### **4.3.5 Predicting Rose-ringed Parakeet distributions in 2071 with increased levels of tree planting**

New habitat rasters for broad-leaved, mixed and yew woodland, coniferous woodland, arable and horticultural land, and grassland, were produced. The mean percentage of land cover of each habitat type in 2015 was ascertained by extracting all values from the habitat rasters and summarising the percentages in *RStudio*. As the placement of future tree planting is impossible to predict, and as trees need to be planted in both forests (van der Gaast et al., 2018) and cities (McHugh et al., 2015), the increase in tree cover was applied to every cell of the tree rasters. Tree cover rasters were increased by a total of 3%, 5% and 7%, split in proportion to the ratio of broad-leaved to coniferous trees in 2015 (constrained at the maximum percentage of land cover seen in 2015) and grassland and arable rasters were reduced accordingly by 3%, 5% and 7%, split in the proportion of grassland to arable land in 2015 (constrained to no lower than 0%).

Weighted ensemble predictions were then produced for both winter and breeding seasons for 2071 for each change in tree cover (with corresponding reductions by 3%, 5% and 7% in grassland, and arable and horticultural land). Once the ensemble distribution rasters had been produced, probabilities of habitat suitability of RRP

under these different tree cover scenarios were extracted and summarised. Differences in the mean probabilities of habitat suitability between these scenarios were tested for statistical significance by analysis of variance (ANOVA) test and post-hoc Tukey Honest Significant Difference (TukeyHSD) tests in *RStudio*. Statistical significance was detected at an alpha threshold of 0.05.

## **4.4 RESULTS**

### **4.4.1 Mean temperature changes across decades in winter and breeding seasons**

Compared with 2011 predicted mean temperatures in winter and breeding seasons of RRP's are likely to be higher in 2021, 2031, 2061 and 2071 (Table 4.2). This was the case particularly in the winter. Table 4.2 also demonstrates that the rise in mean temperature across the decades is unlikely to be smooth: the winter season mean temperature predicted for 2031 is cooler than it was in 2021 and the breeding season mean temperatures predicted for 2031 and 2071 will also lower than for the preceding year. This warming will result in reduced HDD values in both the winter and breeding seasons (Figs 4.3 and 4.4, respectively).

### **4.4.2 Model Performance**

Due to a coarser resolution in the rasters used for modelling in this chapter, model performance varied slightly from the models produced in chapter 3. The models produced for this chapter had marginally better performance values than the models for chapter 3. The mean model performance scores are shown in Table 4.3.

Table 4.2 The mean temperature experienced by Rose-ringed Parakeets (RRPs) (*Psittacula krameri*) in the winter (1st December to 28th February) and the breeding (1st December to 31st May) in 2011 compared with predicted mean temperatures that will be experienced by RRP in 2021, 2031, 2061 and 2071. Predictions are based on the Met Office UKCP18 RCP8.5 outcome 01.

| Year             | Winter                |                                       | Breeding season       |                                       |
|------------------|-----------------------|---------------------------------------|-----------------------|---------------------------------------|
|                  | Mean temperature (°C) | Difference from 2011 temperature (°C) | Mean temperature (°C) | Difference from 2011 temperature (°C) |
| 2011 (actual)    | 3.0                   | -                                     | 6.1                   | -                                     |
| 2021 (predicted) | 5.5                   | +2.5                                  | 6.5                   | +0.4                                  |
| 2031 (predicted) | 4.7                   | +1.7                                  | 6.2                   | +0.1                                  |
| 2061 (predicted) | 6.4                   | +3.4                                  | 7.7                   | +1.6                                  |
| 2071 (predicted) | 6.5                   | +3.5                                  | 7.3                   | +1.2                                  |

Table 4.3 Mean performance scores for SDMs of wintering and breeding distributions of Rose-ringed Parakeets (*Psittacula krameri*) between in 2011 in GB, produced from 5km resolution rasters. Models are: GLM – generalized linear model; maxlike – formal likelihood model; and maxent – maximum entropy model. Model outputs are: AUC/ROC – area under the curve/receiver operating characteristic curve; COR – correlation; TSS – true skills statistic; and Deviance.

| Models          | Mean performance scores |      |      |          |
|-----------------|-------------------------|------|------|----------|
|                 | AUC/ROC                 | COR  | TSS  | Deviance |
| <b>Winter</b>   |                         |      |      |          |
| GLM             | 0.93                    | 0.77 | 0.74 | 0.66     |
| maxlike         | 0.91                    | 0.76 | 0.72 | 1.23     |
| maxent          | 0.94                    | 0.81 | 0.80 | 0.75     |
| <b>Breeding</b> |                         |      |      |          |
| GLM             | 0.95                    | 0.79 | 0.77 | 0.59     |
| maxlike         | 0.94                    | 0.78 | 0.77 | 0.82     |
| maxent          | 0.96                    | 0.84 | 0.84 | 0.60     |

#### 4.4.3 Variable Importance.

The variable importance for the models created in this chapter are shown in Table 4.4.

These models show much less importance for ambient temperatures, though ambient

temperatures remain much the strongest influence, human population density has become more important and statistically significant, while broad-leaved, mixed and Yew woodland has also become a more important variable and more statistically significant. Coniferous woodland remains relatively unimportant but has become statistically significant in the breeding season. Road length per km<sup>2</sup> has gained in importance but has only become significant in the winter season. Elevation, which was the second most influential variable in the chapter 3 models, is less important here and is also no longer of statistical significance. Arable and horticultural land has become less important and remains statistically unimportant.

Table 4.4 Percentage contribution for each predictor variable in the final distribution models by correlation and AUC/ROC curve. %: percentage contribution to the model. p: level of statistical significance. Bold p values are statistically significant.

| Explanatory variable      | Season      |               |         |               |             |               |         |               |
|---------------------------|-------------|---------------|---------|---------------|-------------|---------------|---------|---------------|
|                           | Winter      |               |         |               | Breeding    |               |         |               |
|                           | Correlation |               | AUC/ROC |               | Correlation |               | AUC/ROC |               |
|                           | %           | <i>p</i>      | %       | <i>p</i>      | %           | <i>p</i>      | %       | <i>p</i>      |
| Heating degree days (HDD) | 33.4        | <b>0.0001</b> | 23.3    | <b>0.0001</b> | 41.2        | <b>0.0001</b> | 33.7    | <b>0.0001</b> |
| Human density             | 18.7        | <b>0.0001</b> | 16.1    | <b>0.001</b>  | 13.6        | <b>0.001</b>  | 9.9     | <b>0.01</b>   |
| Broad-leaved woodland     | 19.8        | <b>0.0001</b> | 11.8    | <b>0.01</b>   | 13          | <b>0.001</b>  | 7.7     | <b>0.01</b>   |
| Coniferous woodland       | 3.7         | <i>ns</i>     | 2.2     | <i>ns</i>     | 7.0         | <b>0.05</b>   | 6.3     | <b>0.05</b>   |
| Road length               | 5.4         | <b>0.05</b>   | 3.8     | <i>ns</i>     | 1.5         | <i>ns</i>     | 0.9     | <i>ns</i>     |
| Grassland                 | 3.5         | <i>ns</i>     | 1.8     | <i>ns</i>     | 5.2         | <i>ns</i>     | 3.7     | <i>ns</i>     |
| Urban                     | 2.9         | <i>ns</i>     | 1.7     | <i>ns</i>     | 3.6         | <i>ns</i>     | 2.3     | <i>ns</i>     |
| Elevation                 | 2.3         | <i>ns</i>     | 1       | <i>ns</i>     | 0.9         | <i>ns</i>     | 0.5     | <i>ns</i>     |
| Arable                    | 1.8         | <i>ns</i>     | 0.9     | <i>ns</i>     | -           | -             | -       | -             |

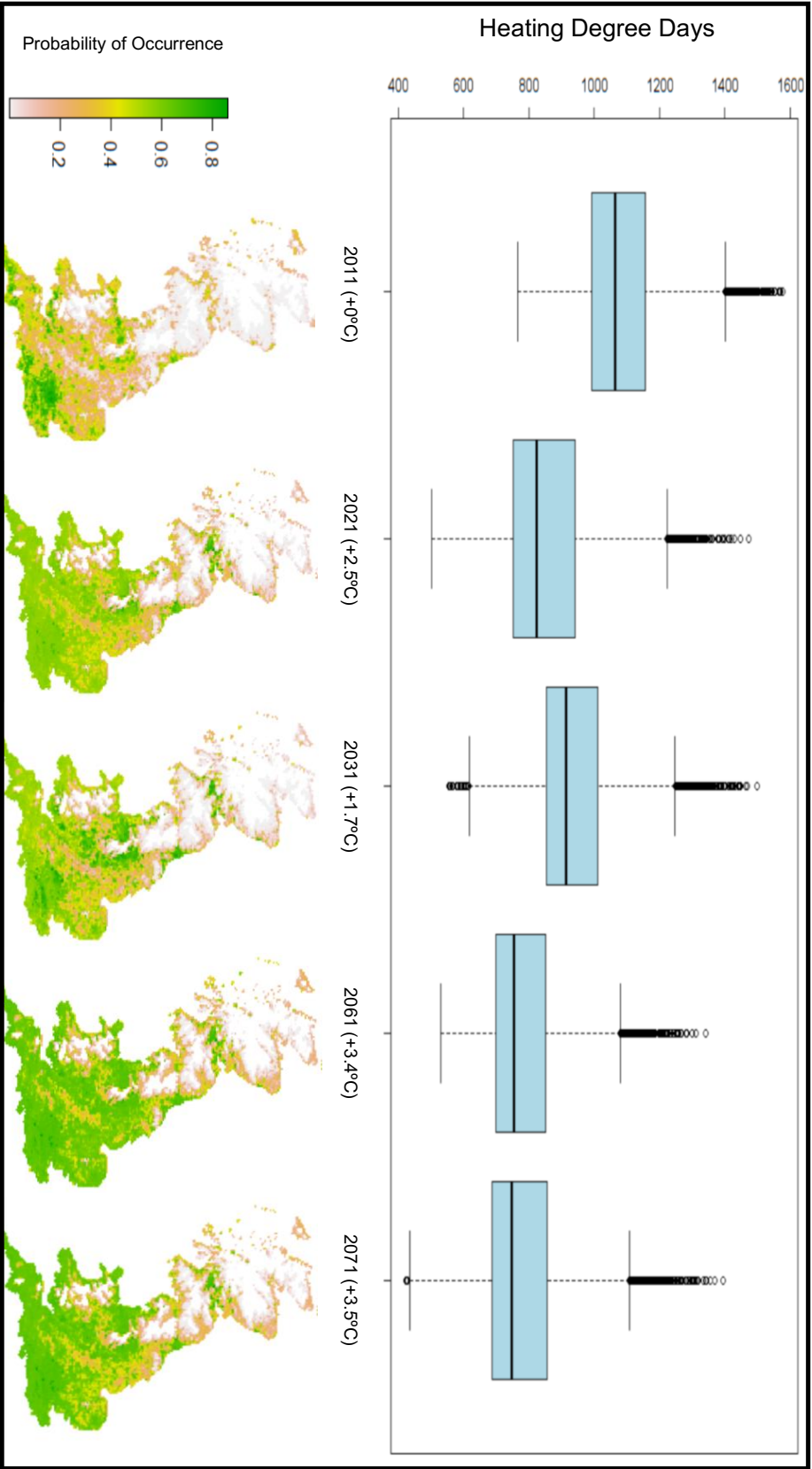


**Figure 4.3** Boxplots of the distributions of values of Heating Degree Days (HDD) (black bar = median, boxes show the interquartile ranges, whiskers show range, black circles show outlying values) and of probabilities of habitat suitability (coloured scale) of Rose-ringed Parakeets (RRPs) (*Psittacula krameri*) in the winter of 2011, and of predicted distributions of RRP in winters of 2021, 2031, 2061 and 2071, Predicted temperatures in future years were based on UKCP18 RCP8.5, outcome 01, climate change scenario.

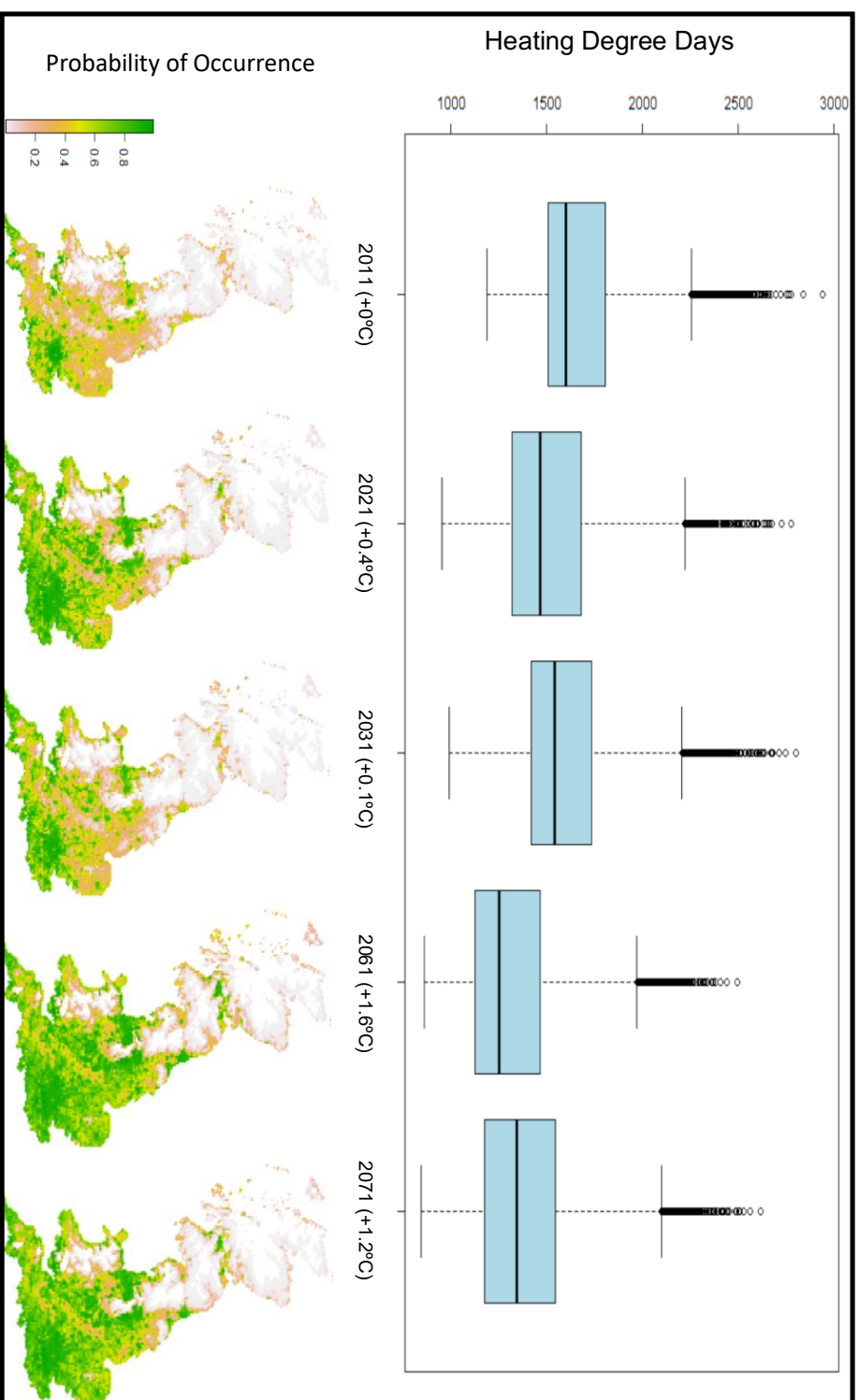


**Figure 4.4** Boxplots of the distributions of values of Heating Degree Days (HDD) (black bar = median, boxes show the interquartile ranges, whiskers show range, black circles show outlying values) and of probabilities of habitat suitability (coloured scale) of Rose-ringed Parakeets (RPPs) (*Psittacula krameri*) in the breeding season of 2011, and of predicted distributions of RPPs in breeding seasons of 2021, 2031, 2061 and 2071, Predicted temperatures in future years were based on UKCP18 RCP8.5, outcome 01, climate change scenario.

#### **4.4.4 Future distributions of Rose-ringed Parakeets in GB in winter**

The ensemble predictions of maximum potential distribution of RRP in the winters of 2011, 2021, 2031, 2061, 2071 are shown in Figure 4.3. They showed increasing probabilities of habitat suitability and wider distributions in England and parts of Scotland, mainly around Glasgow and Edinburgh. The highest probabilities of habitat suitability were in south-west GB, but are predicted to rise across most of lowland GB in subsequent decades. The boxplots of HDD showed falling HDD values over time, corresponding with the rising mean temperatures for each season.

#### **4.4.5 Future distributions of Rose-ringed Parakeets in GB in the breeding season**

Similar to the potential distribution in winter (Fig. 4.3), RRP in the breeding season (Fig. 4.4) were predicted to occur in most of lowland England and Wales, particularly the south-west, with increased probability of habitat suitability around Glasgow and Edinburgh. However, probabilities of habitat suitability were slightly lower than those in the winter. From 2011 the breeding season maximum potential distribution increased as predicted for winter. However, the breeding season distribution was more constrained, probably due to the stronger influence of HDD on RRP distribution in the breeding season, when the mean variable importance was 37.45% (28.35% in winter), see Table 4.4.

#### **4.4.6 Future distribution of Rose-ringed Parakeets in GB in 2071 under different tree cover scenarios**

There was little change in the predicted probability of habitat suitability of RRP in 2071 under different tree cover scenarios (Fig. 4.5). Probabilities of habitat suitability did not

vary significantly between 0%, 3%, 5% and 7% increased tree cover scenarios in either the winter (ANOVA:  $F_{3, 38,048} = 0.57$ ,  $P = 0.64$ ) or the breeding (ANOVA:  $F_{3, 38,048} = 1.56$ ,  $P = 0.20$ ) seasons.

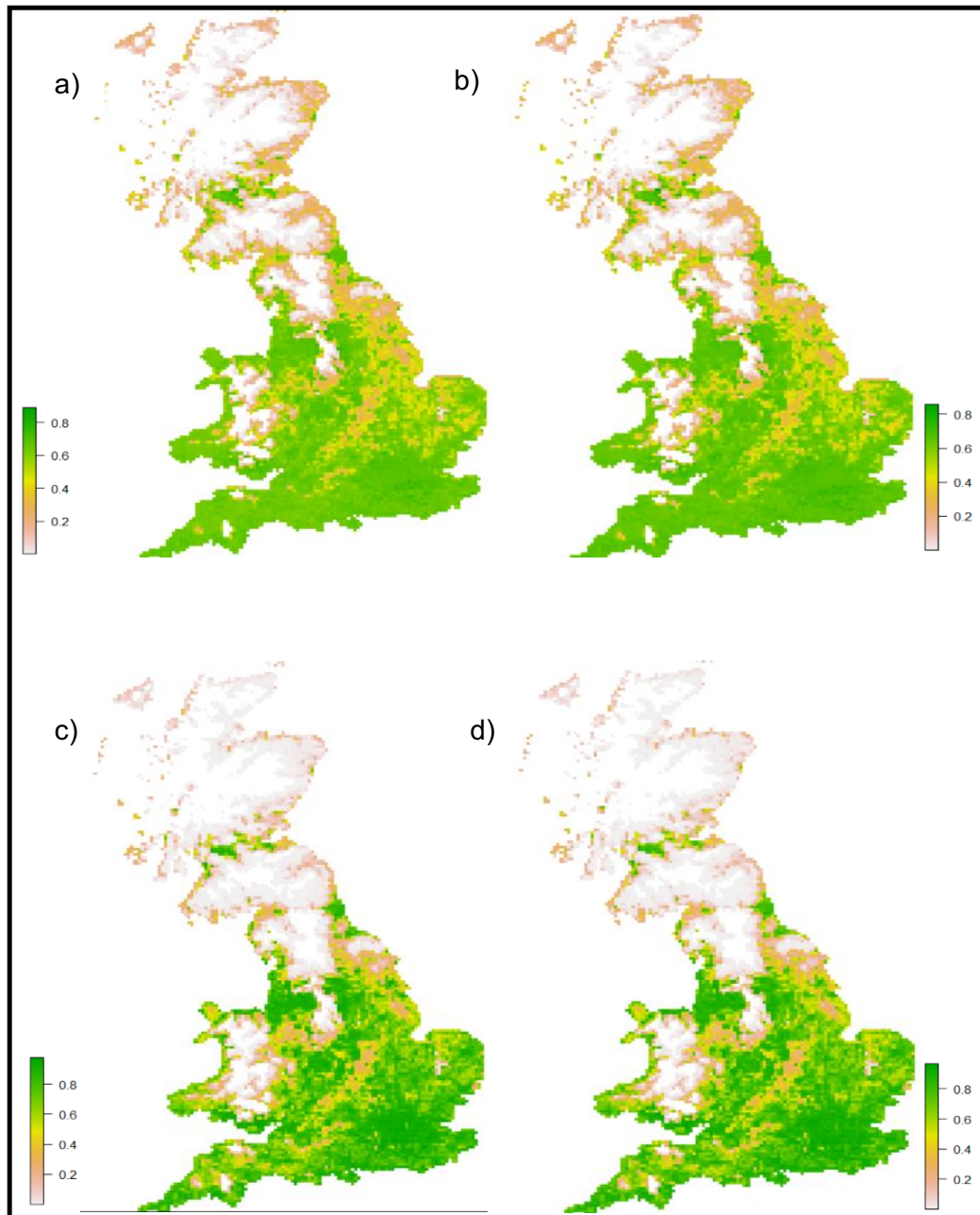


Figure 4.5 Ensemble prediction maps showing the probabilities of habitat suitability (coloured scale) of Rose-ringed Parakeets (*Psittacula krameri*) in GB in the winter of 2071 with (a) no increase in tree cover and (b) a 7% increase in tree cover, and in the

breeding season of 2071 with (c) no increase in tree cover and (d) a 7% increase in tree cover.

## **4.5 DISCUSSION**

The most important findings of the analysis carried out for this chapter are that as ambient temperatures rises, the potential distribution of RRP in GB will show a continued colonisation of lowland, southern GB. In south-west GB, the rural areas are predicted to be colonised by RRP more extensively. The rest of England and Wales is predicted to see some colonisation of rural areas in lowland areas, with towns and cities remaining as centres of RRP distribution in northern England and in Glasgow and Edinburgh.

### **4.5.1 Future increases in ambient temperature**

It is clear from the results shown in Table 4.1 that mean ambient temperatures are predicted to increase during both the winter and breeding seasons experienced by RRP in the next few decades under the UKCP18 RCP8.5, Outcome 01 climate projection (Met Office Hadley Centre, 2019). This results in corresponding declines in values of HDD in both seasons (Figs 4.3 and 4.4). The rise in mean seasonal temperatures predicted by UKCP18 RCP8.5, outcome 01 is not a smooth progression, as variations in the North Atlantic Oscillation (NAO) and the jet stream will continue to influence the weather in GB (Hall and Hanna, 2018; Kendon et al., 2019, 2021). This is demonstrated by the mean temperatures and HDD values in 2031, as show in Figs 4.3 and 4.4. It is noticeable that there is a greater predicted rise in mean temperature in the winter season than in the breeding season of RRP in future decades. This follows the pattern noted by Kendon et al. (2019, 2021) in the reports on the State of

the UK Climate. The rise in ambient temperatures seen under the UKCP18 RCP8.5, outcome 01, is the result of a rather extreme scenario of climate change, and yet mean temperature rises in the years examined here, under this scenario are 3.5°C in the winter season and just 1.6°C in the breeding season.

#### **4.5.2 Changes in Rose-ringed Parakeet distribution during the winter**

The predicted future distributions of RRP in the winter (Fig. 4.3) clearly showed extensive further colonisation of GB is likely accompanying climate warming. This species has the potential to colonise rural areas in the south-west of GB (Hui et al., 2017). This suggests a high likelihood of an invasion process of RRP starting in towns and cities enabled by the UHI effect (Parris and Hazell, 2005; Piano et al., 2017), followed by expansion of their range into surrounding cooler, rural areas, once ambient temperatures are sufficiently close to the Lower Critical Temperature (LCT) for RRP to maintain body temperatures. Under such circumstances, towns and cities may act as UHI-enabled population sources for colonisation of GB (Hui et al., 2017).

The consequence of this invasion process will be RRP expanding their range over the next few decades over much of lowland GB, as shown in Figures 4.3 and 4.4. Although most rural areas in the south-west of GB are predicted to be occupied by RRP in 2071, it is apparent that in the north of England and southern to central Scotland, there are still lowland areas where RRP will not occur or have only low probability of habitat suitability, due to ambient temperatures limiting the distribution of RRP to urban settings, such as Newcastle, Glasgow and Edinburgh. The occupation of larger areas of GB by RRP, is likely to lead to damaging impacts of RRP on

economic activities (farming and fruit growing ([FERA, 2009]), and is likely to enable the detection of impacts on native species and biodiversity not previously identified.

#### **4.5.3 Changes in Rose-ringed Parakeet distribution during the breeding season**

The predicted distributions of RRP during the breeding season appear slightly more restricted than during the winter. This restricted distribution may reflect different foraging patterns between seasons: whilst male parakeets generally forage within a few hundred metres of the nest (Strubbe and Matthysen, 2011) when provisioning females during incubation and early chick rearing), no equivalent information on foraging distances of RRP in winter could be found in the scientific literature, though Kotagama (1982) and Peck (2013) refer to RRP feeding in flocks. Feeding in flocks may be less frequent in summer, when food is plentiful (male foraging distances are generally short: 400 – 1700m [Strubbe and Matthysen, 2011]).

Another explanation of the more limited breeding distribution could be the vulnerability of eggs and chicks to lower temperatures (Shwartz et al., 2009), making warmer ambient temperatures during breeding vital to the breeding success of this sub-Tropical and tropical species. It is believed that cold ambient temperatures in GB result in a failure to hatch of 40% of eggs laid in GB compared with 12% in Israel and 10% in India, for example (Shwartz et al., 2009), though little is known about RRP egg fertility and breeding in the introduced range. If cold ambient temperatures are causing high rates of egg infertility in GB, rising ambient temperatures in GB may lead to lower levels of egg infertility and a higher reproduction rate in towns and cities. This may increase dispersal as population densities of RRP rise.

In its native range the date of first egg laying of RRP varies between early January in southern India to late-April in northern India (Luna et al., 2017b) when mean ambient temperatures can vary between 21°C and 27°C compared with 4.3°C in GB (Shwartz et al., 2009). Egg laying can start as early as January in GB in some years (Ferguson-Lees et al., 2011), though Butler et al. (2013) reported 26th March as the mean first egg date. As in the winter, the UHI effect raises ambient temperatures above a thermal threshold, enabling RRP to breed. Therefore, it is likely that RRP will breed in cities such as Edinburgh, Carlisle and Norwich in the future where breeding has not previously been recorded (Balmer et al., 2013).

#### **4.5.4 Tree cover and changes in Rose-ringed Parakeet distribution**

It is surprising that a 7% increase in tree cover across the whole of GB produced little detectable difference in the probability of habitat suitability of RRP in either the winter or the breeding seasons across the decades. The species requires trees for feeding and for nesting (Dodaro and Battisti, 2014; Charter et al., 2016; Şahin and Arslangündoğdu, 2019), and, therefore, it would seem logical to predict wider distribution of birds under scenarios involving increased tree availability. The SDM developed in Chapter 3 to explain historical and current distributions of birds was highly temperature-sensitive, suggesting that RRP require sustained ambient temperatures above their LCT (i.e. high HDD values) for breeding to be successful. Adult RRP may be able to survive at ambient temperatures below the LCT when they 'work' harder to maintain their body temperature through behavioural adaptations such as seeking warmer nesting sites (Grandi et al., 2018) and through thermogenic shivering (Marjoniemi and Hohtola, 1999; Milbergue et al., 2018) for example. However, energy

budgets may not permit successful breeding at such sites resulting in an absence of RRP. Temperature sensitivity of such SDMs is borne out by the mean variable importance of ambient temperatures represented by HDD values that for the models created for this chapter were 28.35 in the winter season and 37.45% in the breeding season, while for Broad-leaved, mixed and Yew woodland mean variable importance was 15.80% in winter and 10.35% in the breeding season. These values make it likely that the influence of ambient temperatures tend to swamp the influence of a 3.549% increase in broad-leaved, mixed and Yew woodland (the other 3.451% of the 7% increase in tree cover being in coniferous woodland).

In addition, the habitat rasters used for this analysis only start to include habitats when the habitat patch size reaches 0.5 hectares (Rowland et al., 2017b). Forests are avoided by RRP (Shiels and Kalodimos, 2019) and so small clumps of trees may be important to RRP; these tree assemblages may not be detected by methods used in this chapter. This may have led to the importance of trees in the models, both in this chapter and chapter three, being underestimated. The solution would be to obtain a dataset of tree cover produced with a resolution fine enough to detect every tree, allowing aggregation of tree cover even at a resolution of 1km to represent all trees. With technology advancing rapidly, such a dataset will inevitably arrive soon, and is likely to be applied to all habitat types.

#### **4.5.5 Suitability of a LCT of 15°C for Rose-ringed Parakeets in GB**

The models developed in both this chapter and Chapter 3 used 15°C as the LCT of RRP from research findings of Thabethe et al. (2013) who studied captive-bred RRP

kept in an aviary in Pietermaritzberg, South Africa. A meta-analysis carried out by Davidson et al. (2011) found that many invasive species have a high phenotypic plasticity that can allow some plants to evolve higher tolerances of lower ambient temperatures (Araújo et al., 2013; Buckley et al., 2018). RRP in GB are derived mainly from two sub-species, but have diverged morphologically, showing a degree of phenotypic plasticity that may enable adaptation to adverse weather conditions and lower temperatures than those in the native range (Le Gros et al., 2016). It could, therefore, be argued that a reduced LCT of RRP ought to be reflected when creating the rasters of HDD by reducing the critical temperature of 15°C.

The main objection to reducing the established LCT is that the colonisation of new towns and cities in GB by RRP may be achieved through repeated escapes of birds due to short dispersal distances (Pithon and Dytham, 2002; Butler, 2003). of as little as 400 m and there is no evidence of any movements of ringed RRP other than for foraging and roosting (Pithon and Dytham, 2002; Wernham et al., 2002). New breeding colonies have been found to have been established near other colonies, at an average distance of 3km away, and a maximum distance of 13km (Butler, 2003).

It is believed that the London population of RRP originated from escaped/released birds from a number of locations across the city (Heald et al., 2020). If RRP do not move between cities, then escaped/released birds must be the source of new breeding colonies. If colonisation is achieved only through escapes the gene pool would be constantly diluted by new birds derived from the native range. If colonisation of new areas is occurring through dispersal and those populations persist without repeated propagule events, then phenotypic plasticity may enable the development of a lower value of LCT, leading to a wider colonisation of GB than is predicted in this chapter.

in Gauteng, South Africa, the first breeding of RRP's occurred in 1985, though at least 5-8 birds were in the area for 15 years prior to first breeding (Symes, 2014). Information on the number of escaping birds is minimal, but it is feasible that damage to one aviary could release sufficient birds into a location to establish a new self-sustaining colony of RRP's.

#### **4.5.6 Climate projections**

This study used the UKCP18 RCP8.5, outcome 01 predictions to produce the ambient temperature rasters used in the analysis. This is only one dataset of 12 in the UKCP18 RCP8.5 and other scenarios for climate change do exist. Any projection of climate change could have been used, with the only difference being the magnitude of increased RRP distribution predicted for each year. It is the ambient temperatures of the projections that decided the potential distributions produced here. If mean ambient temperature rises by 2°C, the predicted change in distribution would be the same, regardless of the length of time taken for that temperature rise.

#### **4.5.7 Changes in variable importance**

It is noticeable in the results reported in this chapter that the importance of the variables used to create the models in this chapter, differs from the importance of variables in the last chapter. The reason for this lies in the resolution of the rasters used to produce the models. By aggregating to a 5km resolution raster for each variable in this chapter, the fine detail has been lost from some of the rasters. Changing the resolution of the rasters, will lead to a more uniform set of rasters, with smaller peaks and troughs in

their values. This is likely to be particularly important where rapid changes in values occur, such as in HDD on the edges of cities.

Setting the resolution at 5km instead of 1km, also has the effect of distributing human population density more widely. In areas such as Richmond Park in London, human population would be spread over the whole of the park and the high concentrations of trees within the park would be spread over the surrounding areas. Had it been possible to create HDD rasters on a 1km resolution from the UKCP18 RCP8.5, outcome 01, files, in a logical way, it would have been feasible to utilise the same models that were developed for chapter 3.

#### **4.5.8 Potential improvements to the models**

Finer resolution of patch sizes would enable better representation of small habitat patches. Rasters that included every individual tree within the percentage of each cell covered by the relevant tree type would almost certainly improve the accuracy of the model but at present no such publicly available dataset is freely available for the whole of GB.

Towns and cities contain a variety of native and exotic tree species and this is certainly true of GB. For example, Monteiro et al. (2020) found that the percentage of non-native tree species in 12 cities in GB, identified by citizen scientists, ranged between 26% and 50%. For a generalist feeder such as the RRP (FERA, 2009) the diversity of trees in towns and cities (Monteiro et al., 2020) may aid their colonisation of GB through the availability of many different food sources, allowing them to outcompete populations of more specialist feeding native species (Evans et al., 2021). Therefore, the future

development of a raster describing coverage of non-native tree species percentage across GB would add to meaningful predictor variables available for this study.

Human population density was included in the SDMs to explore the dependence of RRP on us; this was a statistically significant retained variable in the models for both seasons. This may reflect the importance of the UHI effect (Levermore and Parkinson, 2019) and/or the reliance of RRP on human-stocked bird feeders in gardens (Clergeau and Vergnes, 2011) that are more concentrated in areas of higher human population density (Tryjanowski et al., 2015). Certainly, the inclusion of more detailed information on the location and contents of bird feeders and frequency of replenishment of such feeders might shed more light on the seemingly intimate relationship between humans and RRP (Strubbe and Matthysen, 2009a; Barua, 2021; Loiselle et al., 2010). Data on the location of gardens with bird feeders used for the Garden BirdWatch survey run by the BTO can be requested. However, most bird feeders are not used as part of this scheme. An estimate of the number of bird feeders could be made by carrying out some survey work in a number of locations, counting bird feeders to enable a comprehensive extrapolation of feeder numbers to be made from the Garden BirdWatch data.

Whilst not used in this chapter, hierarchical species distribution models (hSDM) are capable of providing finer resolution of possible distributions. These hSDMs model not only the regional scale of distributions (as modelled in this chapter), but by using Bayesian modelling techniques and fine scale predictors, can make predictions of ecological niches at the landscape scale, thus enabling precise habitat detail, the presence of competitors and/or predators to be closely modelled (Botero-Delgadillo et

al., 2012; Mateo et al., 2019; Mertes et al., 2020). Not only can this approach give predictions with a resolution of 60 metres (Mertes et al., 2020), but it also enables accurate distribution models to be created from citizen reporting (Dell'apa et al., 2018; Lopes et al., 2019).

This chapter examined RRP distribution across GB and lacked fine-scale data on tree size and tree species distribution. Lacking fine scale resolution data and only having a resolution of 2km for the occurrence of RRP, hierarchical modelling was not a suitable technique for this study. As finer resolution of habitats, species distributions and the size of trees become available, hSDMs of RRP distribution will become more appropriate. Further development of spatial statistics will enable modelling to take account of interactions of study species with their environment at several different resolutions in one model (Lechner and Rhodes, 2016). This would allow the modelling of environmental factors, such as rainfall and temperature at relatively coarse resolution, the presence of other species, such as competitors, predators and prey at a finer resolution and intricate details, such as tree area, tree trunk diameter, tree age, presence of nest sites, at very fine resolution.

#### **4.5.9 Rose-ringed Parakeets in rural areas**

As RRP colonise rural areas, it is likely that foraging birds will feed on the crops of farmers and horticulturalists because in their native range they are a major agricultural pest (Cramp, 1985; Babu and Muthukrishnan, 1987; Ahmad et al., 2012). In the introduced range, invasive RRP are also agricultural pests on the islands of Hawaii, often feeding on Maize (*Zea mays*) (, of Figs (*Ficus spp.*), Mangoes (*Mangifera indica*)

and Dates (*Phoenix spp.*) in South Africa (Shivambu et al., 2021), vineyards and orchards in England (FERA, 2009). As RRP are generalist-opportunistic feeders, and are capable of changing their foraging behaviour to utilise new resources (Shivambu et al., 2021), RRP colonising rural parts of GB are likely to cause damage to crops. In future analyses of RRP distributions, further attention needs to be paid to the distribution of crops, particularly crops affected by foraging RRP. At present, the Land Cover Maps 2015 (Rowland et al., 2017a), only identify arable and horticultural land. Producing additional rasters of individual types of crops and orchards, would enable distributions of RRP to be related to the economic interests of farmers and horticulturalists.

#### **4.6 CONCLUSION**

We cannot accurately predict the degree of climate warming under current climate projections but increases in ambient temperatures in the future are likely to enable changes in potential distribution of RRP in GB, with increasing likelihood of colonisation of rural areas in the south-west of GB. As ambient temperatures rise, colonisation of rural areas by RRP from urban centres is likely to occur. Rising temperatures will also allow RRP to colonise some towns and cities that were previously too cold to sustain a population, as long as there is a colonisation mechanism such as release/escape of birds or dispersal from nearby sites. Founder populations for new populations of RRP may be small. Dispersal distances in GB have not been definitively determined but Butler (2003) suggested that the range of RRP in London was expanding at just over 400 m per year and that new breeding sites away

from the main range were on average 4 km (but up to 13 km maximum) distant from existing breeding sites.

If new colonies are established by dispersal, towns and cities are likely to act as sources for colonisation of surrounding rural areas as the climate warms, with RRP presence in urban areas aided by the UHI effect. If colonisation occurs through new escapes/releases, new colonies can only be established where those escapes/releases occur, if the ambient temperature allows it. Planned increased tree planting appears to have little influence on the distribution of RRP, according to the SDMs developed in this chapter

## CHAPTER 5: GENERAL DISCUSSION

When examining the health of the ecosystems in GB, knowing the distribution of birds, enables assessments of their conservation status (Santini et al., 2019), the targeting of efforts to protect them, and the identification of threats to native bird species (Morales and Bretagnolle, 2021). This thesis has examined distributional changes in a non-native exotic, the Ringed-necked Parakeet (RRP), as a model species that has significantly increased its distribution in Great Britain (GB). The results show that:

1. RRP distribution in GB is mainly in cities. RRP are increasing their range, with a northwards and westwards spread from the south-east of GB.
2. The distribution of RRP in GB in the winter season (1<sup>st</sup> December to 28<sup>th</sup> February) is predominantly limited by cold ambient temperatures, with elevation and broad-leaved, mixed and Yew woodland as lesser factors. The Urban Heat Island (UHI) ameliorates city temperatures compared to the surrounding rural areas and enables RRP to survive in isolated islands of relative warmth.
3. The distribution of RRP in GB in the breeding season (1<sup>st</sup> December to 31<sup>st</sup> May) is predominantly limited by cold ambient temperatures (more strongly than in winter), with elevation and broad-leaved, mixed and Yew woodlands as lesser factors. The cold ambient temperatures may be the cause of high levels (40%) of failure to hatch in RRP eggs, which may be the cause of the greater limitation of RRP distribution in the breeding season.
4. In Chapter 4, this study predicted an expansion to the north and east in the potential distribution of RRP in GB over the next few decades, as the ambient temperatures increase. This pattern of change may be mimicked by other synanthropic bird species

shifting their range northwards, colonising new areas previously unavailable to them due to cold temperatures.

As RRP's are becoming a feature across more of GB, it is worth discussing the impacts of habitat change, climate change, mechanisms of colonisation and possible impacts of an increasing population of RRP's.

### **5.1 The influence of landcover on range-expanding species**

One of the biggest challenges facing such modelling is the prediction of change in habitats. Habitat change impacts many bird species: woodland bird species in GB (Newson et al., 2012); waterbirds around the Mediterranean Sea (Gaget et al., 2020); and Eurasian Wigeon (*Anas penelope*) in Europe. Habitat change will always happen, but the location and time of habitat change are almost impossible to predict.

As the British government plans to combat climate change include tree planting, it is almost certain that the area of tree cover in GB will increase over the coming years, with increasing maturity of those trees leading to increasing habitats for feeding and breeding RRP's becoming available.

Many changes in habitat are linked to climate change (Castillo et al., 2018; Gaget et al., 2020; Williams et al., 2022). Changes in climate will affect the distribution of plant species. Some species will alter their distribution more than others, leading to changing habitats and ecosystems. Habitat change and climate change are key, and often

synergistic, factors influencing range change in avian species (Loiselle et al., 2010; Yalcin and Leroux, 2018; Evans et al., 2021)

## **5.2 Implications for species' ranges under climate change**

The effects of climate change are already being documented (Isaak et al., 2012; Tao et al., 2018; Kendon et al., 2019, 2021). In addition, further impacts of climate change on birds are expected (Burns et al., 2020; Stanbury et al., 2021; Morales and Bretagnolle, 2021; Frost et al., 2021).

As climate change influences ambient temperatures in the future, it is expected that the ranges of many bird species will shift poleward (Zuckerberg et al., 2011; Davey et al., 2012; Bellard et al., 2013; Virkkala et al., 2013; Virkkala and Lehikoinen, 2017). These poleward shifts in range are likely to lead to species occurring naturally in France and the Low Countries shifting their range to GB. Those species that adapt well to heavily human-influenced habitats, such as the Black Redstart (*Phoenicurus ochruros*), may colonise towns and cities first. Similar outcomes are likely for non-native species such as RRP, which in common with other introduced species of bird in GB, are living outside their climate envelope (Border et al., 2018). The modelling work carried out as part of this thesis suggests that as ambient temperatures rise in line with climate change predictions, we can expect to see RRP colonising more of GB and not just in urban habitats but elsewhere.

Species shifting range due to climate change are likely to colonise GB, This is most likely to occur through dispersal in resident species (Gaston and Blackburn, 2002) or through over-shooting migrants returning from their wintering grounds (Mustin et al.,

2014; Whytock et al., 2018). Whilst the mechanisms of colonisation of range shifting birds are known, the same cannot be said for the mechanism of colonisation for RRP in GB. This is probably due to a combination of the belief that such a sedentary bird will not disperse until nest cavity and/or food resources are low, and low numbers of birds ringed for the British Trust for Ornithology Ringing Scheme: just 2,785 RRP ringed in GB up to the end of 2020 (Robinson et al., 2021), limiting the ability to detect movements of dispersing birds.

### **5.3 Mechanisms of colonisation**

This has not yet been established for RRP in GB. While Butler (2003) concluded that new colonies of RRP can arise up to 13 km from established breeding locations, possibly by dispersing birds, there is no support as yet for dispersing birds being able to establish new colonies at greater distances than this.

By using techniques normally used for forensic investigations of crimes, Heald et al. (2020) concluded that the establishment of the London population of RRP occurred as a result of a series of escapes/releases across London. The number of introductions and the number of individuals introduced, collectively known as propagule pressure, are often significant in the success or failure of introductions (Lockwood et al., 2005). Successful introductions can arise from a very small founder population, just 5-8 RRP in Gauteng, South Africa (Symes, 2014).

New colonies are being established, such as in Glasgow, at great distance from previous breeding locations (Scottish Birds Records Committee, 2021) Some of these new locations may be the result of yet more escapes/releases of RRP into the wild.

This species is essentially sedentary (Pithon and Dytham, 2002; Butler, 2003) and bird ringing has not revealed any movements of RRP's over long distances (Wernham et al., 2002). This process is likely to proceed in a 'stepping stone' pattern with expansion northward into cities which then act as sources of populations for rural areas once ambient temperatures are sufficiently warm. This process will likely be enhanced by escaped birds from aviaries that are then able to establish rural populations (Cardador and Blackburn, 2020b).

Working from the mean value for Heating Degree Days (HDD), 997.65, where RRP's were present during the winter Timed Tetrad Visits (TTVs) for the BTO Bird Atlas 2007-2011 (Balmer et al., 2013), it is possible to calculate that the mean temperature for the period 1<sup>st</sup> December 2010 to 28<sup>th</sup> February 2011 for locations where RRP's were present could not have been below 3.915°C (days when the mean temperature was above 15°C were not included, so the actual mean temperature could have been slightly higher).

#### **5.4 Impacts of Rose-ringed Parakeet range expansion**

If RRP populations continue to increase and spread into rural areas, the scope for these birds to cause damage is likely to increase. This species is a cavity nester and is thus likely to increase competition for nesting space for native species with similar nesting requirements, e.g. Eurasian Nuthatch (*Sitta europaea*), especially where cavities are limited in number (Strubbe and Matthysen, 2009b). As yet there are no proven impacts of RRP's on the populations of native bird species in GB (Newson et

al., 2011). RRP in GB are, however, known to monopolise bird-feeders, reducing access to the feeders for Blue Tits (*Cyanistes caeruleus*) and Great Tits (*Parus major*).

In both the native and the introduced range, RRP are known to use cavities in buildings (Hernández-Brito et al., 2014a; Grandi et al., 2018) where tree cavities are in short supply. Behavioural plasticity in RRP has been noted on the island of Tenerife, where nesting cavities in trees are few, and RRP have been observed excavating nesting cavities in palms (Hernández-Brito et al., 2021). Excavating their own nesting cavities reduces the dependence of RRP on other species excavating cavities for them to use later.

In their native range RRP are agricultural pests and as some of the crops damaged by RRP in the native range are grown in GB (e.g. Apple [*Malus domestica*] and Maize [*Zea mays*]). It is likely that RRP in rural areas will cause economic damage. In addition, and as a contemporaneous example, orchards have recently been identified as a declining feature of GB countryside (Dommett, 2022). Therefore, RRP in orchards will cause both economic and biodiversity losses.

The Natural England General Licence already lists RRP as a target species to control numbers (DEFRA, 2022). While FERA (2009) examined possible methods of deterrence, most did not work or the birds became habituated, it is likely that protection of economic interests will lead to many RRP being shot, even though non-lethal methods are available, such as reflective tapes, flags and rags hung among the crops, Their expansion to pest levels in rural areas is likely to lead to calls for a nationwide cull of RRP (Birdguides, 2021). If impacts on native species are detected, this would also support calls for a cull. Culling is expensive and takes time. The culling of Monk

Parakeets (*Myopsitta monachus*) cost £259,000 for the first four years of work, to remove 62 birds, 212 eggs and 21 nests (DEFRA, 2014). Culling the RRP population in GB would require far greater investment because the breeding population was estimated to be 12,000 breeding pairs in 2016 (Woodward et al., 2020). This would suggest a possible population size now to be around 40,000 birds, though this is no more than speculation. Culling is also an emotive subject, with many people being concerned about the deaths of large numbers of birds (Crowley et al., 2017, 2018). Problems are likely to arise in cities such as London, where many people value the 'splash of colour' (Hunt, 2019; Barua, 2021) and life that RRP's bring to their gardens and would actively and vehemently oppose any cull.

While oral contraceptives can reduce fertility, this would require a huge campaign of feeding of RRP's across the whole of their range in GB and successful production of a species specific feeder (FERA, 2009). This would need to be sustained for many years as the contraceptive is only up to 66.5% effective, thus reducing rather than stopping fertility. The current longevity record of ringed RRP's in GB is over 8 years (Robinson et al., 2021). However, few RRP's have been ringed, let alone recovered, so that longevity record may be a large underestimate. Giving contraceptives to a long-lived bird species to control its population requires a major investment of time and money across the duration of potentially three or more UK Parliaments, would require a major exercise of political will to maintain.

## 5.5 Future research

A number of things need to happen for an improvement in the species distribution models (SDMs) developed in this study. First, improved habitat suitability data are required. If enough escapes/releases of RRP are occurring to enable new colonies of the birds in new locations, the spread of RRP might be limited by an effort to reduce/prevent these escapes/releases. This is an area where citizen science may be able to help. It is possible that dispersal of young RRP is occurring but is mistaken for newly escaped birds in areas where the birds are not normally seen. As time passes, increasing records of RRP away from the main population centres, especially in well-surveyed areas, such as north Norfolk, may begin to demonstrate patterns of movement over time that suggest dispersal is or is not happening.

Secondly, improved covariate data are needed that capture details at sufficient spatial resolution to quantify elements of habitat that are important in the autecology of RRP. In particular, more detail is needed on the tree cover and tree species found across GB. Finer resolution of habitat mapping will enable SDMs to take the actual distribution of individual trees, rather than patches of trees larger than 0.5 hectares into account. Refinements in satellite mapping and detection of trees will enable fine resolution datasets to be created, where crown and trunk biomass data might enable one to model likely nest hole provision. Individual trees can be important to cavity-nesting birds, such as RRP, as many streets, for example in parts of London and Birmingham, are lined with large mature trees. These tree-lined streets are potential nesting habitat for a variety of bird species but at the present time, these habitats are not well

represented in the Land Cover datasets currently available and used in this study (Morton et al., 2011; Rowland et al., 2017c).

The third possibility is the use of hierarchical models to map RRP distribution in very fine scale. The development of finer resolution datasets of tree size and species distribution, alongside the finest resolution of Land Cover Map (currently 25m), may enable fine scale mapping of the precise habitat requirements of RRP. This may need to be done over a small geographic area, but may also elucidate the habitat requirements of dispersing RRPs, if the study area is able to follow the population expansion of RRPs.

Lastly, information on the role of bird feeders in possibly aiding the establishment and persistence of RRP populations is also needed. While the BTO has information on the location of members of its Garden Birdwatch Scheme (<https://www.bto.org/our-science/projects/gbw>), this dataset may not reflect the demographics of all people that feed birds. Research into the spatial distribution of bird feeding may also give greater insights into the role of bird feeders in influencing the populations of native species and enable the early detection of harmful impacts on native bird populations due to RRPs.

## **5.6 Conclusions**

This study has shown that ambient temperatures play a role in limiting the distribution of RRPs. The study has also highlighted the role of the Urban Heat Island (UHI) effect in enabling the colonisation of towns and cities by RRPs, and the possible colonisation of rural areas from city-based source populations of RRPs, if the mechanism of colonisation allows.

Colonisation of rural areas of GB by RRP is likely to lead to harm to biodiversity, native species and economic interests of farmers, wine producers and fruit growers.

Further research is needed to establish the method of colonisation of new areas by RRP, their impact on native cavity nesting birds and means of controlling. In addition, further species distribution modelling of RRP and other alien invasive birds would benefit from enhanced datasets of trees (counting every mature tree) and the location and type of crops.

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## APPENDICES

### Appendix 2.1.

The README file for the Feral Parakeet Sightings website (<https://www.parakeetsightings.bham.ac.uk>).

All other code can be found at <https://gitlab.bham.ac.uk/rdb781>.

### README.md

#### Running Project - for development

Assuming code is cloned to ~/Desktop/University of Birmingham/Python Coaching/Django:

```
cd "Desktop/University of Birmingham/Python Coaching/Django"
source venv/bin/activate
test -f Sightings/settings.py || cp Sightings/settings-development.py
Sightings/settings.py
python manage.py runserver
```

## Setup sqlite database

This only needs doing once - first time the application is used with a blank database.

Firstly, run the migrations to create the database tables:

```
cd "Desktop/University of Birmingham/Python Coaching/Django"
source venv/bin/activate
python manage.py migrate
```

Open the database with the sqlite3 tool:

```
sqlite3 db.sqlite3
```

Then import the CSV files:

```
.mode csv
.import Parakeetsightings/Parakeetspecies.csv species_tmp
INSERT INTO Parakeetsightings_parakeetspecies (scientific_name,
en_common_name, fr_common_name, de_common_name, es_common_name) SELECT
"Scientific name", "En common name", "Fr common name", "De common name", "Es
common name" FROM species_tmp;
DROP TABLE species_tmp;
.import Parakeetsightings/Countries.csv countries_tmp
INSERT INTO Parakeetsightings_country (en_name, fr_name, de_name, es_name)
SELECT En_country_name, Fr_country_name, De_country_name, Es_country_name
FROM countries_tmp;
DROP TABLE countries_tmp;
.import Parakeetsightings//ParakeetImages.csv images_tmp
UPDATE Parakeetsightings_parakeetspecies SET image_file=(SELECT "Name of
file" FROM images_tmp WHERE "Scientific Name" = scientific_name),
```

```
image_attribution=(SELECT Attribution FROM images_tmp WHERE "Scientific Name"
= scientific_name);
DROP TABLE images_tmp;
.quit
```

## Translations

This is a two step process:

1. extract the messages for translation
2. compile them.

### Extracting translatable messages

```
cd ParakeetSightings
django-admin makemessages -l(two letter code for language)
```

That extracts the messages into files in (app)/locale/(two letter code for language)/django.po

Complete the translations for each language (including en)

### Compiling the translated messages

```
django-admin compilemessages
```

### Running project in production on Castles

Clone the code into /srv/uwsgi on the virtual machine:

```
cd /srv/uwsgi
git clone https://gitlab.bham.ac.uk/reynoljx-parakeet-sightings/django_web_application.git .
```

Create the uwsgi.wsgi file that uwsgi is configured to look for:

```
ln -s Sightings/wsgi.py uwsgi.wsgi
```

Setup the virtual environment and install prerequisites:

```
virtualenv -p python36 venv  
source venv/bin/activate  
pip install -r requirements.txt
```

Compile the translations on the production system:

```
python manage.py compilemessages
```

Use the production settings.py:

```
cp Sightings/settings-production.py Sightings/settings.py
```

Gather all the static files to be served by the webserver:

```
python manage.py collectstatic
```

## **Setup postgres database**

This only needs doing once - first time the application is used with a blank database.

Firstly, run the migrations to create the database tables:

```
cd /srv/uwsgi  
source venv/bin/activate  
python manage.py migrate
```

Then import the CSV files:

```

cd Parakeetsightings

cat Countries.csv | psql -h bberdb.bham.ac.uk -U reynoljx-parakeet-sightings
-c "copy \"Parakeetsightings_country\"(en_name,fr_name,de_name,es_name) FROM
STDIN DELIMITER ',' CSV HEADER;" reynoljx-parakeet-sightings

cat Parakeetspecies.csv | psql -h bberdb.bham.ac.uk -U reynoljx-parakeet-
sightings -c "copy
\"Parakeetsightings_parakeetspecies\"(scientific_name,en_common_name,fr_com
mon_name,de_common_name,es_common_name) FROM STDIN DELIMITER ',' CSV HEADER;"
reynoljx-parakeet-sightings

psql -h bberdb.bham.ac.uk -U reynoljx-parakeet-sightings -c "CREATE TABLE
images_tmp (scientific_name TEXT PRIMARY KEY, image_name TEXT, attribution
TEXT);" reynoljx-parakeet-sightings

cat ParakeetImages.csv | psql -h bberdb.bham.ac.uk -U reynoljx-parakeet-
sightings -c "copy \"images_tmp\"(scientific_name,image_name,attribution)
FROM STDIN DELIMITER ',' CSV HEADER;" reynoljx-parakeet-sightings

psql -h bberdb.bham.ac.uk -U reynoljx-parakeet-sightings -c "UPDATE
\"Parakeetsightings_parakeetspecies\" ps SET image_file=it.image_name,
image_attribution=it.attribution FROM images_tmp it WHERE ps.scientific_name
= it.scientific_name;" reynoljx-parakeet-sightings

psql -h bberdb.bham.ac.uk -U reynoljx-parakeet-sightings -c "DROP TABLE
images_tmp;" reynoljx-parakeet-sightings

```

## Appendix 2.2

### Python code to translate British National Grid Tetrad reference into British National Grid Reference to the nearest metre for the centre of the tetrad.

```
#!/usr/bin/env python3
import csv
input_file = 'TetradPlay.csv'
output_file = 'TetradPlayOutput.csv'
values_file = 'LetterValues.csv'
tetrads_file = 'Tetrads.csv'

def read_values(values_file):
    """
    Read the csv of letters to eastings and northings and return the
    information

    :param values_file: Name of the values file
    :return: a dict mapping grid square names to a eastings, northings
    tuple
    """
    result = {}
    with open(values_file) as csvfile:
        reader = csv.DictReader(csvfile)
        for row in reader:
            result[row['Grid square:']] = (int(row['Easting metres:']),
int(row['Northing metres:']))
    return result

def read_tetrads(tetrads_file):
    """
    Read the csv of letter to kilometer offset from eastings and northings
    and return the information

    :param tetrads_file: Name of the values file
    :return: a dict mapping grid square names to a eastings, northings
    tuple
    """
    result = {}
    with open(tetrads_file) as csvfile:
        reader = csv.DictReader(csvfile, fieldnames=('letter', 'value'))
        for row in reader:
            value = row['value']
            result[row['letter']] = (int(value[0])*1000,
int(value[1])*1000)
    return result

if __name__ == '__main__':
    values = read_values(values_file)
    print(values)
    tetrads = read_tetrads(tetrads_file)
    print(tetrads)

    with open(output_file, 'x') as csv_out:
```

```

with open(input_file) as csvfile:
    reader = csv.DictReader(csvfile)
    writer = None

    for row in reader:
        easting = 0
        northing = 0

        if writer is None:
            column_names = list(row.keys())
            column_names.extend(['eastings', 'northings',
'eastingnorthings'])
            writer = csv.DictWriter(csv_out, column_names)
            writer.writeheader()

        grid = row['grid']
        letter_square = grid[0:2]

        try:
            # Get eastings, northings for the square
            en_square = values[letter_square]
            easting = easting + en_square[0]
            northing = northing + en_square[1]
        except KeyError:
            print('unknown letter square', letter_square)
            continue

        easting = easting + int(grid[2])*10000
        northing = northing + int(grid[3])*10000

        try:
            # Grid references without tetrad letter will cause
error
            t_square = tetrads[grid[4]]
            easting = easting + t_square[0]
            northing = northing + t_square[1]
        except IndexError:
            print('No tetrad letter in reference', grid)
            continue

        out_row = row
        out_row['eastings'] = "%06d" % easting
        out_row['northings'] = "%06d" % northing
        out_row['eastingnorthings'] = "%06d%06d" % (easting,
northing)

        writer.writerow(out_row)

```

## Appendix 2.3

Anonymised data for the 133 sightings of Rose-ringed Parakeet reported to the Feral Parakeet Sightings website (<https://www.parakeetsightings.bham.ac.uk>) and retained after checking data.

Latitude and Longitude are given to two decimal places to maintain anonymity of locations.

| expertise    | date                         | location                                                                                                                                                                                                                                                                                                                                                                                                                              | Lat   | Long  | No |
|--------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Intermediate | 2014-11-01<br>00:00:00+00:00 | <p>Hello, retrospective sighting as I have since moved to York</p> <p>In November 2014 I had a single Parakeet turn up in my garden. In addition to the usual bird seed I started putting out apples and grapes. Within a few weeks I had 2 more Parakeets arrive. They over wintered and in summer 2015 another 2 birds joined them.</p> <p>The same 5 birds visited my garden daily to feed until I left in the summer of 2017.</p> | 53.89 | -1.45 | 5  |

|              |                              |                                                                                                                                                                                                                                                                                                                                                                                                     |       |       |    |
|--------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Intermediate | 2015-03-08<br>00:00:00+00:00 | Backhouse Park<br><br>Sunderland                                                                                                                                                                                                                                                                                                                                                                    | 54.89 | -1.38 | 7  |
| Expert       | 2015-12-22<br>00:00:00+00:00 | Shard end park b34 roost site<br><br>2016                      24            birds<br><br>2017                      44            birds<br><br>2018 75 birds                                                                                                                                                                                                                                        | 52.49 | -1.77 | 75 |
| Intermediate | 2016-11-01<br>00:00:00+00:00 | Ring necked parakeets are regularly seen in the Didsbury area of South Manchester, especially around the River Mersey, Stenner Woods and Fletcher Moss Gardens- I see (and definitely hear) them pretty much every time I walk in this area (I have lived in the area since late 2016). Normally they are in pairs or small groups but a few times I have seen much larger groups of perhaps 20-40. | 53.41 | -2.24 | 40 |

|  |  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |  |  |  |
|--|--|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|--|
|  |  | <p>They can sometimes but less frequently be seen coming into the residential areas of Didsbury (and I have seen them also once or twice in Withington, a couple of miles North towards the city centre). They seem to often get harassed by magpies. They tend to stay quite high up in the trees or on buildings.</p> <p>I have commonly seen pairs of greater spotted woodpeckers in the area (but more often in the suburban rather than rural parts) but never a nest. That said, I have never located a parakeet nest either. Nuthatches (with which I have heard parakeets are also a competitor) are</p> |  |  |  |
|--|--|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|--|

|          |                              |                                                                                                                                                                                                                                                                                                                         |       |       |    |
|----------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|          |                              | <p>quite abundant in the area.</p> <p>Food is commonly left out for birds in the suburban parts of the area but not the rural parts where the parakeets are more commonly seen.</p> <p>I have been told that this population originates in Liverpool and expanded towards Manchester by following the River Mersey.</p> |       |       |    |
| Beginner | 2017-05-09<br>00:00:00+00:00 | At my balcony almost every day in 2016-17.                                                                                                                                                                                                                                                                              | 51.49 | -0.29 | 15 |
| Beginner | 2018-01-21<br>00:00:00+00:00 | In a large evergreen tree at the bottom of a garden. The garden backs onto a field used for football and dog                                                                                                                                                                                                            | 52.45 | -2.15 | 1  |

|              |                              |                                                                                                                                                                                                                                                                                                                                                      |       |       |    |
|--------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                              | walking. There is a park nearby (Mary Stevens Park). The next door garden (RHS) has multiple bird feeders. A parakeet was also seen in the same location a month earlier in December 2018 (the exact date seen is not known & it won't let me enter just the month) - there was a lot of snow that month. I will send a photo to your email address. |       |       |    |
| Intermediate | 2018-05-20<br>00:00:00+00:00 | Seen multiple occasions during spring/early summer 2016-2019. Numbers seen/heard at any one time vary between 3 and 10+. Holders woods and edge of Cannon Hill Park in Selly Park, Birmingham, B29.                                                                                                                                                  | 52.44 | -1.91 | 10 |
| Beginner     | 2018-09-01<br>00:00:00+00:00 | Moss Side Park, Manchester.<br><br>Alexandra Park, Manchester.                                                                                                                                                                                                                                                                                       | 53.45 | -2.25 | 10 |

|              |                              |                                                                                                                                                                                                                                                                                       |       |       |    |
|--------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                              | Whitworth Park, Manchester.                                                                                                                                                                                                                                                           |       |       |    |
| Intermediate | 2018-09-12<br>00:00:00+00:00 | Ttler grove<br><br>Birmingham<br><br>B436dl                                                                                                                                                                                                                                           | 52.55 | -1.92 | 3  |
| Beginner     | 2018-10-26<br>00:00:00+00:00 | Beecholme<br><br>High beeches<br><br>Banstead<br><br>Sm7 1np                                                                                                                                                                                                                          | 51.32 | -0.20 | 3  |
| Beginner     | 2018-11-17<br>00:00:00+00:00 | I've just seen your plea for data on Springwatch so thought I'd let you know my encounter, even though it was a while ago. The date is accurate as I'd posted about my sighting on social media.<br>Wollaton Park, Nottingham (17th November 2018)green parakeets (I believe the same | 52.94 | -1.22 | 10 |

|  |  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                  |  |  |  |
|--|--|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|--|
|  |  | <p>breed as in St James Park, London, though not an expert) nest around one end of the lake at Wollaton Park, the park is backed onto by houses/gardens where people likely put feeders out though this is unknown. Great Spotted, Lesser Spotted and Green Woodpeckers all nest within the park. I visit Wollaton Park fairly regularly, though haven't seen (or heard) the parakeets for a few months though this could be more to do with timing - I saw lots of parakeets at dusk when visiting in November though tend to usually go late morning/early afternoon. I would be happy to visit the park if more data is needed/required. We DO NOT get parakeets visiting</p> |  |  |  |
|--|--|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--|--|--|

|              |                              |                                                                                                                                                                                                                  |       |       |    |
|--------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                              | our home in Widmerpool Park (NG12 5SB) which is a gated community within 20 acres of communal land (incl woodland) (sounded by fields/countryside), we do have breeding great spotted and green woodpeckers here |       |       |    |
| Expert       | 2018-12-01<br>00:00:00+00:00 | Wollaton Park, Nottingham                                                                                                                                                                                        | 52.95 | -1.21 | 4  |
| Beginner     | 2018-12-25<br>00:00:00+00:00 | Garden                                                                                                                                                                                                           | 54.56 | -1.34 | 2  |
| Intermediate | 2018-12-27<br>00:00:00+00:00 | Knowledge Park Sevenoaks.<br>In the trees in the Deer park                                                                                                                                                       | 51.27 | 0.21  | 10 |
| Beginner     | 2019-01-01<br>00:00:00+00:00 | In my back garden almost every day (B76 1WG) and also at Sandwell Valley RSPB (Sandwell).                                                                                                                        | 52.53 | -1.81 | 5  |
| Beginner     | 2019-01-05<br>00:00:00+00:00 | There are a whole flock of parakeets on the Garscube campus of the University of                                                                                                                                 | 55.90 | -4.32 | 30 |

|              |                           |                                                                                                                                                                                                                                                                                                                                                                                                                             |       |       |    |
|--------------|---------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                           | <p>Glasgow G61 1QH and Dawsholm park which is adjacent.</p> <p>I have seen a nest with 2 parakeets entering and leaving next to the river on the Maryhill road side of the campus this week.</p>                                                                                                                                                                                                                            |       |       |    |
| Intermediate | 2019-01-10 00:00:00+00:00 | <p>Local National trust property, Saltram house has a group of parakeets that fly around and has had regular sightings, no idea if nesting there. They have been seen also in the nearby Plym valley, also owned by National Trust, at least at the lower course of the river, which is close in proximity to Saltram property, (within a mile or two) Also in more central plymouth in the city central park there has</p> | 50.38 | -4.08 | 12 |

|              |                              |                                                                                                                                                                                                     |       |       |    |
|--------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                              | been parakeets there for a good several years now.                                                                                                                                                  |       |       |    |
| Beginner     | 2019-01-28<br>00:00:00+00:00 | On the New River in Broxbourne, UK                                                                                                                                                                  | 51.74 | -0.02 | 3  |
| Beginner     | 2019-02-05<br>00:00:00+00:00 | multiple sightings on the Thames River near Kew Bridge - they live on the Ait opposite                                                                                                              | 51.48 | -0.30 | 1  |
| Intermediate | 2019-02-21<br>00:00:00+00:00 | Gibson road.<br><br>Handsworth<br><br>Bham<br><br>B20 3su                                                                                                                                           | 52.51 | -1.92 | 1  |
| Beginner     | 2019-02-28<br>00:00:00+00:00 | A406 Eastbound lane near Brent Park. I can't remember the exact date though. Sometime in February or March there was a tree full of Green parrots which I later found out that they were parakeets. | 51.55 | -0.26 | 30 |

|              |                              |                                                                                                                                                                                                                                                                                                                                                                                      |       |       |    |
|--------------|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Intermediate | 2019-03-08<br>00:00:00+00:00 | My garden at the bird feeders.                                                                                                                                                                                                                                                                                                                                                       | 55.91 | -4.34 | 3  |
| Intermediate | 2019-03-10<br>00:00:00+00:00 | <p>Northdown Park - Cliftonville, Kent</p> <p>Holly Gardens, Cliftonville, Kent</p> <p>Holly Lane, Cliftonville Kent</p> <p>All of the above - thriving and with multiple nests in a small area, not difficult to find as they are so abundant. Spotted between February to May 2019.</p> <p>The Terrace, Gravesend, Kent - less abundant than cliftonville, spotted only twice.</p> | 51.38 | 1.41  | 20 |

|              |                              |                                                                                                                                   |       |       |   |
|--------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
|              |                              | No nests seen. Seen February this year.                                                                                           |       |       |   |
| Intermediate | 2019-03-13<br>00:00:00+00:00 | North Oxford (University Parks)                                                                                                   | 51.76 | -1.25 | 1 |
| Beginner     | 2019-03-31<br>00:00:00+00:00 | Sefton Park, Liverpool. High up, about 9 of them, singing and swapping branches. I have seen them in this location several times. | 53.38 | -2.94 | 9 |
| Intermediate | 2019-03-31<br>00:00:00+00:00 | Old Cemetery, Belvedere Road, Ipswich                                                                                             | 52.04 | 1.10  | 2 |
| Beginner     | 2019-04-03<br>00:00:00+00:00 | Lorrimore Square, Kennington                                                                                                      | 51.48 | -0.10 | 2 |
| Intermediate | 2019-04-05<br>00:00:00+00:00 | 14 Dorset Road, Birmingham, West Midlands.                                                                                        | 52.48 | -1.96 | 1 |

|              |                              |                                                                                                                                                                                                                                                         |       |       |    |
|--------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Beginner     | 2019-04-06<br>00:00:00+00:00 | Warley Woods, Bearwood, Birmingham.                                                                                                                                                                                                                     | 52.47 | -1.98 | 10 |
| Beginner     | 2019-04-08<br>00:00:00+00:00 | Hirst Wood, Shipley                                                                                                                                                                                                                                     | 53.84 | -1.80 | 1  |
| Intermediate | 2019-04-09<br>00:00:00+00:00 | New Road, Middlestown, Wakefield, West Yorkshire                                                                                                                                                                                                        | 53.65 | -1.59 | 1  |
| Intermediate | 2019-04-11<br>00:00:00+00:00 | Hesketh Park, Albert Road, Southport                                                                                                                                                                                                                    | 53.66 | -2.99 | 4  |
| Beginner     | 2019-04-13<br>00:00:00+00:00 | Streatham Hill, my garden!                                                                                                                                                                                                                              | 51.43 | -0.12 | 6  |
| Beginner     | 2019-04-18<br>00:00:00+00:00 | 2 parakeets in a tree in my back garden which backs onto Wollaton Park, about 4pm 18/4/2019 about They potted about in the tree for a few minutes then flew away. No idea what species. Bright green, reddish beak maybe a little bigger than a magpie. | 52.94 | -1.22 | 2  |

|              |                              |                                                                                                                                                  |       |       |    |
|--------------|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Beginner     | 2019-04-21<br>00:00:00+00:00 | PlymouthNorth Hill<br>roundabout                                                                                                                 | 50.37 | -4.16 | 24 |
| Beginner     | 2019-04-21<br>00:00:00+00:00 | We saw 4 or 5 parakeets in<br>the trees in Shoreham,<br>Sevenoaks                                                                                | 51.33 | 0.18  | 4  |
| Beginner     | 2019-04-27<br>00:00:00+00:00 | 4 green parakeets flew across<br>my back garden and into the<br>trees behind my house.                                                           | 52.55 | -1.98 | 4  |
| Intermediate | 2019-04-27<br>00:00:00+00:00 | Cobham Rise, Gillingham<br>Kent ME7 2LA.<br><br>It was originally seen around<br>the railway line but now visits<br>the bird feeder in my garden | 51.38 | 0.57  | 1  |
| Beginner     | 2019-04-28<br>00:00:00+00:00 | Newington Green, London,<br>N16 9PX                                                                                                              | 51.55 | -0.09 | 4  |
| Beginner     | 2019-05-01<br>00:00:00+00:00 | Fog Lane park<br><br>Manchester                                                                                                                  | 53.42 | -2.22 | 5  |
| Intermediate | 2019-05-01<br>00:00:00+00:00 | On public footpath heading<br>toward North end of<br>University Parks, Oxford. Two                                                               | 51.76 | -1.25 | 2  |

|              |                              |                                                                                                                                                                                                                                                                                                                                   |       |       |   |
|--------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
|              |                              | birds seen flying and perched on large willow trees either side of the path.                                                                                                                                                                                                                                                      |       |       |   |
| Intermediate | 2019-05-01<br>00:00:00+00:00 | <p>Kings heath, Birmingham</p> <p>1/5/19 single parakeet heard (not seen) flying across back gardens of Springfield road, B14, ? from Moseley golf course towards Highbury park/the railway line</p> <p>Autumn 2017-autumn 2018 sporadic sightings in or close to Highbury park, kings heath. Maximum seen in one sighting: 4</p> | 52.43 | -1.89 | 4 |

|          |                              |                                                                                  |       |       |    |
|----------|------------------------------|----------------------------------------------------------------------------------|-------|-------|----|
|          |                              | Never seen close enough/long enough to identify species                          |       |       |    |
| Beginner | 2019-05-02<br>00:00:00+00:00 | At my home, address above.<br><br>This is a rural location, just inside the M25. | 51.28 | -0.18 | 1  |
| Beginner | 2019-05-02<br>00:00:00+00:00 | Rock ferry, Wirral                                                               | 53.37 | -3.00 | 10 |
| Beginner | 2019-05-03<br>00:00:00+00:00 | Putney, west london                                                              | 51.47 | -0.24 | 12 |
| Beginner | 2019-05-03<br>00:00:00+00:00 | Sturgess Field<br><br>Kedleston Road<br><br>Derby<br><br>UK<br><br>De223aw       | 52.93 | -1.50 | 4  |

|              |                              |                                                                                                                                                                                                                                                                                 |       |       |     |
|--------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|-----|
| Beginner     | 2019-05-03<br>00:00:00+00:00 | Roughly 10 parakeets live in Chorlton as far as I can work out. They fly in a flock together sometimes or in smaller groups. Their numbers have increased in the last 2 years.                                                                                                  | 53.26 | -2.17 | 10  |
| Intermediate | 2019-05-03<br>00:00:00+00:00 | We have them all over West London. They fill our parks. I am sat at Hounslow station and you can hear them all around. They go as far out as Windsor and Ascot. But not to Bracknell or Reading yet. First saw them on the Thames. There thousands of them all over West London | 51.46 | -0.36 | 100 |
| Intermediate | 2019-05-03<br>00:00:00+00:00 | At a neighbour's garden bird feeder, Western Drive, Liverpool                                                                                                                                                                                                                   | 53.36 | -2.92 | 1   |
| Beginner     | 2019-05-04<br>00:00:00+00:00 | HA49JF                                                                                                                                                                                                                                                                          | 51.34 | -0.23 | 13  |

|              |                              |                                                                                                  |       |       |     |
|--------------|------------------------------|--------------------------------------------------------------------------------------------------|-------|-------|-----|
| Beginner     | 2019-05-04<br>00:00:00+00:00 | Numerous ring necks in trees<br>around my house                                                  | 51.46 | -0.04 | 50  |
| Beginner     | 2019-05-04<br>00:00:00+00:00 | I see feral parakeets all over<br>Tooting Bec Common!                                            | 51.51 | -0.13 | 100 |
| Intermediate | 2019-05-05<br>00:00:00+00:00 | Hoglands Park in<br>Southampton- SO14 7LY<br><br>Sorry, I don't know the<br>long/lat of the park | 50.90 | #REF! | 4   |
| Intermediate | 2019-05-06<br>00:00:00+00:00 | Residential garden at above<br>address                                                           | 52.28 | -1.56 | 3   |
| Beginner     | 2019-05-07<br>00:00:00+00:00 | Barlow wood Chorlton<br>manchester                                                               | 53.25 | -2.16 | 4   |
| Expert       | 2019-05-07<br>00:00:00+00:00 | Havering Country Park<br><br>Romford<br><br>East London                                          | 51.61 | 0.17  | 12  |

|              |                              |                                                                                                                                                                                                                                                                                                       |       |       |    |
|--------------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Intermediate | 2019-05-07<br>00:00:00+00:00 | <p>Epsom and Ewell (Borough) - pretty much anywhere. The numbers below relate to groups I've seen. They tend to fly out at night - possibly to the large roost at Esther (?rugby club).</p> <p>Not seen any in Guildford though.</p>                                                                  | 51.34 | -0.27 | 6  |
| Beginner     | 2019-05-08<br>00:00:00+00:00 | <p>In my garden maybe 6 they roost in the tree in the garden backing on to mine.</p> <p>Along the Hogsmill river at the end of my road I saw about 10. Both sightings today.</p> <p>Thankfully fewer than last year when there were flocks of approx 40. As well as disturbing sleep because they</p> | 51.39 | -0.28 | 10 |

|              |                              |                                                                                                                                                                                                                       |       |       |      |
|--------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|------|
|              |                              | are noisy so early they decimated my apple crop.                                                                                                                                                                      |       |       |      |
| Beginner     | 2019-05-08<br>00:00:00+00:00 | Wormwood scrubs park near Hammersmith hospital                                                                                                                                                                        | 51.52 | -0.24 | 1000 |
| Expert       | 2019-05-08<br>00:00:00+00:00 | Yes, we have them in and around our local park and the streets beyond. In the park they swoop about in groups.                                                                                                        | 50.83 | -0.16 | 12   |
| Intermediate | 2019-05-08<br>00:00:00+00:00 | Parakeets seen in the garden sitting in a cherry tree.                                                                                                                                                                | 51.46 | -0.30 | 5    |
| Intermediate | 2019-05-08<br>00:00:00+00:00 | Tottenham, London (N17).<br><br>These animals are seen and heard on a daily basis (even throughout the winter) in this area. Flocks generally do not exceed 20 animals, however there are several flocks in the area. | 51.60 | -0.08 | 12   |

|              |                              |                                                                                                                                                                          |       |       |   |
|--------------|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
| Beginner     | 2019-05-11<br>00:00:00+00:00 | Large tree                                                                                                                                                               | 51.55 | -0.08 | 1 |
| Intermediate | 2019-05-16<br>00:00:00+00:00 | Durlston Country Park<br>Swanage Dorset                                                                                                                                  | 50.60 | -2.48 | 1 |
| Beginner     | 2019-05-18<br>00:00:00+00:00 | Throughout Windsor Road on Ealing Broadway, perched on the backyard trees of the gardens and sometimes on the trees along the road.                                      | 51.30 | -0.18 | 3 |
| Intermediate | 2019-05-20<br>00:00:00+00:00 | Numerous locations throughout West London including Twickenham (local streets, Marbell Hill Park), Teddington (Bushy park) and Richmond (Richmond Park)                  | 51.45 | -0.31 | 5 |
| Intermediate | 2019-05-20<br>00:00:00+00:00 | 2 parakeets flying over Albert Drive near houses and the trees lining the Glasgow Golf Club. One parakeet visited a garden on Albert Drive regularly about 20 years ago. | 55.91 | -4.31 | 2 |

|              |                              |                                                 |       |       |   |
|--------------|------------------------------|-------------------------------------------------|-------|-------|---|
|              |                              | I have not seen any since till this year.       |       |       |   |
| Intermediate | 2019-05-21<br>00:00:00+00:00 | Holders woods, cannon hill park, Birmingham     | 52.44 | -1.91 | 5 |
| Beginner     | 2019-05-23<br>00:00:00+00:00 | In my garden. seem be feeding on the blossom.   | 51.45 | -0.06 | 2 |
| Beginner     | 2019-05-23<br>00:00:00+00:00 | Ladybrook, Bramhall, Stockport - beech woodland | 53.37 | -2.14 | 2 |
| Beginner     | 2019-05-25<br>00:00:00+00:00 | Southampton, riverside park                     | 50.93 | -1.38 | 2 |
| Beginner     | 2019-05-26<br>00:00:00+00:00 | Address as above                                | 51.61 | -0.37 | 2 |
| Beginner     | 2019-05-26<br>00:00:00+00:00 | In garden on feeders in Grimsby                 | 53.54 | -0.11 | 1 |
| Intermediate | 2019-05-26<br>00:00:00+00:00 | daily in the garden of our home                 | 51.38 | -0.29 | 4 |

|              |                              |                                                                                                                                                                                                                                                                                     |       |       |   |
|--------------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
| Intermediate | 2019-05-30<br>00:00:00+00:00 | Spotted in a residential area in Oxford                                                                                                                                                                                                                                             | 51.77 | -1.24 | 1 |
| Beginner     | 2019-06-02<br>00:00:00+00:00 | 3 Parakeets near Neasden tube station                                                                                                                                                                                                                                               | 51.55 | -0.25 | 3 |
| Beginner     | 2019-06-02<br>00:00:00+00:00 | Multiple and frequent sightings of parakeets in the trees outside my window and in Sunny Hill Park nearby. Date and number listed is for most recent sighting.<br><br>Population size given is a guess, since there is no option for unknown and it won't let me submit without it. | 51.59 | -0.23 | 2 |
| Intermediate | 2019-06-02<br>00:00:00+00:00 | 1 breeding pair observed on many occasions.<br><br>Last year (2018) one fledgling                                                                                                                                                                                                   | 50.97 | -1.23 | 1 |

|          |                              |                                                                                                                                                                                                                                                                                     |       |       |          |
|----------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----------|
|          |                              | Unknown this year.                                                                                                                                                                                                                                                                  |       |       |          |
| Beginner | 2019-06-03<br>00:00:00+00:00 | Northbrook park and grove park nature reserve. They live high up, tops of tallest trees, flocks of 20+ will fly by early and at sunset, again very high up. I've never seen one anywhere near feeders or as low down as robins and blackbirds tits etc.                             | 51.43 | 0.01  | 50       |
| Beginner | 2019-06-03<br>00:00:00+00:00 | Northwest London Greenford Perivale park along the tree lining the tallest trees hold so many ringnecks.<br><br>I regularly go for a morning walk and I love see the trees move with bright green what appears to be at first leaves but the sweet sounds are beautiful to walk by. | 51.53 | -0.34 | 100<br>0 |

|              |                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |       |       |   |
|--------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
| Intermediate | 2019-06-03<br>00:00:00+00:00 | Nesting in a tree near to me, also picked up every day on the bird song ID app                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 50.86 | -1.29 | 3 |
| Beginner     | 2019-06-04<br>00:00:00+00:00 | I have just watched your clip on Springwatch on the BBC. At the back of our house there is a small park (Allerton Bywater Cricket Club for reference) where I see the Ring necked Parakeets daily for the last 4 years at least. There are a flock of around 5-6 that I have seen flying together & see daily. I am confident these are the ring necked parakeets as I've recently just completed a Bird Trainer experience at Blackpool Zoo & saw the Ring Necked Parakeets up close so I am certain these are what are flying around. | 53.74 | -1.37 | 6 |

|              |                              |                                                                                                                                                                                     |       |       |    |
|--------------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Expert       | 2019-06-04<br>00:00:00+00:00 | Garden feeders                                                                                                                                                                      | 52.54 | -1.83 | 1  |
| Intermediate | 2019-06-04<br>00:00:00+00:00 | In our garden (32 acres) Knockholt - we are the highest village in Kent - above Biggin Hill and Westerham<br><br>We have lots in the trees here.                                    | 51.18 | 0.06  | 20 |
| Intermediate | 2019-06-04<br>00:00:00+00:00 | In my garden at home, I saw at least two on a daily basis during the winter months. I haven't seen them so frequently since about March but did see one today                       | 52.47 | -1.98 | 1  |
| Intermediate | 2019-06-04<br>00:00:00+00:00 | on feeders and trees in Garden in Handsworth, Birmingham. Flew between back garden to trees that line the road. I have also previously seen them in trees on nearby Linchmere Road. | 52.51 | -1.95 | 3  |

|              |                              |                                                                                                                                                                                                      |       |       |   |
|--------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
| Intermediate | 2019-06-04<br>00:00:00+00:00 | Redhouse Lane<br><br>Aldridge<br><br>WS9 0DB                                                                                                                                                         | 52.60 | -1.94 | 3 |
| Intermediate | 2019-06-04<br>00:00:00+00:00 | 3 x Parakeets<br><br>Adel School<br><br>Tile Lane<br><br>Adel<br><br>Leeds<br><br>LS16 8DY                                                                                                           | 53.85 | -1.58 | 3 |
| Beginner     | 2019-06-05<br>00:00:00+00:00 | At my address and in the local vicinity. Up to 3 birds counted in one sighting. Currently stripping my tulip trees and cherry trees of fruit and flowers. Only females identified but there are more | 50.62 | -3.39 | 3 |

|              |                              |                                                                                                                                                                                                                                                                                                                        |       |       |    |
|--------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                              | birds in the area so keeping a look out for males                                                                                                                                                                                                                                                                      |       |       |    |
| Beginner     | 2019-06-05<br>00:00:00+00:00 | Pear tree estate by the fields between the estate and the m5. We have a little colony of 5 birds. They love my cockatiels food.                                                                                                                                                                                        | 52.55 | -1.96 | 5  |
| Beginner     | 2019-06-05<br>00:00:00+00:00 | Backhouse Park, Sunderland<br><br>Between 12and 15 birds in residence year round.<br><br>First sighted in 2012                                                                                                                                                                                                         | 54.89 | -1.38 | 12 |
| Intermediate | 2019-06-05<br>00:00:00+00:00 | In my garden particularly on the peanut feeder but i have only lived at this address since 2005 and they were here before then. Other people spoke of them but they are seen regularly now. There are four but if they are two pairs or a family group i have no idea. This place backs onto Alvaston park and is only | 52.90 | -1.43 | 4  |

|              |                              |                                                                                                                                                                                                                                                                                                                                    |       |       |    |
|--------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                              | about 1/4 mile from the river Derwent.                                                                                                                                                                                                                                                                                             |       |       |    |
| Beginner     | 2019-06-06<br>00:00:00+00:00 | I see parakeets most days when cycling to work, either in Sefton Park or Princes Park in south Liverpool.                                                                                                                                                                                                                          | 53.38 | -2.94 | 12 |
| Intermediate | 2019-06-26<br>00:00:00+00:00 | 3 LOCATIONS...1st Lytham StAnnes Lancs. Crematorium grounds (a colony)2nd Mobile birds in Runcorn in Cheshire switching between at least 3 sites and been there now over a year.3rd Bolton Lancs. Attempted breeding of 2 of 3 birds seen. Nesting in an old woodpecker hole failed, suspected predated by squirrel or woodpecker. | 53.34 | -2.73 | 3  |
| Intermediate | 2019-06-26<br>00:00:00+00:00 | 3 LOCATIONS...<br><br>1st Lytham StAnnes Lancs. Crematorium grounds (a                                                                                                                                                                                                                                                             | 53.75 | -2.98 | 3  |

|              |                              |                                                                                                                                                                                                                                                                                     |       |       |   |
|--------------|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
|              |                              | colony)<br><br>2nd Mobile birds in Runcorn in Cheshire switching between at least 3 sites and been there now over a year.<br><br>3rd Bolton Lancs. Attempted breeding of 2 of 3 birds seen. Nesting in an old woodpecker hole failed, suspected predated by squirrel or woodpecker. |       |       |   |
| Intermediate | 2019-06-30<br>00:00:00+00:00 | Back garden. Had been hearing it for a few weeks. Seen on 30/6/2019 it was a blue one. I have a photo                                                                                                                                                                               | 52.57 | -0.29 | 1 |
| Intermediate | 2019-07-16<br>00:00:00+00:00 | Landgate Rd, Handsworth, Birmingham.                                                                                                                                                                                                                                                | 52.51 | -1.95 | 5 |
| Beginner     | 2019-08-15<br>00:00:00+00:00 | 2 parakeets sighted flying across garden and then landing in tree.                                                                                                                                                                                                                  | 51.40 | -0.44 | 2 |

|              |                              |                                                                                                                      |       |       |    |
|--------------|------------------------------|----------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| Beginner     | 2019-10-02<br>00:00:00+00:00 | The Delves Green near out home address.<br><br>Around about 20-30 Birds in an Oak tree eating acorns                 | 52.56 | -1.97 | 25 |
| Expert       | 2019-10-12<br>00:00:00+00:00 | Sandwell Nature Reserve                                                                                              | 52.32 | -1.57 | 5  |
| Intermediate | 2019-12-21<br>00:00:00+00:00 | Selly Oak (flew over my garden)                                                                                      | 52.44 | -1.95 | 1  |
| Expert       | 2020-01-02<br>00:00:00+00:00 | Tonge Cemetery Bolton                                                                                                | 53.58 | -2.41 | 3  |
| Intermediate | 2020-01-19<br>00:00:00+00:00 | Old Cemetery, Belvedere Road, Ipswich                                                                                | 52.04 | 1.10  | 4  |
| Beginner     | 2019-05-08<br>00:00:00+00:00 | In my garden maybe 6 they roost in the tree in the garden backing on to mine.<br><br>Along the Hogsmill river at the | 51.39 | -0.28 | 10 |

|              |                              |                                                                                                                                                                                                                                   |       |       |   |
|--------------|------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
|              |                              | <p>end of my road I saw about 10. Both sightings today.</p> <p>Thankfully fewer than last year when there were flocks of approx 40. As well as disturbing sleep because they are noisy so early they decimated my apple crop.</p> |       |       |   |
| Expert       | 2020-02-01<br>00:00:00+00:00 | Single bird seen flying approximately north over RSPB Middleton Lakes just after 9AM                                                                                                                                              | 52.59 | -1.70 | 1 |
| Expert       | 2020-02-01<br>00:00:00+00:00 | <p>Liverpool</p> <p>Sefton park south of the Palm House</p> <p>At least 5 individuals observed at the same time</p>                                                                                                               | 53.38 | -2.93 | 5 |
| Intermediate | 2020-04-27<br>00:00:00+00:00 | <p>Dawsholm park small wood north side of Glasgow run next to the river Kelvin, birds sight in park number between</p>                                                                                                            | 55.90 | -4.32 | 5 |

|              |                              |                                                                                                                                       |       |       |    |
|--------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|              |                              | five and seven .The photographed birds seem to have paired using a old wood peckers hole as nest with a other pair using a dead tree. |       |       |    |
| Intermediate | 2020-05-28<br>00:00:00+00:00 | Top of tree in garden of house on abbeyfield road. B23 5lw                                                                            | 52.54 | -1.85 | 5  |
| Intermediate | 2020-05-28<br>00:00:00+00:00 | Top of tree in garden of house on abbeyfield road. B23 5lw                                                                            | 52.54 | -1.85 | 5  |
| Intermediate | 2020-06-06<br>00:00:00+00:00 | Tutbury ave open space, coventry                                                                                                      | 52.39 | -1.54 | 1  |
| intermediate | 2020-10-09<br>00:00:00+00:00 | 53.666872, -1.597379                                                                                                                  | 53.67 | -1.60 | 6  |
| beginner     | 2020-10-17<br>00:00:00+00:00 | Riverside Country Park Rainham kent                                                                                                   | 51.39 | 0.60  | 1  |
| expert       | 2020-10-17<br>00:00:00+00:00 | Highbury Park, Birmingham                                                                                                             | 52.44 | -1.90 | 12 |

|              |                              |                                                                                                                                                                                                                                                                |       |       |    |
|--------------|------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
| beginner     | 2020-11-28<br>00:00:00+00:00 | 3 parakeets at bird feeder in residential back garden,                                                                                                                                                                                                         | 51.44 | -0.04 | 3  |
| intermediate | 2020-12-14<br>00:00:00+00:00 | Over the past two weeks Ring-necked Parakeets have been roosting in the trees on the Kelvin walk way, river Kelvin at Cowal Road, arriving in small groups, counts around 20 plus birds, leaving at first light heading to wards Dawsholm Park, Maryhill Park. | 55.89 | -4.30 | 26 |
| intermediate | 2020-12-15<br>00:00:00+00:00 | ws5 3qd. small area of woodlands surrounded by 1960s estate. inside area between barr rd, greenslade rd, lake av. near pool, possible duck food present.                                                                                                       | 52.57 | -1.95 | 2  |
| expert       | 2020-12-20<br>00:00:00+00:00 | Johnston gardens, Aberdeen                                                                                                                                                                                                                                     | 57.14 | -2.15 | 2  |

|              |                              |                                                                                                                                                                                                                                                                                 |       |       |   |
|--------------|------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
| beginner     | 2020-12-27<br>00:00:00+00:00 | One parakeet feeding from my garden feeder. We have a flock of them staying in the trees behind my house.                                                                                                                                                                       | 51.77 | -0.23 | 1 |
| intermediate | 2020-12-27<br>00:00:00+00:00 | Frequently landing in the tall conifers of the back gardens                                                                                                                                                                                                                     | 51.58 | -0.43 | 6 |
| expert       | 2021-01-01<br>00:00:00+00:00 | Copse east of Melton Park, Gosforth, Newcastle upon Tyne. 2 - 3 present on 1 January, 2021. Up to 8 have been present on occasion over at least the past 2 years and nest in tree holes in the copse. Larger numbers are present and breed in Walker Park, Newcastle upon Tyne. | 55.02 | -1.61 | 3 |
| expert       | 2021-01-09<br>00:00:00+00:00 | Smithies/ Fleets ponds Barnsley and surrounding properties.                                                                                                                                                                                                                     | 53.34 | -1.28 | 7 |
| intermediate | 2021-01-09<br>00:00:00+00:00 | Burpham, Guildford                                                                                                                                                                                                                                                              | 51.26 | -0.54 | 2 |

|              |                              |                                                                                                                                                                                                                                                                                                                                                                                            |       |       |   |
|--------------|------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
| intermediate | 2021-01-29<br>00:00:00+00:00 | Chellow Dene Reservoir, BD15 Bradford. A nature reserve managed by Yorkshire Water. The woods to the left of the second reservoir                                                                                                                                                                                                                                                          | 53.81 | -1.82 | 3 |
| intermediate | 2021-01-31<br>00:00:00+00:00 | Back garden. Two birds on bird feeder, one bird accompanying. Recently arrived in nearby park (Western Park), but have been in Braunstone Park for a little longer. Understand that 2020 is the first confirmed breeding of the parakeets in Western Park, nesting just by the primary school on Glenfield Road. Noticeable increase in sightings (and hearings!) over the past 12 months. | 52.64 | -1.17 | 3 |
| intermediate | 2021-02-10<br>00:00:00+00:00 | Haslam Park Bristow Avenue Ashton-on-Ribble Preston Lancashire PR21JE                                                                                                                                                                                                                                                                                                                      | 53.77 | -2.73 | 1 |

|              |                              |                                                                                                                                                                  |       |       |   |
|--------------|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|---|
| beginner     | 2021-02-21<br>00:00:00+00:00 | Stoke Bruerne                                                                                                                                                    | 52.15 | -0.91 | 1 |
| beginner     | 2021-02-26<br>00:00:00+00:00 | Abbey fields park in Kenilworth around 8am. See the parakeet regularly. It is not part of a flock and is known in the town to have escaped in 2019               | 52.35 | -1.59 | 1 |
| intermediate | 2021-03-27<br>00:00:00+00:00 | Cannon Hill Park, Birmingham<br><br>2 green parakeet-shaped birds flew in between tall trees near the Moor Green allotments and then sat in the trees chirruping | 52.45 | -1.91 | 2 |
| intermediate | 2021-06-22<br>00:00:00+00:00 | Walton, Warrington UK<br><br>.Close to Appleton Reservoir. 22/01/21. Two in a tree and then flying.                                                              | 53.36 | -2.61 | 2 |
| expert       | 2021-08-11<br>00:00:00+00:00 | Three parakeets in my back garden in Moseley on 11.8.2021. This is the first                                                                                     | 52.44 | -1.89 | 3 |

|          |                                  |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |       |       |    |
|----------|----------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|-------|----|
|          |                                  | time I've seen three together.<br><br>(Our seed and peanut feeders had been visited by one or two parakeets most days over the past fortnight.) The parakeets only come early in the morning (6-8am) and don't stay for very long. They are eating sunflower seeds and peanuts and seem quite accustomed to using hanging feeders. The other small garden birds (greenfinches, goldfinches, bullfinches, chaffinches, blue tits, great tits, hedge sparrows, nuthatches) don't seem to be bothered by them being there. |       |       |    |
| beginner | 2021-09-22<br><br>00:00:00+00:00 | Sale Water Park, Arnesby Avenue, Ravenstone Drive, Skaife Road - all M33 area                                                                                                                                                                                                                                                                                                                                                                                                                                           | 53.43 | -2.30 | 20 |
| beginner | 2021-11-03<br><br>00:00:00+00:00 | 362 Church Road<br><br>Yardley                                                                                                                                                                                                                                                                                                                                                                                                                                                                                          | 52.47 | -1.80 | 10 |

|              |                              |                                       |       |      |   |
|--------------|------------------------------|---------------------------------------|-------|------|---|
|              |                              | Birmingham                            |       |      |   |
|              |                              | B25 8XT                               |       |      |   |
| Intermediate | 2020-01-23<br>00:00:00+00:00 | old cemetery, Belvedere Road, Ipswich | 52.04 | 1.10 | 2 |

### Appendix 3.1

**Variance Inflation Factors for all environmental variables for Species Distribution Modelling for winter and breeding seasons.**

| Variables                  | Variance Inflation Factor |                 |
|----------------------------|---------------------------|-----------------|
|                            | Winter Season             | Breeding Season |
| Broad-leaved, woodland     | Infinity                  | Infinity        |
| Coniferous woodland        | 2.733119                  | 2.45374         |
| Arable land                | 4.898051                  | 5.594505        |
| Grassland                  | 3.850256                  | 4.275906        |
| Urban                      | 1.522318                  | 1.488748        |
| Suburban                   | Infinity                  | Infinity        |
| Human population density   | 2.471395                  | 2.778912        |
| Elevation                  | 1.758181                  | 1.828270        |
| Wood Area km <sup>-2</sup> | 1.370101                  | 1.266725        |
| Road Length km-2           | 1.026341                  | 1.035079        |
| Ground Frost               | 1.509615                  | 1.159439        |
| Minimum temperature        | 12.841697                 | 4.624313        |
| Heating Degree Days        | 13.528395                 | 5.710192        |

## Appendix 3.2

**Variance Inflation Factors for environmental variables retained in the final Species Distribution Models for winter and breeding seasons.**

| Variables                    | Variance Inflation Factor |                 |
|------------------------------|---------------------------|-----------------|
|                              | Winter Season             | Breeding Season |
| Broad-leaved Woodland        | 1.6909954                 | 1.112800        |
| Coniferous Woodland          | 1.235362                  | 1.083739        |
| Arable Land                  | 4.587673                  | Not retained    |
| Grassland                    | 3.505524                  | 1.194113        |
| Urban                        | 1.769977                  | 1.680010        |
| Human population density     | 2.989065                  | 1.816666        |
| Elevation                    | 1.653615                  | 1.759217        |
| Road length km <sup>-2</sup> | 1.043925                  | 1.036602        |
| Heating Degree Days          | 1.641841                  | 1.805725        |

### Appendix 3.3

**Raw model outputs used to assess the models in the process of model refinement by dropping variables in turn.**

Models are identified by letters and numbers, with the predictors identified within the stack() command. Environmental variables are as follows: HDDWin11S is Heating Degree Days for the winter season; HDD11S is Heating Degree Days for the breeding season; Hab1S = Broad-leaved, mixed and Yew woodland; Hab2S is Coniferous woodland; Hab3S is Arable and Horticultural Land; GrassS is Grassland. Hab22S is Urban; HouDen1S is Human Population Density per km<sup>2</sup>; Elevat1S is Mean Elevation per km<sup>2</sup>; RoadLengthS is Road Length per km<sup>2</sup>; WoodAreaS is Area of Woodland per km<sup>2</sup>.

km<sup>2</sup>; RoadLengthS is Road Length per km<sup>2</sup>; WoodAreaS is the area of woods per km<sup>2</sup>.

#### Round 1 – Winter Season

**Win1a <- stack(Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.8  |  | 0.43 |  | 0.48 |  | 0.75     |
| maxlike | : | 0.79 |  | 0.4  |  | 0.46 |  | 1.31     |
| maxent  | : | 0.82 |  | 0.45 |  | 0.5  |  | 0.98     |

**Win1b <- stack(HDDWin11S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.87 |  | 0.53 |  | 0.58 |  | 0.65     |
| maxlike | : | 0.84 |  | 0.47 |  | 0.56 |  | 1.56     |
| maxent  | : | 0.87 |  | 0.53 |  | 0.59 |  | 0.76     |

**Win1c <- stack(HDDWin11S, Hab1S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  | COR  | TSS  | Deviance |
|---------|---|------|------|------|----------|
| glm     | : | 0.88 | 0.57 | 0.58 | 0.64     |
| maxlike | : | 0.87 | 0.54 | 0.59 | 0.88     |
| maxent  | : | 0.88 | 0.57 | 0.6  | 0.74     |

**Win1d <- stack(HDDWin11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  | COR  | TSS  | Deviance |
|---------|---|------|------|------|----------|
| glm     | : | 0.87 | 0.54 | 0.6  | 0.65     |
| maxlike | : | 0.87 | 0.51 | 0.58 | 1.06     |
| maxent  | : | 0.88 | 0.54 | 0.6  | 0.77     |

**Win1e <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, Hab22S, HouDen1S, Elevat1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  | COR  | TSS  | Deviance |
|---------|---|------|------|------|----------|
| glm     | : | 0.88 | 0.56 | 0.61 | 0.61     |
| maxlike | : | 0.85 | 0.49 | 0.58 | 1.35     |
| maxent  | : | 0.89 | 0.56 | 0.62 | 0.72     |

**Win1f <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, HouDen1S, Elevat1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  | COR  | TSS  | Deviance |
|---------|---|------|------|------|----------|
| glm     | : | 0.86 | 0.52 | 0.58 | 0.66     |
| maxlike | : | 0.85 | 0.49 | 0.57 | 1.11     |
| maxent  | : | 0.87 | 0.53 | 0.59 | 0.77     |

**Win1g <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, Elevat1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  | COR  | TSS  | Deviance |
|---------|---|------|------|------|----------|
| glm     | : | 0.88 | 0.57 | 0.62 | 0.61     |
| maxlike | : | 0.86 | 0.5  | 0.58 | 1.37     |
| maxent  | : | 0.88 | 0.56 | 0.63 | 0.7      |

**Win1h <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, RoadLengthS, WoodAreaS)**

| methods | : | AUC  | COR  | TSS  | Deviance |
|---------|---|------|------|------|----------|
| glm     | : | 0.86 | 0.53 | 0.57 | 0.65     |
| maxlike | : | 0.85 | 0.47 | 0.56 | 1.47     |
| maxent  | : | 0.86 | 0.52 | 0.58 | 0.78     |

**Win1i <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, WoodAreaS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.87 |  | 0.54 |  | 0.6  |  | 0.63     |
| maxlike | : | 0.86 |  | 0.51 |  | 0.58 |  | 0.87     |
| maxent  | : | 0.88 |  | 0.55 |  | 0.61 |  | 0.73     |

**Win1j <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.69     |
| maxlike | : | 0.92 |  | 0.75 |  | 0.69 |  | 0.81     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.82     |

**Model Win1j is best performing model and outperforms initial model. WoodAreaS is therefore dropped from the model.**

## Round 2 – Winter season

**Win2a <- stack(Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.85 |  | 0.61 |  | 0.57 |  | 0.97     |
| maxlike | : | 0.84 |  | 0.6  |  | 0.57 |  | 1.12     |
| maxent  | : | 0.86 |  | 0.63 |  | 0.6  |  | 0.99     |

**Win2b <- stack(HDDWin11S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.72     |
| maxlike | : | 0.91 |  | 0.73 |  | 0.68 |  | 0.96     |
| maxent  | : | 0.92 |  | 0.74 |  | 0.68 |  | 0.83     |

**Win2c <- stack(HDDWin11S, Hab1S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.71 |  | 0.7      |
| maxlike | : | 0.91 |  | 0.75 |  | 0.7  |  | 0.8      |
| maxent  | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.83     |

**Win2d <- stack(HDDWin11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.73     |
| maxlike | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.88     |
| maxent  | : | 0.91 |  | 0.74 |  | 0.7  |  | 0.83     |

**Win2e <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, Hab22S, HouDen1S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS |  | Deviance |
|---------|---|------|--|------|--|-----|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.7 |  | 0.71     |
| maxlike | : | 0.91 |  | 0.75 |  | 0.7 |  | 0.94     |
| maxent  | : | 0.92 |  | 0.74 |  | 0.7 |  | 0.82     |

**Win2f <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, HouDen1S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.72     |
| maxlike | : | 0.91 |  | 0.74 |  | 0.69 |  | 0.89     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.69 |  | 0.82     |

**Win2g <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, Elevat1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.76 |  | 0.7  |  | 0.69     |
| maxlike | : | 0.91 |  | 0.75 |  | 0.69 |  | 0.84     |
| maxent  | : | 0.92 |  | 0.76 |  | 0.7  |  | 0.81     |

**Win2h <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, RoadLengthS)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.71     |
| maxlike | : | 0.91 |  | 0.74 |  | 0.7  |  | 0.93     |
| maxent  | : | 0.91 |  | 0.73 |  | 0.67 |  | 0.84     |

**Win2i <- stack(HDDWin11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S)**

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.91 |  | 0.77 |  | 0.72 |  | 0.67     |
| maxlike | : | 0.92 |  | 0.76 |  | 0.71 |  | 0.8      |
| maxent  | : | 0.91 |  | 0.76 |  | 0.71 |  | 0.81     |

**No model outperforms Model Win1j. No variables are dropped in this round.**

## Round 1 – Breeding season

```
Brea1a <- stack(Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.81 |  | 0.39 |  | 0.5  |  | 0.53     |
| maxlike | : | 0.8  |  | 0.34 |  | 0.48 |  | 1.53     |
| maxent  | : | 0.8  |  | 0.36 |  | 0.49 |  | 0.96     |

```
Brea1b <- stack(HDD11S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.87 |  | 0.57 |  | 0.61 |  | 0.46     |
| maxlike | : | 0.85 |  | 0.48 |  | 0.58 |  | 0.89     |
| maxent  | : | 0.88 |  | 0.54 |  | 0.62 |  | 0.61     |

```
Brea1c <- stack(HDD11S, Hab1S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.9  |  | 0.6  |  | 0.67 |  | 0.41     |
| maxlike | : | 0.88 |  | 0.52 |  | 0.63 |  | 0.59     |
| maxent  | : | 0.89 |  | 0.56 |  | 0.66 |  | 0.55     |

```
Brea1d <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.88 |  | 0.56 |  | 0.62 |  | 0.44     |
| maxlike | : | 0.87 |  | 0.51 |  | 0.58 |  | 0.55     |
| maxent  | : | 0.89 |  | 0.55 |  | 0.65 |  | 0.56     |

```
Brea1e <- stack(HDD11S, Hab1S, Hab2S, Hab3S, Hab22S, HouDen1S, Elevat1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.89 |  | 0.55 |  | 0.62 |  | 0.43     |
| maxlike | : | 0.87 |  | 0.46 |  | 0.58 |  | 0.9      |
| maxent  | : | 0.89 |  | 0.53 |  | 0.62 |  | 0.62     |

```
Brea1f <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, HouDen1S, Elevat1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.88 |  | 0.54 |  | 0.6  |  | 0.44     |
| maxlike | : | 0.86 |  | 0.48 |  | 0.58 |  | 0.69     |
| maxent  | : | 0.89 |  | 0.53 |  | 0.64 |  | 0.55     |

```
Brea1g <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, Elevat1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.9  |  | 0.6  |  | 0.66 |  | 0.4      |
| maxlike | : | 0.87 |  | 0.48 |  | 0.61 |  | 0.86     |
| maxent  | : | 0.9  |  | 0.57 |  | 0.64 |  | 0.51     |

```
Brea1h <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S,
RoadLengthS, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.87 |  | 0.54 |  | 0.59 |  | 0.44     |
| maxlike | : | 0.85 |  | 0.46 |  | 0.56 |  | 0.74     |
| maxent  | : | 0.87 |  | 0.51 |  | 0.6  |  | 0.63     |

```
Brea1i <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S,
Elevat1S, WoodAreaS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.87 |  | 0.53 |  | 0.61 |  | 0.44     |
| maxlike | : | 0.86 |  | 0.5  |  | 0.59 |  | 0.58     |
| maxent  | : | 0.88 |  | 0.54 |  | 0.62 |  | 0.56     |

```
Brea1j <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S,
Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.76 |  | 0.71 |  | 0.7      |
| maxlike | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.74     |
| maxent  | : | 0.93 |  | 0.76 |  | 0.73 |  | 0.75     |

**Model Brea1j is best performing model and outperforms initial model. WoodAreaS is therefore dropped from the model.**

## Round 2 – Breeding Season

```
Brea2a <- stack(Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S,
RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.84 |  | 0.59 |  | 0.54 |  | 0.98     |
| maxlike | : | 0.84 |  | 0.58 |  | 0.54 |  | 1.01     |
| maxent  | : | 0.86 |  | 0.62 |  | 0.58 |  | 0.96     |

```
Brea2b <- stack(HDD11S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.72     |
| maxlike | : | 0.91 |  | 0.73 |  | 0.68 |  | 0.79     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.76     |

```
Brea2c <- stack(HDD11S, Hab1S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.71 |  | 0.71     |
| maxlike | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.73     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.72 |  | 0.77     |

```
Brea2d <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.76 |  | 0.73 |  | 0.7      |
| maxlike | : | 0.92 |  | 0.75 |  | 0.72 |  | 0.73     |
| maxent  | : | 0.93 |  | 0.77 |  | 0.74 |  | 0.73     |

```
Brea2e <- stack(HDD11S, Hab1S, Hab2S, Hab3S, Hab22S, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.68 |  | 0.72     |
| maxlike | : | 0.91 |  | 0.72 |  | 0.68 |  | 0.8      |
| maxent  | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.78     |

```
Brea2f <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.73     |
| maxlike | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.78     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.72 |  | 0.77     |

```
Brea2g <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.7      |
| maxlike | : | 0.91 |  | 0.73 |  | 0.68 |  | 0.83     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.77     |

```
Brea2h <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.91 |  | 0.73 |  | 0.67 |  | 0.74     |
| maxlike | : | 0.91 |  | 0.72 |  | 0.67 |  | 0.79     |
| maxent  | : | 0.92 |  | 0.73 |  | 0.68 |  | 0.79     |

```
Brea2i <- stack(HDD11S, Hab1S, Hab2S, Hab3S, GrassS, Hab22S, HouDen1S, Elevat1S)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.7  |  | 0.71     |
| maxlike | : | 0.92 |  | 0.74 |  | 0.71 |  | 0.75     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.71 |  | 0.77     |

**Model Brea2d is best performing model and outperforms best model in round 1. Hab3S is therefore dropped from the model.**

Round 3 – Breeding season

```
Brea3a <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.73 |  | 0.69 |  | 0.74     |
| maxlike | : | 0.91 |  | 0.73 |  | 0.68 |  | 0.77     |
| maxent  | : | 0.92 |  | 0.74 |  | 0.71 |  | 0.78     |

```
Brea3b <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.71 |  | 0.7      |
| maxlike | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.74     |
| maxent  | : | 0.93 |  | 0.75 |  | 0.72 |  | 0.76     |

```
Brea3c <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)
```

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.91 |  | 0.73 |  | 0.69 |  | 0.75     |
| maxlike | : | 0.91 |  | 0.73 |  | 0.68 |  | 0.8      |
| maxent  | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.79     |

Brea3d <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.72     |
| maxlike | : | 0.92 |  | 0.73 |  | 0.68 |  | 0.75     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.71 |  | 0.77     |

Brea3e <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.71 |  | 0.71     |
| maxlike | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.76     |
| maxent  | : | 0.93 |  | 0.76 |  | 0.74 |  | 0.75     |

Brea3f <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.7  |  | 0.73     |
| maxlike | : | 0.91 |  | 0.73 |  | 0.68 |  | 0.75     |
| maxent  | : | 0.92 |  | 0.74 |  | 0.71 |  | 0.78     |

Brea3g <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.74 |  | 0.71 |  | 0.72     |
| maxlike | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.78     |
| maxent  | : | 0.92 |  | 0.75 |  | 0.72 |  | 0.77     |

Brea3h <- stack(HDD11S, Hab1S, Hab2S, GrassS, Hab22S, HouDen1S, Elevat1S, RoadLengthS)

| methods | : | AUC  |  | COR  |  | TSS  |  | Deviance |
|---------|---|------|--|------|--|------|--|----------|
| glm     | : | 0.92 |  | 0.75 |  | 0.72 |  | 0.71     |
| maxlike | : | 0.92 |  | 0.74 |  | 0.69 |  | 0.77     |
| maxent  | : | 0.93 |  | 0.76 |  | 0.72 |  | 0.76     |

**No model outperforms Model Brea2d. No variables are dropped in this round.**