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Potential future distribution and abundance patterns of Common Buzzards *Buteo buteo*

Jennifer A. Border, Dario Massimino & Simon Gillings

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Looking out for birds

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A report to Natural England

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BTO Research Report 707

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SUMMARY

1. To contribute towards the definition of Favourable Conservation Status for the Common Buzzard *Buteo buteo*, estimates of local carrying capacity are required throughout England. In this report we aim to assess the potential for future expansion of the Buzzard breeding range in England and forecast potential densities in 10-km squares using species distribution models.

2. According to *Bird Atlas 2007–11*, Buzzards breed in 94% of English 10-km squares. Many of the 54 squares where Buzzards were present but not breeding, and the 34 where they were not recorded, are coastal (and contain little land) or are suburban/urban areas with limited breeding habitat. Few unoccupied squares contain extensive tracts of suitable breeding habitat so we assess the potential for future range expansion to be limited.

3. To inform the selection of environmental variables required for distribution modelling, a literature review was conducted. This identified 25 factors likely to positively or negatively influence Buzzard presence or abundance; from these we sourced 25 spatially explicit variables. Seven were highly inter-correlated and were not used in models. For some potentially important factors we were unable to source spatial data to incorporate into models.

4. Buzzard abundance data were obtained from the BTO/JNCC/RSPB Breeding Bird Survey, giving numbers of birds counted in a stratified random sample of over 5,000 1-km squares. Count data were corrected for detectability using distance sampling to yield densities (birds per surveyed 1-km square). Two metrics were calculated for modelling: a) maximum observed density per square, and b) mean observed density per square, both calculated over the most recent five years.

5. Generalised additive models were used to relate the two metrics of Buzzard density to the chosen environmental variables. Ten-fold cross validation was used to assess model performance and the effects of individual environmental variables were checked for biological realism. Density predictions were made for all 1-km squares in England, then summed to give estimates per 10-km square.

6. Models trained on maximum observed densities (the "maximum density model") and mean observed density (the "mean density model") performed similarly well; performance was reasonable, and good by abundance modelling standards. Comparisons of predictions and observations showed that models were reasonably well calibrated but they were unable to accurately predict the highest observed densities. Nevertheless, predicted densities were higher compared to published density estimates.

7. The long-term trend in density in each 100-km square was assessed for evidence of stability. Densities were high and stable in the west compared to low but rapidly increasing in the east with little evidence of densities plateauing. In the west, annual densities in the stable parts of the trend fell short of densities predicted from the maximum density model but matched those from the mean density model. In areas of rapid increase in the east, observed densities have already exceeded predictions from the mean density model and appear likely to exceed those from the maximum density model in future.

8. In conclusion, we can be highly confident about the extent of the Buzzards breeding range and its limited scope to expand further. The species distribution models are as robust as we can expect with the data available and they perform comparably to other models of abundance. However, many of the predicted densities are high compared to those in the literature, although it should be noted many of these are quite old and limiting factors may have reduced since then.

9. Further, the ongoing population increase in eastern England and anticipated exceedance of our density predictions indicates that correlative relationships built on variables such as land cover are unable to capture all the fine-scale local environmental influences acting on Buzzards, thereby limiting the application of these models for local management purposes. Mechanistic models using demographic rates are likely to yield more robust predictions.

1. INTRODUCTION

The Common Buzzard, *Buteo buteo* (Buzzard hereafter) is a large raptor which resides in England year round. England's Buzzard population declined in the late 1950s due to plummeting Rabbit *Orytolagus cuniculus* populations from the myxomatosis virus (Taylor et al., 1988), persecution in the 18th, 19th and early 20th centuries (Elliott & Avery, 1991), and organochloride pesticides in the 1950s and 1960s (Parkin & Knox, 2010). However, in the last 40 years the Buzzard population has undergone a rapid increase and associated range expansion, more than doubling its previous range size (Balmer et al., 2013). Reasons for this expansion are not yet well understood, though the reduction in illegal killing (Prytherch, 2013), the ban on organochloride pesticides which came into force in the 1984, recovery of Rabbit populations and upland afforestation are all likely to have played a role (Taylor et al., 1988; Balmer et al., 2013).

In the 20 years between the breeding distribution atlases of 1988–91 (Gibbons et al., 1993) and 2008–11 (Balmer et al., 2013) Buzzard range has expanded eastwards leading to the colonization of eastern Britain, plus the Isle of Man and the Channel Islands, while territory density has increased in western areas. There have been a few small-scale local studies on Buzzard densities in the UK (e.g. Dare & Barry, 1990), and some older ones covering Britain or the UK as a whole (e.g. Moore, 1965; Taylor et al., 1988, Clements, 2002). However, there is still little understanding of how much further Buzzards could spread and how much more populations could increase until they reach the limit of their local environment. There is also little understanding of the influence of environmental variables on Buzzard densities; again, there have been a several small-scale studies looking at correlations between certain environmental variables and breeding success (Austin & Houston, 1997, Sim et al., 2001; Krüger, 2004; Rooney & Montgomery, 2013) or local breeding densities (Graham et al., 1995, Sim et al., 2001), but no large scale studies to identify the key influences on Buzzards across the country.

Conservation and management decisions relating to Buzzards need to take account of these changes, but it is unclear whether populations have stabilised or how much further Buzzards could spread and increase. In particular, information on the potential future extent of Buzzard distribution and expected densities are needed for an assessment of Favourable Conservation Status (FCS) being undertaken by Natural England. FCS requires "securing the inherent genetic diversity of a species" and "maintaining a viable representation across their natural range and distribution". The species must be either stable or increasing and have good prospects of continuing to do so in the future (for more details see: http://jncc.defra.gov.uk/pdf/FCS18_InterAgencyStatement.pdf). Ideally such information would be based on a detailed population model considering demographic rates including survival, productivity, dispersal and density dependence and how these relate to habitat suitability. An alternative approach is to use species distribution models (SDM; Franklin, 2010). SDMs seek to identify the relationships between the presence or abundance of a species and various biologically limiting environmental factors. Knowledge of these relationships can be used to make predictions of species presence or abundance in new settings or under new environmental conditions. In this study we assess whether an SDM approach can help inform the production of the FCS statement. Specifically we aim to:

1. Assess the current 10-km resolution distribution of Buzzards in England, identify unoccupied areas and assess their potential to support breeding Buzzards.

2. Produce 10-km resolution estimates of the saturation density of breeding Buzzards throughout England.

2. METHODS

2.1 Data used in the analyses

The following datasets on Buzzard distribution and abundance were used in these analyses.

2.1.1 Bird Atlas distribution data

The current range extent of Buzzards was determined from *Bird Atlas 2007–11* (Balmer et al., 2013). The atlas presents the latest comprehensive information on the distribution of breeding Buzzards at a 10-km resolution. Full field methods are in Balmer et al. (2013) but in brief each 10-km square was surveyed to assess the likelihood of breeding by each bird species, using standard evidence of breeding criteria. Following the four years of surveys, each 10-km square was assigned one of five categories: i) absent, ii) present but no breeding evidence, iii) possible breeding, iv) probable breeding or v) confirmed breeding. Note that for breeding evidence to be associated with a square, birds must be seen/heard using the square, displaying a number of behaviours that could constitute breeding, and the behaviour must be observed in suitable breeding habitat. For this species, 10-km squares where the species was present but no breeding evidence was assigned are most likely to arise either because of a lack of suitable breeding habitat (e.g. dense urban fabric) or because birds were not using the square (e.g. migrating over the square).

2.1.2 Breeding Bird Survey data

Abundance data for modelling spatial patterns of abundance and for assessing long-term trends came from the BTO/JNCC/RSPB Breeding Bird Survey (BBS; Harris et al., 2017). The survey has been conducted since 1994 and uses a stratified random sampling design. BBS squares are allocated randomly to volunteers. Surveys are conducted during 6am–10am and volunteers are requested not to survey in strong winds and heavy rain. In each square two 1-km transect lines are walked at a slow constant pace and all birds seen or heard are recorded. The transect lines are ideally 500 m apart and 250 m from the edge of the 1-km square, though some deviation may be necessary due to access rights, obstacles and terrain. Each transect line is split into five 200 m sections for recording purposes. Each square receives two visits per year, one in April to mid-May and a second in mid-May to the end of June. The following habitat descriptions are assigned to each 200 m transect section: woodland, scrubland, semi-natural grasslands/marsh, heathland and bogs, farmland, human sites, waterbodies, coastal and inland rock. Birds are recorded in three distance categories measured at right-angles to the transect line: < 25 m, 25–100 m, 100+ m. Birds seen only in flight are recorded separately. Recording of birds in distance bands allows a formal evaluation of how the detectability of a species declines with distance from the transect line, enabling numbers of birds encountered to be corrected for under-detection to derive estimates of absolute density (Buckland et al., 2005). For most species the majority of individuals are recorded in one of the distance bands, with very few encountered only in flight. Exceptions are hirundines, Skylarks *Alauda arvensis* and raptors such as Buzzard. For the purposes of this report we refer to all birds encountered in distance bands as 'perched birds'. Hence we are able to assess how detectability varies with distance for perched birds and make due corrections. Detectability corrections are not possible for flying birds and we have to assume that at any distance (within the 1-km square) flying birds would have been uniformly detectable.

2.2 Assessing current distribution and potential for range expansion

Bird Atlas data (Section 2.1.1) were used to identify all squares were at least possible breeding evidence was noted (= breeding range) and all squares where the species was absent or present only (= unsuitable and potential future range). The latter list of squares was retained for later use. To aid interpretation we determined the land area of each 10-km square.

2.3 Modelling spatial variation in Buzzard densities

Producing species distribution models to enable predictions of Buzzard density per 10-km square involved the following seven steps:

1. Convert observed counts on transects to densities (birds per km^2);

2. Identify key environmental variables likely to determine Buzzard density and obtain spatially referenced data for every 1-km square in the study region;

3. Develop a statistical species distribution model relating the observed density of Buzzards in surveyed squares to the identified environmental variables;

4. Use cross-validation to determine the explanatory power of the best model;

5. Use the model to make predictions for every 1-km square in the study region;

6. Sum 1-km predictions per 10-km square to derive estimates of birds per 10-km square (birds per 100 km^2);

7. Sense-check densities derived in 5) and 6) with published estimates of Buzzard density.

Steps 1–4 are explained in more detail in the following sections.

2.3.1 Converting counts to densities

To convert transect counts to densities of birds per 1-km square, raw count data of Buzzards in each transect section were adjusted via the program Distance (Buckland et al., 2005) to account for detectability using the model: $distance \sim habitat + visit$ where habitat was the main habitat assigned to the transect section and visit was a categorical factor indicating whether the count was derived from the early or late visit. For this purpose some habitat types (waterbodies, coastal and inland rock) that were very rarely occupied by Buzzards had to be combined into a single 'open habitat' category. Detectability estimates were calculated for each year, although as year is not a model covariate the same transect section will get the same detectability over years (unless habitat has changed).

These detectability estimates were used to calculate densities by multiplying the number of individuals in each 200 m section in the distance bands < 25 m and 25–100 m by the habitat-specific detectability coefficients. Sightings in the 100 m+ distance band were discarded due to the lack of an upper bound for this category preventing accurate density estimates. Including Buzzards sighted up to 100 m away means each 200 m transect section covers 400 m^2, so this density was expressed in individuals/4 ha. This was then multiplied by 2.5 to obtain individuals/10ha, under the assumption that density beyond 100 m is the same as density within 100 m. The total number of flying birds detected in each 200 m section was then added to this density estimate. Given the size and high visibility of flying Buzzards, we assumed flying birds were equally detectable throughout the 1-km square. Then the counts were summed over all transect sections to get an estimated density per 1-km square for each visit and each survey year. For each square and survey year the visit with the highest total Buzzard density was selected.

In the development of previous SDMs using BBS data we have summarised multiple years of data from each surveyed square to produce a single estimate per square, usually taking the maximum density across years (e.g. Massimino et al. 2017a). This approach is adopted in an effort to reduce the influence of stochasticity in the observed counts, either due to failure to detect birds or chance year to year fluctuations in abundance. A further argument for this approach is it may more closely reflect the upper bound of density that squares may attain, which is the desired aim of this modelling exercise. However, for a species such as Buzzard, with a potentially large home range, this approach could artificially inflate local density estimates and the mean density across years may be a more realistic figure. For this work we calculated maximum observed density and mean observed density for each surveyed square over the 5-year period, 2012 to 2016. We then repeated all analyses described below using both metrics and we discuss which of these approaches is likely to be most appropriate for Buzzards in Section 3.2.2 and Section 4. It should be noted here that it is not possible to distinguish between breeding and non-breeding Buzzards in these data.

2.3.2 Identifying environmental variables

A literature search was undertaken to identify relevant environmental variables likely to determine Buzzard occurrence and abundance (Table 1). Table 2 lists the variables for which we were able to acquire contemporary spatially referenced data. There are some variables that ideally we would have liked to include but data are either completely lacking or available at an inappropriate spatial or temporal resolution. These include information on the abundance of small mammals such as voles, other rodents and moles, abundance of amphibians and a measure of the number of footpaths in an area as a proxy of human disturbance. There is also evidence that songbirds, thrushes and medium-sized birds are a good food source for Buzzards (Taylor et al., 1988, Jędrzejewski et al., 1994, Swann and Etheridge, 1995, Austin & Houston 1997, Selås, 2001, Rooney & Montgomery, 2013). However, diet seems to be highly dependent on what is available in the local area and these bird food sources tend to be used when other larger food sources are unavailable (Austin & Houston, 1997, Rooney & Montgomery, 2013). Also, including so many species of birds together as a variable is likely to reflect overall habitat quality rather than prey abundance. For these reasons we did not use songbird abundance as a covariate. The following sections detail how the selected environmental variables were sourced.

Table 1. Factors identified from literature review that positively or negatively affect Buzzard distribution and abundance

Environmental factor	Direction of expected effect/explanation	Reference
Rabbit abundance	Positive effect, important food source	Rooney & Montgomery, 2013; Swann & Etheridge, 1995; Austin & Houston, 1997; Graham et al., 1995
Corvid abundance	Positive effect, important food source	Rooney & Montgomery, 2013; Sim et al., 2001
Abundance of medium sized birds (thrushes, woodpeckers)	Positive effect, important food source	Rooney & Montgomery, 2013; Jędrzejewski et al., 1994
Rat/rodent abundance	Positive effect, important food source	Rooney & Montgomery 2013; Goszczynski, 2001
Amphibians/toads abundance	Positive effect, important food source	Swann & Etheridge, 1995; Selås, 2001
Vole and mole abundance	Positive effect, important food source	Swann & Etheridge, 1995; Selås, 2001; Wuczynski, 2003; Graham et al., 1995
Woodpigeon and Pheasant abundance	Positive effect, important food source	Swann & Etheridge, 1995; Selås, 2001
Brown Hare abundance	Positive effect, important food source	Swann & Etheridge, 1995
Passerine abundance including Chaffinch	Positive effect, important food source	Swann & Etheridge, 1995; Selås, 2001; Taylor et al., 1988; Austin & Houston, 1997
Persecution	Negative, limits population growth	Elliot & Avery, 1991; Swann & Etheridge, 1995;Taylor et al., 1988; Goszczynski, et al. 2005
Rainfall	Negatively effects reproductive success	Krüger, 2002; 2004
Human disturbance	Negatively effects reproductive success	Krüger, 2004
Competition	Negatively effects reproductive success	Krüger, 2004
Cold temperatures	Reduces fitness	Krüger, 2002
Open areas	Positive relationship as used for foraging	Kruger, 2002
Number of buildings	Negative effect, unsuitable habitat	Krüger, 2002
Coniferous plantations	Positive relationship, good nesting and foraging habitat	Newton et al., 1982
Agricultural land	Positive relationship, good nesting and foraging habitat	Baltag et al., 2013
Natural perches-bushes and shrubs	Positive relationship, good nesting and foraging habitat	Baltag et al., 2013
Woodland fringes and scrubs	Good prey densities	Dare & Barry, 1990
Unimproved pasture	Positive relationship, good nesting and foraging habitat	Sim et al., 2001
Mature deciduous woodlands	Positive relationship, good nesting and foraging habitat	Sim et al., 2001; Gibbons et al., 1994
Corvids	Negative, predate on chicks, cause nest failure	Sim et al., 2001
Agricultural intensification	Possible negative effect, makes habitat more unsuitable	Sim et al., 2001
Grazed pasture	Positive relationship, good nesting and foraging habitat	Gibbons et al., 1994

Table 2. A summary of the environmental variables collated and their sources. The variables shown in *bold italics* were those retained for use in the models after excluding highly correlated ones.

Influence	Variable	Data source
Prey availability	***Rabbit relative abundance per1-km***	Modelled BBS mammal counts[1]
	Brown Hare relative abundance per1-km	Modelled BBS mammal counts[1]
	Mean Pheasant count per 10-km	*Bird Atlas 2007–11*[2]
	Mean corvid count per 10-km	*Bird Atlas 2007–11*[2]
Predation/competition	***Mean corvid count per 10-km***	*Bird Atlas 2007–11*[2]
	Goshawk presence/absence	*Bird Atlas 2007–11*[2]
	Mean Buzzard count from Bird Atlas	*Bird Atlas 2007–11*[2]
Habitat	***% cover semi-natural grassland***	2015 Land Cover Map[3]
	% cover improved grassland	2015 Land Cover Map[3]
	% cover arable	2015 Land Cover Map[3]
	% cover built up areas and gardens	2015 Land Cover Map[3]
	% cover of mature trees	National Forest Inventory for 2011[4]
	% tree cover	Pan-European HRL Tree Cover Density 2012[5]
	Log ratio of % cover of coniferous to deciduous woodland	2015 Land Cover Map[3]
Climate	Mean monthly temperature over whole year (°C)	UKCP09[6]
	Mean monthly breeding temperature (°C)	UKCP09[6]
	Mean monthly wintering temperature (°C)	UKCP09[6]
	Mean of total monthly precipitation over whole year (mm)	UKCP09[6]
	Mean of total monthly breeding precipitation (mm)	UKCP09[6]
	Mean of total monthly wintering precipitation (mm)	UKCP09[6]
	Total precipitation over whole year (mm)	UKCP09[6]
	Total breeding precipitation (mm)	UKCP09[6]
	Total monthly wintering precipitation (mm)	UKCP09[6]
Topography	***Slope (degrees)***	GGIAR-SRTM 90m raster[7]
	Elevation (m above sea level)	GGIAR-SRTM 90m raster[7]

[1] (Massimino et al., in review)
[2] (Balmer et al., 2013)
[3] (Rowland et al., 2017)
[4] Forestry Commission (https://www.forestry.gov.uk/inventory)
[5] Copernicus (land.copernicus.eu/pan-european/high-resolution-layers)
[6] Met Office https://www.metoffice.gov.uk/climate/uk/data/ukcp09/datasets#monthly
[7] (Jarvis et al., 2008, available at http://srtm.csi.cgiar.org)

Prey availability

Data on abundance of European Rabbit and Brown Hare *Lepus europaeus* were extracted from Massimino et al. (in review) which gives spatially interpolated estimates (at 1-km resolution) of relative abundance for mammals across Britain. It is important to note that these values are not densities or 'real abundances' but an index of abundance. Common Pheasant *Phasianus colchicus* abundance came from *Bird Atlas 2007–11* (Balmer et al., 2013) data. Using a sample of timed tetrad visits in each 10-km square we calculated the mean count per survey hour for Common Pheasant to give a measure of relative abundance per 10-km square. In the same way we calculated the mean count per survey hour for each of Carrion Crow *Corvus corone*, Hooded Crow *Corvus Cornix*, Jay *Garrulus glandarius*, Raven *Corvus corax* and Rook *Corvus frugilegus*, and then summed these values to give a measure of corvid relative abundance for each 10-km square.

Predation/competition

Corvids (crows) are both potential prey items and potential predators of Buzzard chicks, and the variable mean corvid count per 10-km square is explained in the prey availability section above. To reflect the abundance of Northern Goshawks *Accipiter gentilis* we used the presence or absence of breeding Goshawks in each 10-km square because densities of this species are so low the data were likely to be highly zero inflated and there is minimal variation in density between squares. In order to account for intraspecific competition, data on Buzzard abundance was included using mean count per survey hour at the 10-km square resolution. This variable is also likely to provide a further proxy for the suitability of 10-km squares for Buzzards and in some way compensates for the lack of detailed habitat quality data (e.g. of other mammalian prey). The atlas dataset is an entirely different dataset from the BBS data set used as the dependent variable (see section 2.1), and is collected using different methods, therefore including it as a variable will not compromise model independence.

Habitat

Land cover data came from the 1-km square percentage cover summary of the 2015 Land Cover Map (LCM) from the Centre for Ecology and Hydrology (Rowland et al., 2017). The percentage cover of Improved Grassland and Arable (encompassing Arable and Horticultural habitat) were taken directly from this dataset. For the other variables, land cover categories within the LCM data set were combined to create two broader categories: (i) Semi-Natural Grasslands, inclusive of neutral grassland, calcareous grassland, acid grassland, fen, marsh and swamp; (ii) Built-up areas, inclusive of urban and suburban habitats which includes settlements, other man-made structures such as industrial estates and urban gardens and parks. The log ratio of coniferous to deciduous woodlands was also calculated using the following equation:

log10((% cover coniferous woodland+0.01) / (% cover deciduous woodland+0.01))

The 0.01 was added to all counts to avoid obtaining infinite values when the percentage cover equalled zero.

Data on percentage tree cover came from the Copernicus Pan-European HRL Tree Cover Density 2012 raster dataset (HRL; land.copernicus.eu/pan-european/high-resolution-layers). The dataset consists of a raster of 20 m resolution giving the percentage tree cover per pixel. The data were re-projected from the European ETRS89 grid to the British National Grid and percent cover estimates were derived for each 1-km square. This dataset includes single trees and hedgerows and was therefore preferred over the 2015 LCM which only includes blocks of trees.

To determine the percentage cover of mature woodland we used the Forestry Commission's National Forest Inventory for 2011 (https://www.forestry.gov.uk/inventory). Area of mature woodland was extracted for each 1-km square by intersection of the forestry shape file and a polygon layer of 1-km squares in ARCGIS.

Climate (temperature and precipitation)

Gridded climate data at the 5 km resolution were obtained from the Metoffice UKCP09 (available at: www.metoffice.gov.uk/climatechange/science/monitoring/ukcp09/download/index.html). The data are generated for a regular 5 km grid via regression and interpolation of data from the irregular weather station network, taking into account longitude, latitude, elevation, terrain shape, coastal influence, and urban land use (Perry & Hollis, 2004). For year round conditions mean monthly temperature and total monthly rainfall were averaged over all months of the year. To encompass conditions when the birds were breeding we used the mean monthly temperatures and the total monthly rainfall averaged over the months March, April, May and June. For winter conditions, the mean monthly temperatures and the total rainfall were averaged over the months of December, January and February before the breeding season of interest (i.e. December 2010 for the 2011 survey). For rainfall we also calculated the total rainfall for each period (yearly, breeding, wintering) by summing the monthly total values. These annual values for each 5 km square were then averaged over the years 2012 to 2016 to match the BBS data used in models.

Topography (elevation and slope)

Elevation (in meters above sea level) was extracted from the GGIAR-SRTM 90 m raster (Jarvis et al., 2008) taking the mean elevation over each 1-km square. Slope was calculated from elevation in ARCGIS (ESRI 2011). The slope of each elevation raster cell is the maximum rate of change in elevation in one raster cell compared to its eight neighbours. The lower slope values indicate flatter areas, higher values indicate steeper areas. The mean slope was taken for each 1-km square.

2.3.3 Developing a Species Distribution Model for Buzzard densities

Prior to attempting future predictions we developed models to test how well the environmental variables could explain current observed spatial variation in Buzzard abundance. We chose to use Buzzard data from the whole of Britain rather than just England to increase the sample size and particularly to allow better parameterisation of predictions in upland sites of which there are relatively few in England. Generalised Additive Models (GAMs) were used to quantify the form of relationship between environmental factors and Buzzard abundance. GAMs were chosen as they allow non-linear relationships which are more biologically plausible than linear effects for many of these variables. Additionally GAMs reduce the likelihood of extreme predictions arising when predicting outside the range of the model input data. For example, a strong positive linear relationship with forest cover might lead to implausibly high predictions of Buzzard abundance (in the 100s) in squares with very high forest cover, compared to the rest of Britain.

With so many potential environmental predictors it is very likely that pairs of variables could be very highly correlated (collinearity). In such cases, entering both variables into models can prevent the identification of the causal relationship. To test for the degree of collinearity, univariate models relating each environmental variable (from Table 2) to Buzzard abundance were run and Variance Inflation Factors (VIFs; Zuur et al., 2009) were calculated. Pearson's Product Moment Correlation Coefficients were also calculated among all pairwise combinations of variables. Ideally, variables with VIFs > 3 and correlations to other variables > 0.7 were removed. Where two or more variables were strongly correlated, variables with a stronger relationship to Buzzard abundance from the single models were preferred over variables with weaker relationships. In this way the climate variables mean breeding season temperature and mean breeding precipitation were selected to represent the climate and arable habitat and improved grassland habitat were combined into one category (farmed habitat). After combining, farmed habitat was no longer highly correlated to any of the other variables; however it still had a VIF > 3 due to moderate correlations with many different variables. Elevation also presented a problem, as it was highly correlated to the climate variables. Both of these variables are likely to be very important determinants of Buzzard abundance, therefore we decided to include them in the final model despite possible multi-collinearity issues. Multi-collinearity can lead to unstable parameter estimates that are very sensitive to changes in the model specification but it will not affect the overall fit or the predictions made, nor will it cause any bias in the parameter estimates (Studenmund, 2000; Kutner et al., 2004). The purpose of this model was mainly to make reliable predictions and not to determine how different environmental parameters influence Buzzards, therefore possible inaccuracies in parameter estimates will not interfere with the model's main purpose.

Next the chosen variables (shown in bold italic) were put into a model together. A negative binomial family was used to account for over-dispersion and a weight was included to account for regional variation in survey effort. Initially, smoothed terms, using thin plate splines, were applied to every variable but in order to avoid overfitting and to ensure biologically meaningful relationships, k was restricted to a maximum of 3, meaning only linear or quadratic relationships were allowed. Then smoothed terms were removed one at a time based on the effective degree of freedom (edf) values, where values close to 1 indicate a linear trend. The smoothed term with the lowest edf was removed and the Akaike Information Criterion (AIC) was used to compare the models with and without the smoothed term. If dropping a smoothed term resulted in a rise in AIC > 2 then the smoothed term was retained. No variables were removed from the model as all variables had been selected for inclusion based on scientific evidence and the objective was to create a good predictive model so a conservative model was preferred. Model residuals were examined visually to ensure a reasonable fit.

As mentioned earlier, these procedures were performed twice, once with the maximum observed density per square ("maximum density model") and again using the mean observed density per square ("mean density model").

2.3.4 Assessing the predictive ability of the model

The best model as outlined in the previous section is the one that uses the available variables optimally, but we need to assess how good it is at explaining Buzzard abundance with independent data (i.e. data not used to train the model). To assess this we conducted ten-fold cross validation using the cvAUC package (Sing et al., 2005). The best model formulation was fitted using 90% of the data ('training data'). This model was then used to predict Buzzard abundance based on the variable values from the remaining 10% of the data ('test data'). The predicted abundances were then compared to the observed abundances from the test data using Spearman's Rank Correlation Coefficient. This process was repeated 10 times using a different 10% of the data for testing each time and the mean correlation coefficient (and 95% confidence intervals) across the 10 replicates was calculated. The predicted values for each of the 10 folds were also plotted against the observed BBS values to visually assess fit.

2.3 Assessing suitability of the unoccupied range

In section 2.2 we explained how existing atlas distribution data were used to identify 10-km squares that were currently unoccupied by breeding Buzzards. We used the SDM developed above to make predictions of the likely current abundance of Buzzards in the 1-km squares within these unoccupied squares to determine how suitable they were. For this analysis one minor change was made to the model formula: we removed the mean Buzzard count from Bird Atlas variable from the model because this variable might restrict the abundance of Buzzards predicted for these squares as they are squares where no Buzzards have yet been found breeding. Predictions made at 1-km resolution were summed for each 10-km square to assess square suitability. Two sets of predictions were made, based on the maximum density model and the mean density model. Model fit and the magnitude (and biological realism) of the densities predicted by these two models were investigated and one of them was selected as the most appropriate method to predict Buzzard densities.

2.4 Predicting saturation densities of Buzzards

Having developed a model and ascertained its ability to explain and predict currently observed Buzzard densities, it was our intention to use the same environmental variables in a quantile regression model which would have given us the ability to predict the likely maximum density achievable under certain environmental conditions. However, currently available quantile regression methods are only designed to work with normally distributed data as opposed to count data (which typically follows a Poisson distribution, with a lower bound of zero). Transforming our densities to a normal distribution did not work as models then returned negative predicted densities which are biologically unrealistic.

Instead we adopted the following approach, using the model developed above to predict abundances and using locally generated population trends to ascertain the likelihood that predictions reflect realistic saturation densities. As Buzzards have spread across England at different times, and densities have had longer to stabilise in some areas, this analysis took a regional approach, using 100-km squares to delineate regions. First, the model created in section 2.3.3 was used to make predictions of Buzzard density in every 1-km square in England. These predictions were averaged in each 100-km square to give our nominal estimate of saturation density for that region. Next the full time series of BBS data in each 100-km square was used to generate a trend for that 100-km square. Squares which were only surveyed in one year were removed. The trends were produced using a simple Generalised Linear Model, similar to how national trends are produced. Buzzard density (from the detectability adjusted raw BBS count see section 2.3.1) was modelled as a function of year and 1-km square (both as factors) to account for repeat observations of the same square in multiple years. A weight was also included to account for regional variation in survey effort. These models were then used to predict the Buzzard density for each year and each surveyed 1-km square. The predict abundances were then averaged for each year, over all surveyed 1-km squares in each 100-km square, and the trend plotted. The 95% confidence intervals for the trend were determined by averaging the standard errors for all 1-km predictions within each 100-km square for each year and then multiplying by 1.96 and either adding or subtracting from the mean predicted value for the square and year to get the upper and lower confidence interval respectively. We looked for an asymptote in the trend indicating a levelling off of the Buzzard density and compared this to the predicted densities from the SDM.

3. RESULTS

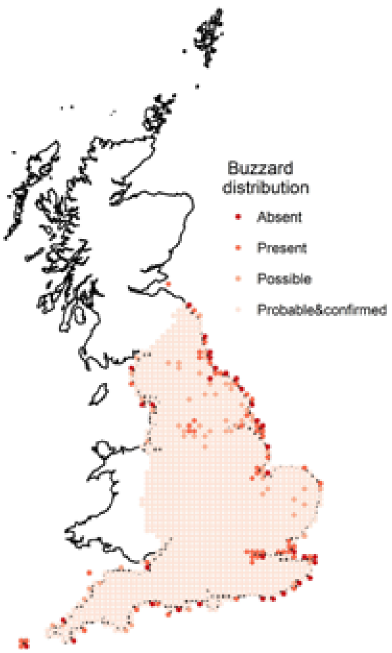
3.1 Current distribution and potential for range expansion

The current distribution of Buzzards in England according to *Bird Atlas 2007–11* is shown in Figure 1, coloured to emphasise gaps. Buzzards were recorded with breeding evidence (possible, probable or confirmed breeding) in 94% of 10-km squares in England (Table 3). The only squares where Buzzards were not recorded were mostly coastal or highly urbanised (e.g. centre of London). Squares with birds present but apparently not breeding included urban areas, coastal eastern England and small parts of the Pennines. In western England only a few coastal squares and the Isle of Scilly do not have breeding evidence.

Table 3. The number of 10-km squares where Buzzards were recorded as absent, present but not breeding, possibly breeding and probably or confirmed breeding from *Bird Atlas 2007–11*.

Buzzard status	Number of 10-km squares
Absent	34
Present	54
Possible breeding	59
Probable or confirmed breeding	1,347

Figure 1. A map showing the current status of occupancy by Buzzards of 10-km squares throughout England, based on *Bird Atlas 2007–11*.

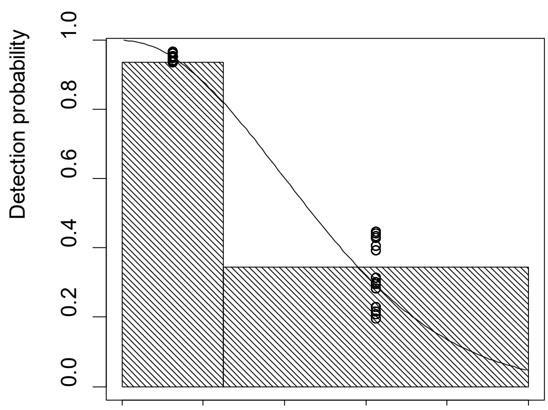


3.2 Species distribution model of Buzzard densities

3.2.1 Generating density estimates from counts

The total number of perched Buzzards detected in raw counts during 2012–16 was 5,248 and the total detected in flight was 10,808. Distance sampling, relating numbers in distance bands, produced an average detectability estimate of 0.49, indicating 49% of perched Buzzard individuals are detected within 100 m of the transect line (this number then needing to be extrapolated to the unsurveyed parts of the square, and flying birds added to produce final density). This is consistent with previous research where BBS data from 18 years were used (detection probability = 0.48, Johnston et al., 2014). There was moderate variation in detectability across habitats, with higher detectability in natural and semi-natural open habitats and human sites, intermediate detectability in farmland and lower detectability in woodland and scrubland. Variation between early and late visits was minimal.

Figure 2. The detectability function fitted to detected perched Buzzards. During the fitting of the curve detectability was permitted to vary with habitat and visit.



3.2.2 Assessing the explanatory and predictive ability of the model

The final model for current Buzzard abundance using the maximum density across years had an adjusted R-squared value of 0.19 and explained 23.4% of the model deviance. The final model for current Buzzard abundance using the mean density across years had an adjusted R-squared value of 0.17 and explained 24.4% of the model deviance.

For the maximum density model, from ten-fold cross validation the Spearmans' rank correlation coefficient between observed and predicted counts was 0.503

(CI: 0.476–0.531), for the mean density model this was 0.526 (CI: 0.498 – 0.554). Both of these values may not seem high but for models of count data they actually represent a very good fit (c.f. Johnston et al., 2013; Newson et al., 2015; Border et al., 2017). To put these figures in context we also determined the correlation between maximum Buzzard counts in the same 1-km square for the period of 2012–16 and the period of 2007–11 and the mean 1-km square Buzzard counts for the same two time periods. The resulting figures of 0.453 and 0.498 respectively indicated that even within the same square over a relatively short period of time, observed Buzzard counts may show substantial fluctuation.

When comparing observed densities versus predicted densities at the 1-km square level, the predicted densities from the maximum density models are low compared to the observed maximum densities (Figure 3a & c). However, when predictions are averaged to give a 10-km level prediction, the match between predicted and observed densities improves substantially (Figure 3b & d). One of the key differences is that the observed BBS data contains some extreme densities (30–50 Buzzards per 1-km square), which skew the distribution (Figure 3, Figure 4), whereas the modelled densities follow an approximately normal distribution (see Figure 5 in the next section). The results of the mean density models and the maximum density models are relatively similar.

Figure 3. Relationships between observed densities and predicted densities at different scales. a) and b) use the predictions from the maximum density model as the response; c) and d) use the predictions from the mean density model as the response. Separate graphs are shown for the individual 1-km squares (a, c) and for values averaged over all 1-km squares in each 10-km (b, d). The red line shows the 1:1 relationship expected from a perfectly calibrated model.

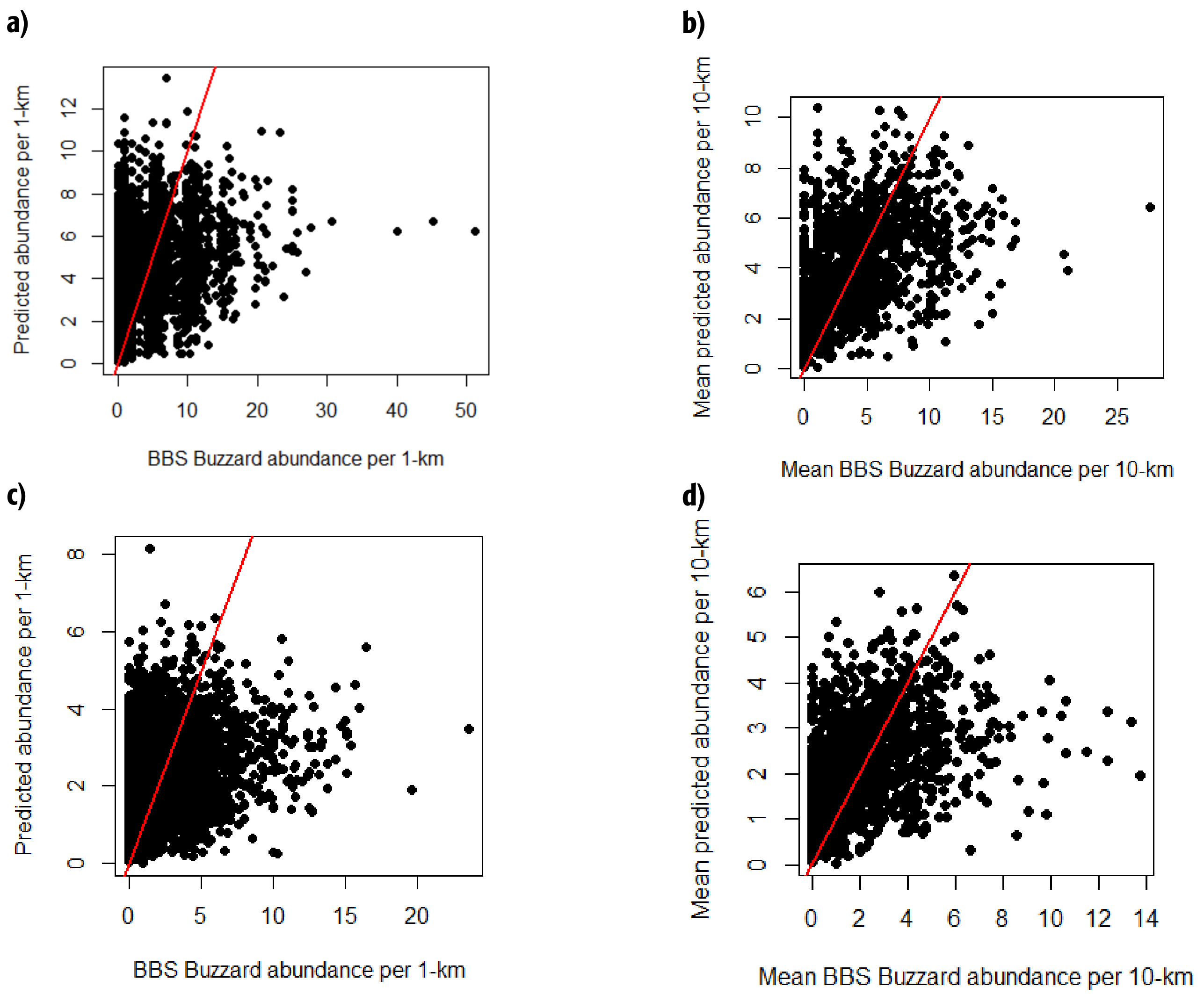
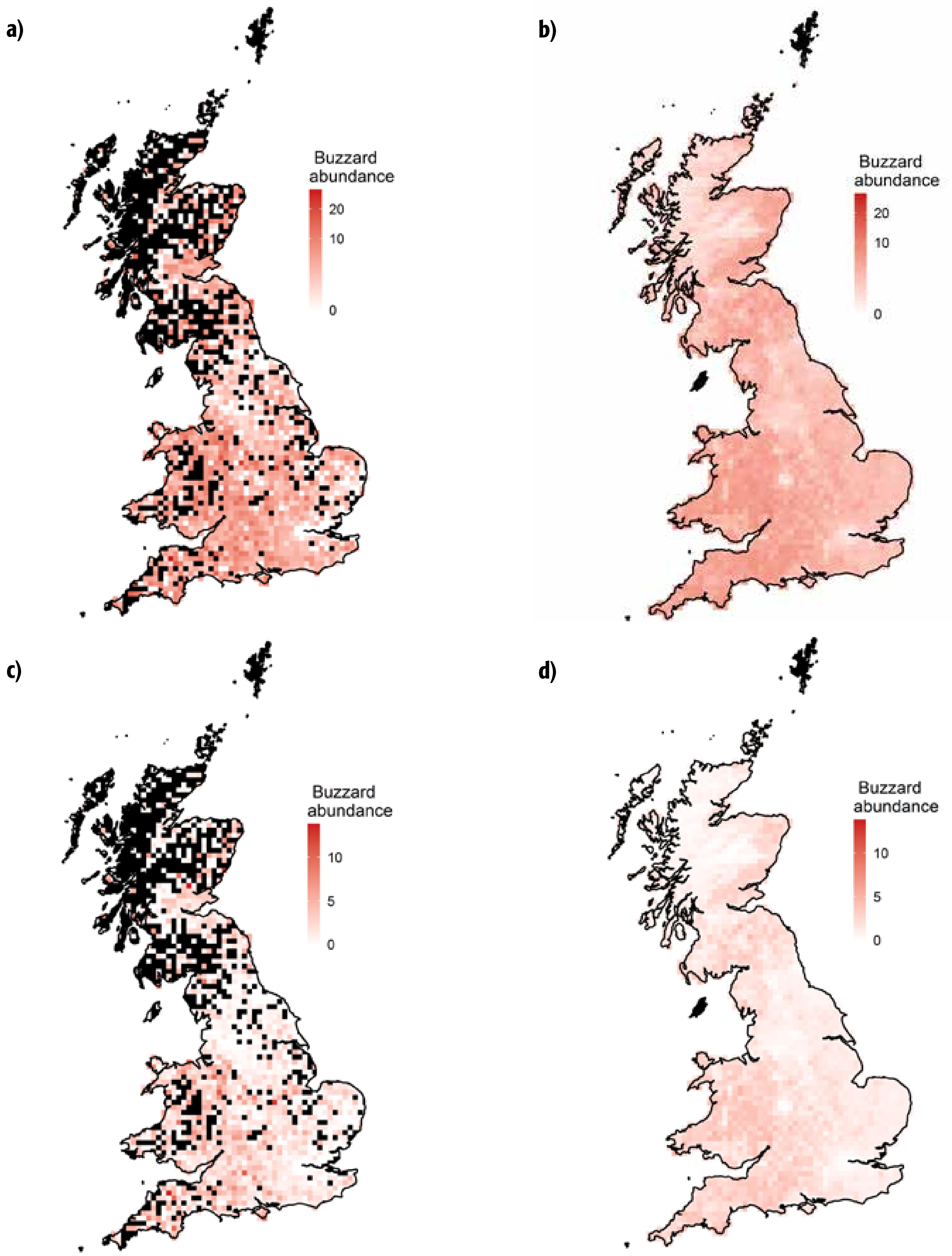


Figure 4. Maps showing a) observed maximum Buzzard density during 2012–16, b) predicted Buzzard density from the maximum density model, c) observed mean Buzzard density during 2012–16 and d) predicted Buzzard density from the mean density model. In a) and c) the observed BBS data were averaged over all 1-km BBS survey squares in each 10-km, in b) and d) the 1-km square predictions were averaged over all 1-km squares in each 10-km square. Black areas had no surveyed BBS squares during the study period or were excluded from modelling due to missing environmental data.

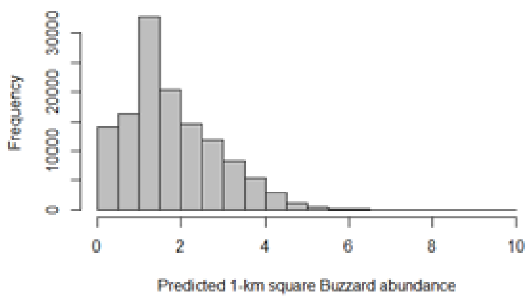


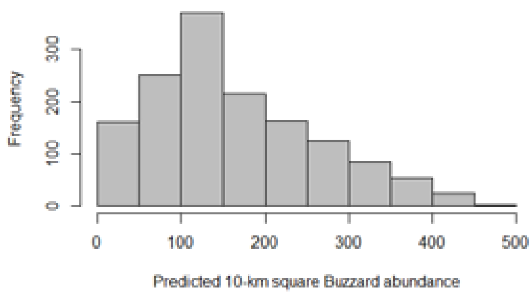
Examination of the density estimates from the maximum density model and mean density model indicated that the mean density model was more biologically realistic. Subsequent analyses use the mean density model results, with results of the maximum density model in Appendix A. Reasons for this decision are given in the Discussion.

3.2.3 Predicted abundance and importance of environmental variables

Predictions for Buzzard abundance in England (based on the mean density model) at the 1-km square level were in the range 0–10; when summed over all 1-km squares within a 10-km square predictions were in the range 0–482 (Figure 5). The predicted Buzzard abundances follow an approximately normal distribution, especially when summed over a 10-km square. Predicted Buzzard abundances for each 10-km square from the maximum density and mean density models are presented in Appendix B. In both cases these are from predictions for 1-km squares summed across all 1-km squares per 10-km.

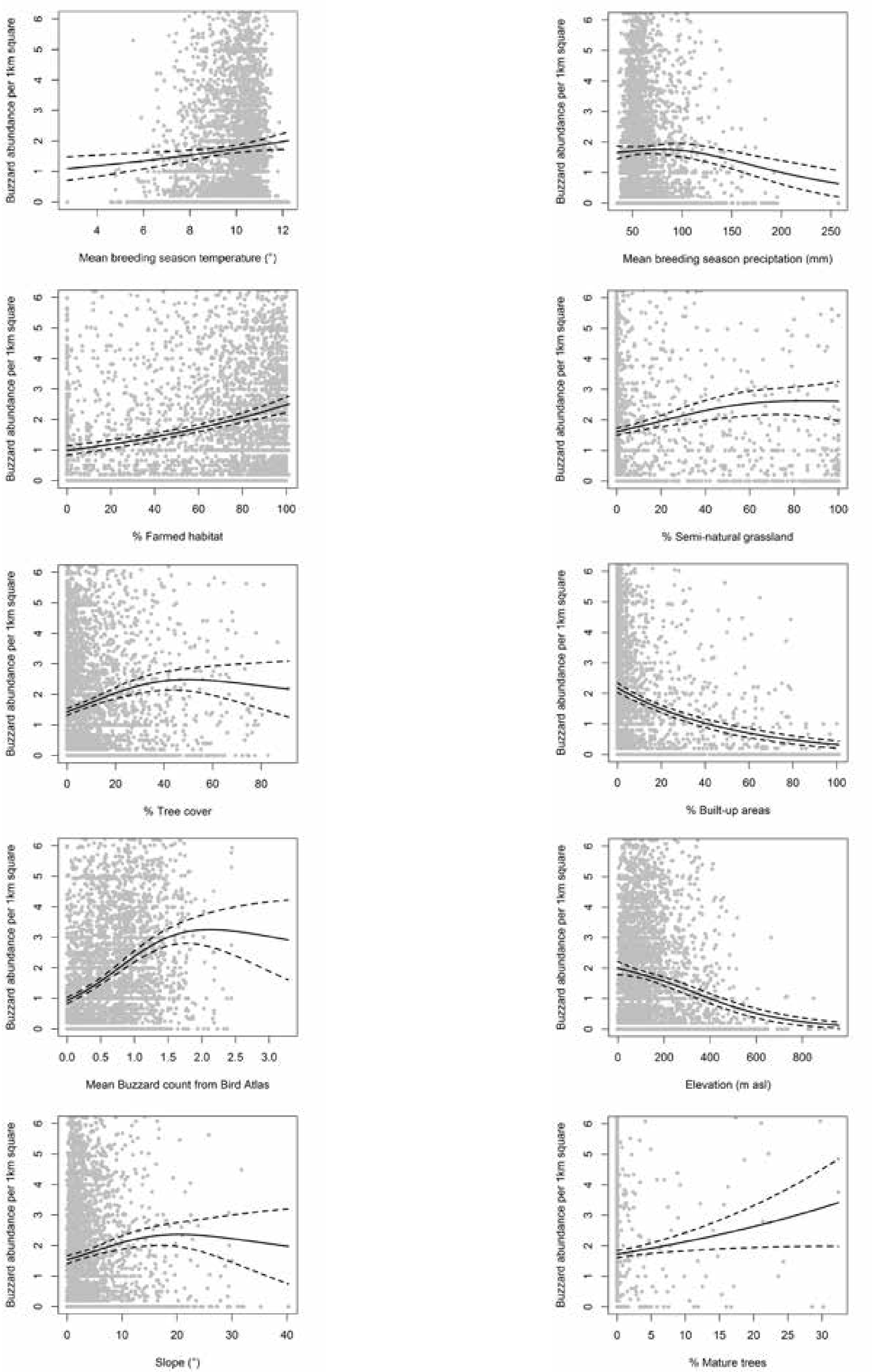
Figure 5. Histograms of a) the predicted abundance of Buzzards in England per 1-km and b) the predicted abundance of Buzzards in England per 10- km (summed 1-km predictions), both from the mean density model.





Plots of the effect of all significant ($P < 0.05$) variables in the model are displayed in Figure 6. Buzzards were more abundant in areas with higher average breeding season temperatures and a higher percentage cover of farmland. High mean breeding season precipitation (above a monthly average of approximately 100 mm) was negatively associated with Buzzard abundance. Tree cover was positively associated with Buzzard abundance up to a point, when 40% of a 1-km square was covered in trees, further increases in tree cover did not correspond with further increases in Buzzards. Increases in the percentage of semi-natural grassland (up to 40%), and in the percentage of mature trees, were linked to small increases in Buzzard abundance. Built-up areas were negatively correlated with Buzzard abundance. There was a quadratic or possibly asymptotic effect of local mean Buzzard count from the Bird Atlas. Buzzards were most abundant at lower elevations and in areas with moderate slopes (as opposed to very flat or very mountainous areas). However, as mentioned earlier, there is a possibility that the parameter estimates for average breeding season temperature, elevation and farmed habitat may be affected by multi-collinearity and therefore these interpretations should be treated with caution. The presence and absence of Goshawks had a marginally significant positive effect on Buzzard abundance. Corvid abundance, Rabbit abundance, Brown Hare abundance and Pheasant abundance, all variables relating to food sources, were not significant ($P > 0.05$) in the model.

Figure 6. The effect of significant variables ($P < 0.05$) in final GAM model of Buzzard abundance. Buzzard abundance is modelled at the 1-km square level using the mean density model. The solid black line is the predicted effect of a variable when all other variables are set to their mean levels, the dotted black lines depict the 95% confidence interval, the grey dots are the raw data.



3.3 Suitability of currently unoccupied range for Buzzards

For the 86 10-km squares where Buzzards are either absent or present with no breeding evidence, Table 4 gives predicted total Buzzard abundances (summed 1-km abundances per 10-km). As mentioned earlier, these predictions were made from our above model but the variable, mean Buzzard count from Bird Atlas, was removed. Thirty-five of the squares do not have predictions for Buzzard abundance because data were missing for one or more of the environmental variables needed to make the prediction, usually due to very little of the square being on land. Based on these predictions, the squares in the east of Britain which are not right on the coast seem the most suitable for Buzzards (e.g. SE,TA, TF grid references). The squares with lower predicted Buzzard abundances often had very little land or were highly urbanized (e.g. TQ38, TQ37, TQ28, TQ48, all in central London). There were also a few squares with apparently high land cover and low predicted Buzzard abundance which were predominantly estuaries or sandbanks (e.g. TQ88, TA31, TA09).

Table 4. A list of all 10-km squares where Buzzards were absent or present without breeding evidence, with the % of the square on land (as determined by LCM 2015, Rowland et al., 2015), and the total abundance of Buzzards predicted to occur in that square from the mean density model (PA). Squares without a prediction represent gaps in the coverage of the environmental variables included in the model, usually due to very little of the square being on land.

10-km	Status	Land	PA	10-km	Status	Land	PA	10-km	Status	Land	PA
NT69	present	0.62	-	SV91	present	13.03	-	TL90	present	89.05	97
NU05	absent	4.74	-	SW65	absent	0.3	-	TQ18	present	100.00	26
NU14	present	15.53	-	SW81	absent	0.28	-	TQ26	present	100.00	40
NX90	present	7.83	9	SX03	present	0.44	-	TQ27	present	100.00	27
NX93	absent	1.42	-	SY07	present	2.47	-	TQ28	present	100.00	20
NZ25	present	100.00	87	SY38	absent	0.07	-	TQ37	present	100.00	19
NZ26	present	100.00	26	SY48	present	2.94	-	TQ38	present	100.00	17
NZ38	present	14.54	0	SY66	present	1.68	-	TQ47	absent	100.00	30
NZ39	absent	1.43	-	SY87	absent	3.25	-	TQ48	present	100.00	22
NZ41	absent	100.00	71	SZ28	absent	0.15	-	TQ78	present	98.16	61
NZ44	present	44.86	30	SZ99	present	9.2	1	TQ80	absent	3.19	-
NZ45	absent	15.54	5	TA02	present	83.31	49	TQ88	present	77.68	21
NZ46	absent	5.69	-	TA09	absent	22.27	15	TQ98	present	72.37	37
NZ52	present	81.18	26	TA14	present	100.00	146	TQ99	present	95.61	184
NZ53	absent	12.57	1	TA18	present	6.00	3	TR01	present	29.96	14
NZ62	present	31.69	20	TA26	absent	5.11	1	TR07	present	11.36	1
NZ72	absent	2.43	-	TA27	present	15.02	11	TR08	absent	24.40	-
NZ90	present	63.29	52	TA31	present	49.79	12	TR09	present	69.85	45
NZ91	absent	3.44	-	TA32	present	67.05	64	TR12	absent	0.93	-
SD16	absent	15.65	0	TA33	absent	5.57	4	TR27	absent	0.31	-
SD36	absent	41.02	-	TA40	present	9.08	-	TR33	absent	0.51	-
SE01	present	100.00	131	TA41	present	13.28	1	TR37	present	10.70	0
SE02	present	100.00	124	TA42	absent	0.12	-	TR46	absent	0.36	-
SE11	present	100.00	100	TF22	present	100.00	134	TR47	absent	0.06	-
SE13	present	100.00	45	TF33	present	100.00	101	TV49	absent	5.46	0
SS14	present	4.34	-	TF34	present	100.00	106	TV69	absent	4.90	0
ST25	absent	32.09	-	TF53	absent	6.49	-				
ST26	present	1.38	-	TF56	present	75.50	66				
SV80	present	3.08	-	TF58	absent	13.77	6				
SV81	present	7.96	-	TG24	present	11.57	5				
SV90	absent	0.47	-	TG51	present	17.45	8				

3.4 Predicting Buzzard saturation densities

The published population trend for Buzzards in England shows a 194% increase during 1995–2015 (Massimino et al. 2017b) but there is substantial variation in regional trends. Figure 7 displays the trends in Buzzard abundance during 1994–2017 for each 100-km square and shows a pattern of long-term stability in the west and ongoing increases in the east. Note that 100-km squares which only contained a very small amount of land or had large numbers of zero counts, preventing trend model convergence, were combined with adjacent squares (TV+TR+TQ; SV+SW; TG+TM; SC+NX). For three 100-km squares, TA, SE and TM, the earlier year counts were zeros across all 1-km squares and this meant the trend model would not converge. Therefore for these squares we truncated the BBS data to remove the years before Buzzards colonized this region (for SE: 1994–2002 were removed, for TA: 1994–2010, for TM: 1994–2002) and fitted the trend for the remainder of the time series.

The red band on the trend graphs is the 95 % confidence interval for the predicted mean Buzzard abundance per 1-km square across the region in question from our SDM. The predictions are averaged for all 1-km squares per 100-km, so theoretically encompass squares predicted to be unoccupied as well as those predicted to be occupied. In contrast, the trend line is based only on BBS squares that reported Buzzards at least once during the time series. Consequently we might not expect the trend line and predictions to coincide. We assessed the effect of this by creating a version of Figure 7 where the density predictions were averaged across only the BBS squares used to derive the trend but results were visually identical (Appendix C).

There is a distinctive regional divide with trends from squares in western Britain tending to reach an asymptote and stay relatively stable or remain stable throughout the entire time period, whereas squares in eastern Britain show a sharp increase in recent years and have yet to reach an asymptote. The predicted Buzzard abundance varies regionally, with the highest abundances predicted in the south-west and the lowest in the east. Generally, the modelled predictions from the maximum density model were higher than the observed trends (Appendix A) whereas those from the mean density model coincided with the observed trend better (Figure 7). In some eastern areas the trajectory of the trend suggests densities could increase beyond our predicted saturation densities based on either model.

From this study, using the mean density model, we predicted mean densities of 161 Buzzards per 10-km square (across the whole of England), and maximum densities of 482 Buzzards per 10-km square. The mean densities predicted by this model are within the range of the recorded densities in the literature, though at the high end (Table 5).

Figure 7. Map showing how population trends (blue line and shading) and modelled saturation densities (red line and shading) vary by 100-km square across England. Trends, which are all plotted to the same x-axis scale (1994–2017) and y-axis scale (0–7 birds km^2) are based on a simple model of annual Buzzard densities in BBS squares with 95% confidence limits shown by blue shading. Saturation densities are from the species distribution model using the mean density across years per square and are averaged over all 1-km squares within the 100-km square.

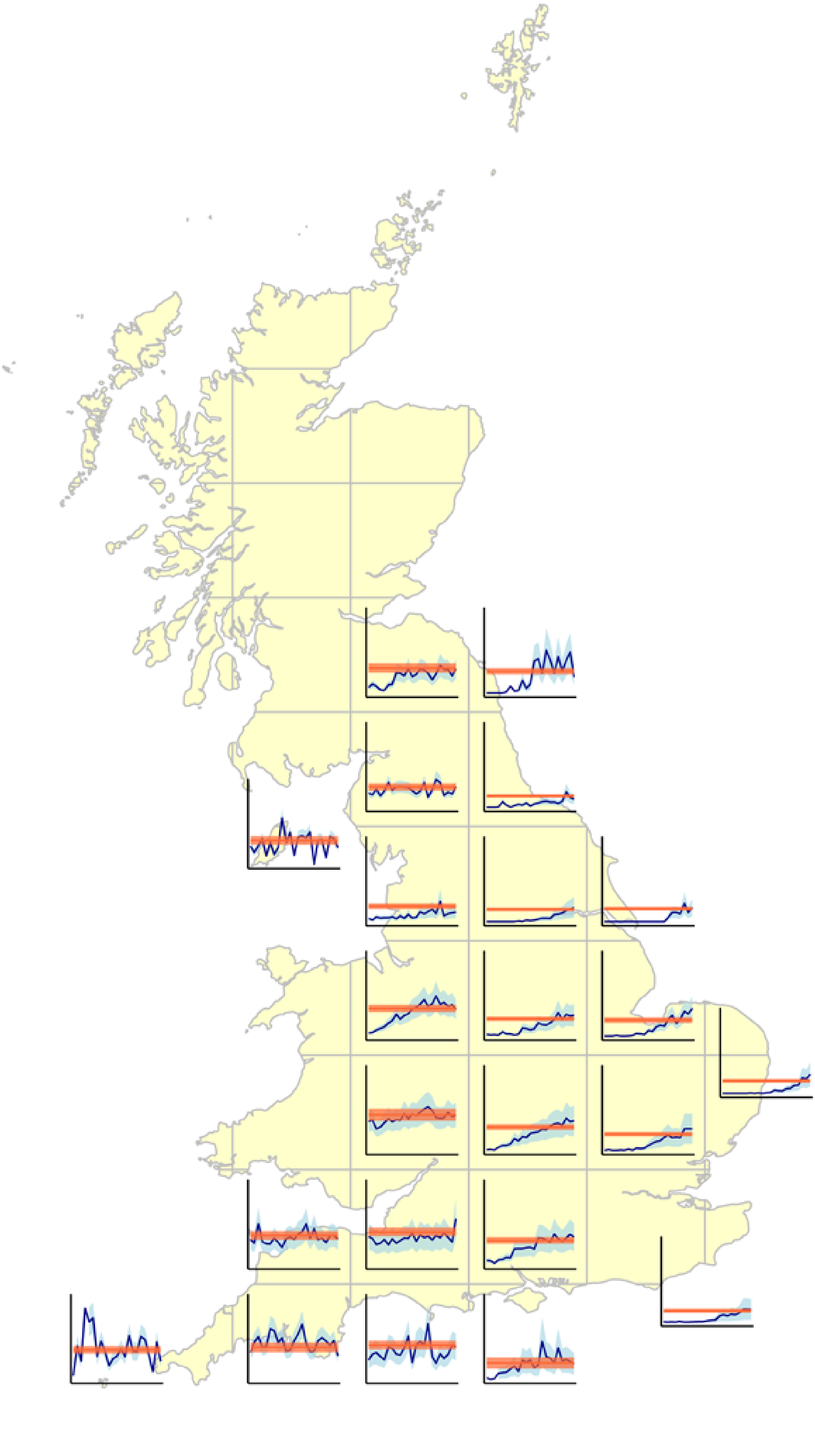


Table 5. Buzzard densities from published population studies. Rows with an asterisk are taken from a review by Clements (2002). Densities were converted into individuals per 10-km square, applying a factor of 2 to densities reported in pairs.

Region	Study period	Density per 10-km square	Study
West Midlands(SO37/SO77)	1994–96	44 and 162	Sim et al., 2001
Whole of Britain	2001	0–120	Clements, 2002
North Somerset (75 km^2)	2001	222	*Prytherch, 1997/verbally
Bath & North Somerset (60 km^2)	2001	156	*J. Holmes (verbally) (Clements, 2002)
Dorset (120km^2)	1996	197–200	*Kenward et al., 2000
Postbridge, Devon (33 km^2)	1990–93	96–102	*Dare, 1998
Devon (2,620 km^2)	1983	50–66	*Sitters, 1988
Cambrian Mountains (475 km^2) farmland	1975–79	82	*Newton et al., 1982
Cambrian Mountains (475 km^2) upland	1975–79	48	*Newton et al., 1982
Snowdonia (926 km^2)	1977–84	11.9–66.7	Dare & Barry, 1990
Migneint-Hiraethog (440 km^2)	1977–84	28.1–59.7	Dare & Barry, 1990
Snowdonia (926 km^2)	1977–84	20–22	*Dare, 1995
Snowdonia (926 km^2)	2000	28–30	*Dare, 1995
Denbigh, Clwyd (440 km^2)	1977–84	28	*Dare, 1995
Upper Strathspey (94 km^2)	1971	28–30	*Halley, 1993
Upper Strathspey (94 km^2)	1988–89	46–48	*Halley, 1993
Whole of Britain	1983	4.5–36	Taylor et al., 1988
Whole of Britain	1954	For mean densities: an average of 11, maximum of 47.9, for maximum densities: average of 116	Moore, 1957
North Eastern Romania	2010–11	33.4–53.9	Baltag et al., 2013
Bulgaria	2006	34	Nikolvo et al., 2006
Poland	1993–2000	70–212	Wuczynski, 2003

4. DISCUSSION

Buzzards are currently breeding or likely to be breeding across the vast majority of 10-km squares in the UK. Unoccupied squares are mainly restricted to coastal areas or city centres where the habitat is unsuitable. However, our model did predict potential high Buzzard abundances for some squares in the east. This suggests that Buzzards are still expanding their range eastward. Our trend plots confirm this conclusion; trends in the east show no sign of plateauing yet. However, eastern population densities are currently still lower than western densities which stabilised prior to the onset of the BBS time series.

We extracted two metrics to summarise BBS data across years – the mean density per square and the maximum density per square. Models using these metrics performed equally well in a statistical sense but we judged the maximum density model to overestimate densities in currently stable areas and to exceed published estimates to a biologically unrealistic degree (Appendix A Figure 1). As evident from the yearly trends here and our comparison of Buzzard counts between two 5-year periods, Buzzard densities may show substantial fluctuation from year to year. It is likely the maximum density model predictions are generally higher than the local trend because the SDM was trained on the maximum density in each square over a 5-year period whereas the trend production essentially generates an average density per square. For bird species with home ranges less than 1-km square, selecting the maximum count would compensate for failures in detection. However, Buzzards have a large range size (on average 180–190 ha, Sim et al., 2001). There may be several 1-km squares on the edge of a Buzzard's range and it is impossible to predict which one the Buzzard may be occupying when the survey is undertaken. Selecting the maximum density of Buzzards over a 5 year period predisposes the selection towards extreme outlier counts (Figures 3 & 4) which may be the result of Buzzards passing through a square, or due to territorial disputes at territory boundaries, and are unlikely to reflect true breeding densities.

Our modelled results matched actual Buzzard abundances recorded from BBS (during 2012–16) reasonably well, especially when averaged over each 10-km square. There was a tendency for high outlier densities from the BBS survey data (Figure 3). These densities could be inflated by Buzzards passing through a square, or due to territorial disputes at territory boundaries so may not reflect true breeding densities. Further information on territory sizes would help in understanding any likely errors here. Compared to the literature our density estimates were at the high end of recorded ranges. However, the densities estimates from the literature for Britain are all at least 17 years old. Although many come from western areas which may have been stable over this period, those applying to the whole of Britain are likely to be out dated. But they can at the least give us confidence that the modelled predictions are not too low. A potential issue with our SDM is the predicted counts for eastern England. Buzzards are still colonising and expanding in this area so while our model accurately represents current densities it is likely to underestimate future densities. One option to deal with this is to train models using data from stable areas but for this to work they would need to mirror conditions in the east in all ways except for the pattern of colonisation history. In reality, it is unlikely that many areas of comparable low-lying arable land exist in western Britain for training a model to make predictions in eastern England.

In terms of relevant habitat characteristics to consider when attempting to match squares in the west and east, our model here suggests important variables are tree cover, farmed area, urban area, climate and topography. The variables included in the model to represent prey sources were not significant. Findings from other studies (Austin & Houston, 1997; Rooney & Montgomery, 2013) indicate that Buzzards are opportunist and will prey on whatever is available, from Rabbits, invertebrates and amphibians to other birds and carrion. Therefore, it is perhaps not so surprising that we failed to find a strong relationship between Buzzard abundance and individual food sources, as favoured food sources may vary substantially depending on what is locally available. Some of the variables likely to influence Buzzard abundance according to our literature review could not be included in models owing to a lack of suitable spatially referenced data. The most notable omission is human disturbance (Krüger, 2004). Therefore the amount of human disturbance in an area should also be considered in relation to our density estimates. The other variables we could not acquire data for were for prey items and as discussed above, this varies too widely from region to region to be a good predictor of Buzzard densities on a national scale so is unlikely to have affected conclusions.

The trends and density predictions produced here relate to numbers of birds in the breeding season. Counts in the breeding season may comprise a combination of breeding and non-breeding individuals but the data do not allow us to differentiate. Densities post breeding could be substantially higher once birds of the year have fledged. Densities may also vary spatially as birds disperse from breeding territories and potentially shift to habitats providing food in winter. Therefore the densities discussed here may bear little relationship to densities observed outside the breeding season.

4.1 Recommendations

We can be confident that the breeding range of the Buzzard has almost fully extended to all suitable 10-km squares, with only a few unoccupied squares capable of sustaining significant new populations. The species distribution models developed here are as good as we can currently hope to produce, being based on a large sample of high quality bird data and most of the key environmental variables. In a statistical sense, the models have reasonable predictive performance but predictions are high compared to published densities. We recommend using the predictions based on the mean density model to avoid over-estimating Buzzard abundance. However, the match between predictions and population trends varies regionally and it is likely predicted densities for eastern regions, where the Buzzard population is still increasing, are underestimates. Further modelling, using information from areas of stability, could help to inform use of densities in areas where populations are still increasing. Ultimately, the most robust estimates of density will likely come from mechanistic models that incorporate vital demographic rates, including productivity, survival, dispersal and density dependence.

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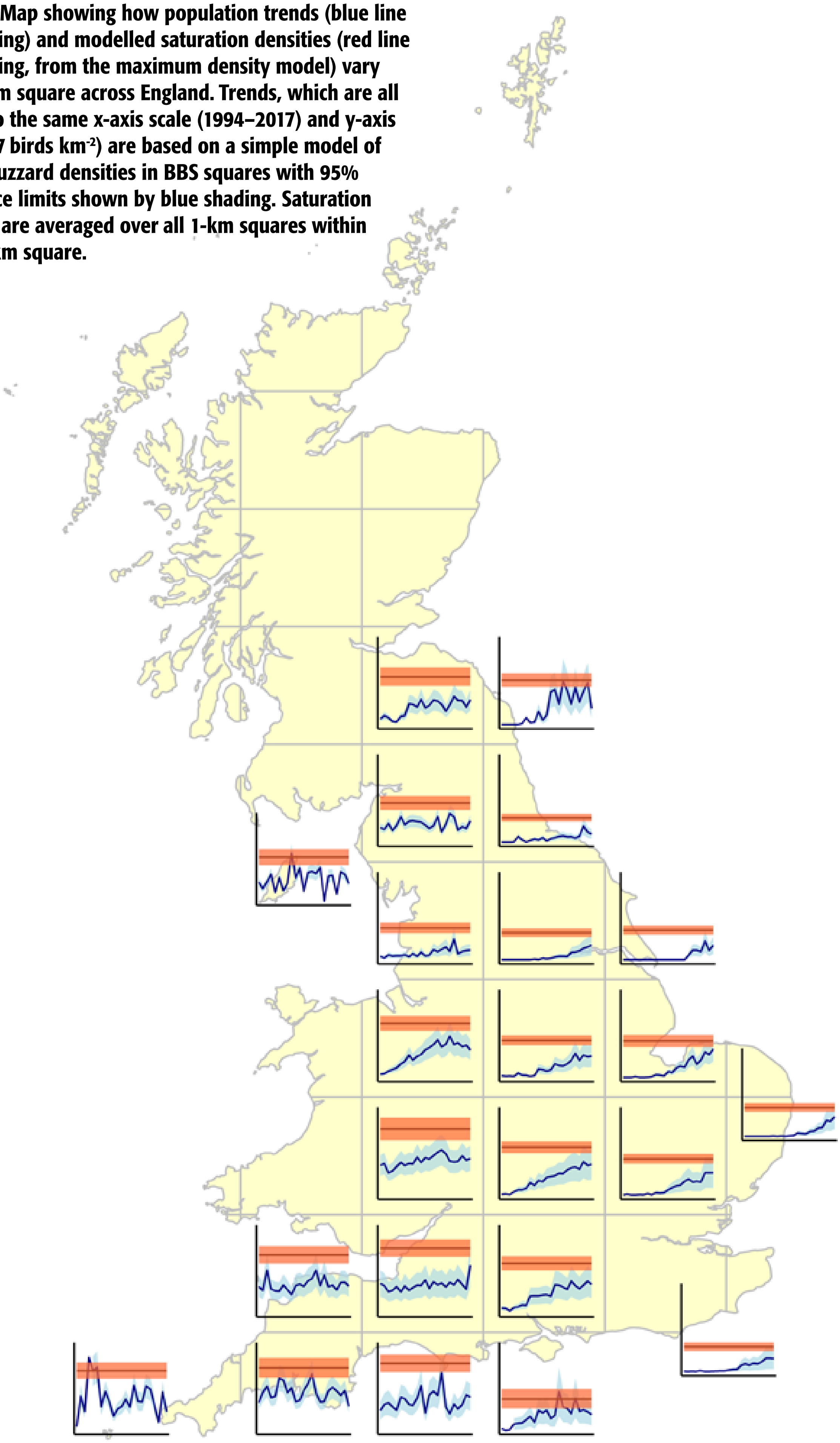
APPENDIX A

Table 1. A list of all 10-km squares where Buzzards were absent or present without breeding evidence, with the % of the square on land (as determined by LCM 2015, Rowland et al., 2017), and the total abundance of Buzzards predicted to occur in that square based on the maximum density model (PA). Squares without a prediction represent gaps in the coverage of the environmental variables included in the model, usually due to very little of the square being on land.

10-km	Status	Land	PA
NT69	present	0.62	-
NU05	absent	4.74	-
NU14	present	15.53	-
NX90	present	7.83	17
NX93	absent	1.42	-
NZ25	present	100.00	189
NZ26	present	100.00	67
NZ38	present	14.54	1
NZ39	absent	1.43	-
NZ41	absent	100.00	164
NZ44	present	44.86	68
NZ45	absent	15.54	10
NZ46	absent	5.69	-
NZ52	present	81.18	65
NZ53	absent	12.57	3
NZ62	present	31.69	47
NZ72	absent	2.43	-
NZ90	present	63.29	108
NZ91	absent	3.44	-
SD16	absent	15.65	0
SD36	absent	41.02	-
SE01	present	100.00	258
SE02	present	100.00	246
SE11	present	100.00	213
SE13	present	100.00	107
SS14	present	4.34	-
ST25	absent	32.09	-
ST26	present	1.38	-
SV80	present	3.08	-
SV81	present	7.96	-
SV90	absent	0.47	-
SV91	present	13.03	-
SW65	absent	0.30	-
SW81	absent	0.28	-
SX03	present	0.44	-
SY07	present	2.47	-
SY38	absent	0.07	-
SY48	present	2.94	-
SY66	present	1.68	-
SY87	absent	3.25	-
SZ28	absent	0.15	-
SZ99	present	9.20	3
TA02	present	83.31	118
TA09	absent	22.27	35
TA14	present	100.00	321
TA18	present	6.00	7
TA26	absent	5.11	2
TA27	present	15.02	25
TA31	present	49.79	30
TA32	present	67.05	150
TA33	absent	5.57	8
TA40	present	9.08	-
TA41	present	13.28	2
TA42	absent	0.12	-
TF22	present	100.00	301
TF33	present	100.00	234
TF34	present	100.00	255
TF53	absent	6.49	-
TF56	present	75.50	161
TF58	absent	13.77	15
TG24	present	11.57	13
TG51	present	17.45	19
TL90	present	89.05	207
TQ18	present	100.00	70
TQ26	present	100.00	97
TQ27	present	100.00	70
TQ28	present	100.00	53
TQ37	present	100.00	51
TQ38	present	100.00	46
TQ47	absent	100.00	79
TQ48	present	100.00	62
TQ78	present	98.16	130
TQ80	absent	3.19	-
TQ88	present	77.68	54
TQ98	present	72.37	83
TQ99	present	95.61	353
TR01	present	29.96	31
TR07	present	11.36	1
TR08	absent	24.40	-
TR09	present	69.85	87
TR12	absent	0.93	-
TR27	absent	0.31	-
TR33	absent	0.51	-
TR37	present	10.70	1
TR46	absent	0.36	-
TR47	absent	0.06	-
TV49	absent	5.46	1
TV69	absent	4.90	1

Figure 1. Map showing how population trends (blue line and shading) and modelled saturation densities (red line and shading, from the maximum density model) vary by 100-km square across England. Trends, which are all plotted to the same x-axis scale (1994–2017) and y-axis scale (0–7 birds km^{-2}) are based on a simple model of annual Buzzard densities in BBS squares with 95% confidence limits shown by blue shading. Saturation densities are averaged over all 1-km squares within the 100-km square.



APPENDIX B

Table 1. Spreadsheet with predicted number of Buzzards per 10-km square in England from the maximum density model (A) and the mean density model (B).

10-km	A	B
NT60	179	86
NT70	369	191
NT71	563	305
NT73	348	172
NT80	487	268
NT81	329	166
NT82	631	337
NT83	598	328
NT84	442	227
NT90	374	192
NT91	317	166
NT92	365	190
NT93	533	274
NT94	507	263
NT95	292	145
NU00	249	121
NU01	464	239
NU02	360	182
NU03	517	262
NU04	170	84
NU10	333	162
NU11	424	220
NU12	394	198
NU13	184	87
NU20	167	79
NU21	176	87
NU22	108	51
NU23	9	4
NX90	9	4
NX91	84	38
NX92	25	11
NY00	307	157
NY01	299	156
NY02	569	306
NY03	212	102
NY04	48	23
NY10	251	160
NY11	170	110
NY12	357	200
NY13	342	172
NY14	393	193
NY15	120	56
NY16	169	85
NY20	106	83
NY21	150	104
NY22	231	129
NY23	347	184
NY24	400	203
NY25	312	149
NY26	209	103
NY30	273	171
NY31	180	121
NY32	356	201
NY33	315	166
NY34	351	174
NY35	290	134
NY36	232	110
NY37	532	292
NY40	315	193
NY41	238	145
NY42	447	242
NY43	365	186
NY44	353	178
NY45	451	220
NY46	587	311
NY47	498	258
NY48	438	241
NY50	410	237
NY51	443	250
NY52	382	191
NY53	433	227
NY54	279	137
NY55	464	244
NY56	487	255
NY57	480	258
NY58	228	113
NY59	411	220
NY60	363	199
NY61	376	194
NY62	530	287
NY63	250	128
NY64	156	76
NY65	234	118
NY66	372	189
NY67	289	143
NY68	155	75
NY69	217	110
NY70	330	169
NY71	323	163
NY72	155	79
NY73	48	20
NY74	161	74
NY75	197	91
NY76	303	150
NY77	273	135
NY78	318	164
NY79	258	132
NY80	93	43
NY81	166	81
NY82	69	31
NY83	107	47
NY84	90	40
NY85	168	79
NY86	444	226
NY87	304	153
NY88	327	177
NY89	536	286
NY90	81	38
NY91	123	58
NY92	211	102
NY93	150	72
NY94	178	83
NY95	195	93
NY96	253	124
NY97	381	193
NY98	411	218
NY99	413	220
NZ00	353	179
NZ01	212	102
NZ02	193	93
NZ03	181	87
NZ04	138	66
NZ05	220	104
NZ06	321	155
NZ07	288	146
NZ08	229	112
NZ09	362	185
NZ10	433	224
NZ11	297	146
NZ12	213	103
NZ13	198	94
NZ14	189	91
NZ15	144	64
NZ16	169	77
NZ17	402	196
NZ18	276	134
NZ19	323	158
NZ20	223	104
NZ21	218	103
NZ22	166	77
NZ23	183	84
NZ24	175	78
NZ25	129	56
NZ26	45	18
NZ27	179	81
NZ28	183	82
NZ29	227	108
NZ30	255	121
NZ31	226	105
NZ32	218	103
NZ33	193	90
NZ34	185	86
NZ35	97	41
NZ36	65	27
NZ37	50	21
NZ38	1	1
NZ40	231	110
NZ41	124	53
NZ42	171	77
NZ43	160	73
NZ44	48	20
NZ45	7	3
NZ50	172	81
NZ51	144	63
NZ52	52	20
NZ53	3	1
NZ60	107	51
NZ61	141	64
NZ62	34	14
NZ70	164	81
NZ71	138	64
NZ80	198	92
NZ81	59	26
NZ90	85	40
SD08	17	8
SD09	60	29
SD16	0	0
SD17	7	3
SD18	431	246
SD19	411	235
SD20	10	4
SD26	23	11
SD27	282	133
SD28	560	308
SD29	524	362
SD30	326	151
SD31	277	132
SD32	60	27
SD33	200	93
SD34	101	45
SD37	78	36
SD38	397	209
SD39	200	108
SD40	256	122
SD41	491	238
SD42	284	127
SD43	349	162
SD44	437	210
SD45	178	82
SD46	118	53
SD47	115	55
SD48	295	144
SD49	360	180
SD50	188	83
SD51	287	129
SD52	162	67
SD53	243	110
SD54	269	125
SD55	224	110
SD56	431	213
SD57	663	370
SD58	422	211
SD59	344	173
SD60	168	71
SD61	169	79
SD62	164	74
SD63	231	107
SD64	240	116
SD65	184	96
SD66	334	168
SD67	328	164
SD68	397	213
SD69	404	227
SD70	102	41
SD71	150	71
SD72	156	71
SD73	207	96
SD74	232	111
SD75	236	116
SD76	259	129
SD77	248	132
SD78	195	104
SD79	222	117
SD80	84	34
SD81	123	57

10-km	A	B
SD82	174	83
SD83	151	71
SD84	223	107
SD85	360	181
SD86	212	107
SD87	197	101
SD88	228	120
SD89	151	74
SD90	99	43
SD91	120	56
SD92	139	67
SD93	115	54
SD94	206	97
SD95	252	122
SD96	265	137
SD97	210	108
SD98	205	101
SD99	176	85
SE00	88	42
SE01	136	63
SE02	133	61
SE03	135	60
SE04	158	73
SE05	221	108
SE06	144	69
SE07	98	46
SE08	233	116
SE09	204	100
SE10	173	82
SE11	119	51
SE12	128	53
SE13	67	27
SE14	153	70
SE15	178	87
SE16	148	71
SE17	155	75
SE18	202	95
SE19	287	142
SE20	202	95
SE21	185	85
SE22	94	38
SE23	90	38
SE24	233	110
SE25	235	113
SE26	252	121
SE27	275	134
SE28	215	101

10-km	A	B
SE29	232	110
SE30	138	58
SE31	200	89
SE32	131	55
SE33	104	46
SE34	269	139
SE35	253	119
SE36	460	224
SE37	304	145
SE38	230	109
SE39	228	110
SE40	183	81
SE41	203	90
SE42	151	64
SE43	296	141
SE44	259	120
SE45	302	147
SE46	272	129
SE47	261	125
SE48	208	98
SE49	202	95
SE50	202	90
SE51	308	143
SE52	236	105
SE53	255	117
SE54	261	123
SE55	204	94
SE56	266	126
SE57	224	104
SE58	178	85
SE59	137	67
SE60	265	118
SE61	271	122
SE62	314	144
SE63	233	106
SE64	300	137
SE65	181	79
SE66	258	120
SE67	285	139
SE68	246	117
SE69	143	69
SE70	269	124
SE71	223	104
SE72	216	98
SE73	246	119
SE74	247	118
SE75	261	123

10-km	A	B
SE76	320	154
SE77	248	118
SE78	228	109
SE79	144	69
SE80	477	225
SE81	219	98
SE82	202	91
SE83	293	134
SE84	281	126
SE85	399	194
SE86	320	151
SE87	322	154
SE88	206	96
SE89	143	68
SE90	257	118
SE91	311	152
SE92	138	61
SE93	327	155
SE94	305	142
SE95	264	120
SE96	343	167
SE97	256	120
SE98	282	109
SE99	162	77
SJ18	41	20
SJ20	510	268
SJ21	629	340
SJ22	628	350
SJ23	471	250
SJ27	92	43
SJ28	116	50
SJ29	9	3
SJ30	533	284
SJ31	600	323
SJ32	632	342
SJ33	517	266
SJ34	387	187
SJ35	530	271
SJ36	361	169
SJ37	469	232
SJ38	65	28
SJ39	34	13
SJ40	601	343
SJ41	466	241
SJ42	486	252
SJ43	466	239
SJ44	640	341

10-km	A	B
SJ45	513	261
SJ46	415	199
SJ47	456	241
SJ48	161	71
SJ49	317	152
SJ50	644	363
SJ51	516	267
SJ52	575	308
SJ53	522	273
SJ54	640	364
SJ55	634	347
SJ56	543	274
SJ57	569	296
SJ58	158	69
SJ59	242	108
SJ60	425	222
SJ61	519	291
SJ62	593	316
SJ63	595	323
SJ64	622	334
SJ65	511	260
SJ66	573	297
SJ67	467	223
SJ68	385	184
SJ69	408	193
SJ70	460	237
SJ71	550	331
SJ72	622	338
SJ73	505	270
SJ74	424	211
SJ75	519	263
SJ76	398	189
SJ77	560	278
SJ78	485	238
SJ79	204	93
SJ80	444	226
SJ81	524	284
SJ82	580	302
SJ83	564	302
SJ84	113	50
SJ85	221	100
SJ86	513	263
SJ87	512	253
SJ88	134	57
SJ89	41	17
SJ90	289	141
SJ91	392	196

10-km	A	B
SJ92	323	153
SJ93	325	161
SJ94	158	73
SJ95	314	152
SJ96	335	169
SJ97	248	123
SJ98	215	100
SJ99	104	44
SK00	199	92
SK01	262	123
SK02	426	212
SK03	505	259
SK04	282	137
SK05	338	170
SK06	231	112
SK07	248	122
SK08	218	104
SK09	126	59
SK10	382	190
SK11	300	143
SK12	420	209
SK13	642	353
SK14	449	225
SK15	304	154
SK16	273	136
SK17	263	132
SK18	229	114
SK19	138	65
SK20	303	144
SK21	467	237
SK22	255	116
SK23	511	253
SK24	400	195
SK25	253	121
SK26	306	141
SK27	338	168
SK28	197	93
SK29	139	65
SK30	507	263
SK31	441	223
SK32	363	171
SK33	115	49
SK34	399	190
SK35	385	182
SK36	265	126
SK37	146	64
SK38	64	27

APPENDIX B (CONT)

Table 1. (continued). Spreadsheet with predicted number of Buzzards per 10-km square in England from the maximum density model (A) and the mean density model (B).

10-km	A	B
SK39	133	58
SK40	384	187
SK41	265	124
SK42	418	198
SK43	216	98
SK44	193	85
SK45	176	77
SK46	217	98
SK47	195	86
SK48	158	68
SK49	137	59
SK50	168	74
SK51	287	131
SK52	339	157
SK53	254	117
SK54	92	40
SK55	242	111
SK56	200	91
SK57	493	262
SK58	288	137
SK59	253	115
SK60	198	93
SK61	378	179
SK62	296	141
SK63	259	119
SK64	287	130
SK65	354	171
SK66	476	233
SK67	437	208
SK68	469	226
SK69	319	145
SK70	374	188
SK71	261	125
SK72	324	156
SK73	328	154
SK74	423	202
SK75	363	168
SK76	370	173
SK77	341	159
SK78	351	165
SK79	354	165
SK80	254	121
SK81	420	205
SK82	357	172
SK83	294	134
SK84	505	244
SK85	294	136

10-km	A	B
SK86	343	157
SK87	305	140
SK88	284	130
SK89	283	132
SK90	383	184
SK91	389	189
SK92	446	220
SK93	459	228
SK94	446	216
SK95	380	177
SK96	293	131
SK97	203	101
SK98	269	122
SK99	304	139
SO17	592	377
SO18	530	364
SO22	355	195
SO23	442	232
SO24	674	397
SO25	594	340
SO26	556	393
SO27	417	340
SO28	671	417
SO29	666	414
SO32	609	335
SO33	703	394
SO34	517	273
SO35	636	365
SO36	666	396
SO37	705	408
SO38	667	409
SO39	676	383
SO41	675	360
SO42	670	399
SO43	617	332
SO44	578	308
SO45	638	378
SO46	736	414
SO47	685	402
SO48	683	384
SO49	456	249
SO50	411	214
SO51	429	215
SO52	720	409
SO53	517	267
SO54	752	433
SO55	570	312

10-km	A	B
SO56	601	322
SO57	580	311
SO58	595	332
SO59	527	292
SO60	300	142
SO61	302	153
SO62	739	401
SO63	784	417
SO64	730	385
SO65	640	364
SO66	611	327
SO67	618	346
SO68	568	315
SO69	510	272
SO70	575	307
SO71	760	394
SO72	855	482
SO73	692	403
SO74	512	260
SO75	686	365
SO76	648	365
SO77	520	268
SO78	558	298
SO79	603	337
SO80	390	189
SO81	360	176
SO82	602	300
SO83	489	240
SO84	740	404
SO85	429	204
SO86	603	316
SO87	276	129
SO88	354	176
SO89	384	192
SO90	465	249
SO91	496	261
SO92	376	185
SO93	605	310
SO94	580	294
SO95	442	218
SO96	508	249
SO97	317	153
SO98	82	36
SO99	39	16
SP00	566	310
SP01	489	256
SP02	537	290

10-km	A	B
SP03	523	267
SP04	385	181
SP05	498	247
SP06	376	183
SP07	191	89
SP08	32	13
SP09	97	43
SP10	602	336
SP11	556	299
SP12	462	241
SP13	580	300
SP14	684	390
SP15	413	204
SP16	513	258
SP17	367	182
SP18	64	27
SP19	166	79
SP20	434	217
SP21	506	252
SP22	387	190
SP23	553	281
SP24	490	243
SP25	659	372
SP26	402	195
SP27	415	206
SP28	529	269
SP29	432	213
SP30	564	293
SP31	273	128
SP32	417	213
SP33	441	223
SP34	541	278
SP35	464	233
SP36	433	215
SP37	267	127
SP38	244	112
SP39	395	196
SP40	421	206
SP41	344	166
SP42	586	308
SP43	541	276
SP44	355	177
SP45	528	272
SP46	425	207
SP47	272	130
SP48	402	198
SP49	329	157

10-km	A	B
SP50	217	97
SP51	550	281
SP52	450	232
SP53	502	263
SP54	510	263
SP55	373	183
SP56	414	207
SP57	262	121
SP58	584	325
SP59	267	125
SP60	518	257
SP61	449	218
SP62	406	223
SP63	416	210
SP64	271	130
SP65	433	213
SP66	559	285
SP67	415	210
SP68	294	142
SP69	332	159
SP70	332	160
SP71	414	203
SP72	349	172
SP73	476	239
SP74	457	226
SP75	345	164
SP76	218	100
SP77	482	239
SP78	274	133
SP79	373	181
SP80	231	108
SP81	287	136
SP82	453	221
SP83	148	66
SP84	389	190
SP85	555	292
SP86	357	171
SP87	303	142
SP88	236	110
SP89	327	156
SP90	284	133
SP91	401	197
SP92	341	162
SP93	362	174
SP94	509	255
SP95	443	215
SP96	282	129

10-km	A	B	10-km	A	B	10-km	A	B	10-km	A	B	10-km	A	B
SP97	269	123	ST13	628	356	ST73	385	199	SU20	307	153	SU67	255	119
SP98	293	140	ST14	261	161	ST74	398	200	SU21	255	123	SU68	334	162
SP99	461	234	ST16	20	9	ST75	583	301	SU22	471	228	SU69	438	221
SS20	481	240	ST20	517	270	ST76	452	225	SU23	705	395	SU70	134	59
SS21	316	158	ST21	558	304	ST77	644	355	SU24	626	332	SU71	511	257
SS22	202	101	ST22	569	291	ST78	357	177	SU25	546	289	SU72	358	171
SS30	508	263	ST23	665	357	ST79	499	251	SU26	436	228	SU73	357	173
SS31	437	226	ST24	196	97	ST80	554	296	SU27	558	363	SU74	407	205
SS32	130	64	ST30	586	301	ST81	571	303	SU28	637	363	SU75	306	144
SS40	423	213	ST31	717	383	ST82	522	274	SU29	393	197	SU76	384	183
SS41	464	235	ST32	735	383	ST83	640	350	SU30	236	110	SU77	209	92
SS42	549	278	ST33	729	383	ST84	390	196	SU31	248	111	SU78	431	213
SS43	129	61	ST34	620	321	ST85	447	220	SU32	500	247	SU79	457	230
SS44	111	55	ST35	449	221	ST86	606	322	SU33	416	206	SU80	350	177
SS50	643	340	ST36	136	63	ST87	489	252	SU34	339	160	SU81	393	190
SS51	388	186	ST40	718	408	ST88	480	247	SU35	619	333	SU82	256	117
SS52	476	236	ST41	746	400	ST89	594	316	SU36	462	234	SU83	153	69
SS53	578	303	ST42	683	357	ST90	720	398	SU37	552	308	SU84	177	79
SS54	353	183	ST43	695	368	ST91	659	359	SU38	523	275	SU85	82	35
SS60	509	263	ST44	686	362	ST92	621	336	SU39	478	239	SU86	95	41
SS61	568	297	ST45	477	244	ST93	573	304	SU40	139	60	SU87	403	189
SS62	573	290	ST46	498	247	ST94	742	427	SU41	107	44	SU88	370	172
SS63	584	321	ST47	268	138	ST95	667	364	SU42	333	155	SU89	299	139
SS64	421	235	ST48	213	104	ST96	388	191	SU43	552	281	SU90	373	172
SS70	477	245	ST50	516	273	ST97	361	178	SU44	437	215	SU91	388	196
SS71	576	377	ST51	466	237	ST98	618	322	SU45	639	348	SU92	369	179
SS72	655	362	ST52	705	375	ST99	423	216	SU46	287	134	SU93	294	142
SS73	451	242	ST53	552	283	SU00	492	251	SU47	506	276	SU94	233	106
SS74	421	232	ST54	552	284	SU01	554	281	SU48	547	289	SU95	138	60
SS80	645	347	ST55	436	227	SU02	718	419	SU49	357	173	SU96	163	69
SS81	478	251	ST56	489	252	SU03	656	356	SU50	122	52	SU97	239	105
SS82	417	217	ST57	145	65	SU04	699	393	SU51	451	215	SU98	251	113
SS83	490	256	ST58	273	133	SU05	608	341	SU52	534	274	SU99	227	106
SS84	266	136	ST59	338	170	SU06	480	250	SU53	514	257	SW32	156	81
SS90	756	422	ST60	611	327	SU07	463	240	SU54	429	215	SW33	81	41
SS91	583	311	ST61	610	327	SU08	380	190	SU55	619	338	SW42	185	91
SS92	501	262	ST62	676	373	SU09	493	252	SU56	397	193	SW43	448	245
SS93	537	296	ST63	730	425	SU10	313	145	SU57	560	298	SW52	34	16
SS94	357	194	ST64	573	320	SU11	426	209	SU58	582	309	SW53	541	295
ST00	562	289	ST65	543	284	SU12	539	269	SU59	348	165	SW54	18	8
ST01	659	360	ST66	471	232	SU13	629	355	SU60	103	45	SW61	34	16
ST02	560	296	ST67	157	69	SU14	597	325	SU61	448	219	SW62	390	201
ST03	573	310	ST68	512	258	SU15	611	329	SU62	480	238	SW63	463	231
ST04	177	89	ST69	523	266	SU16	529	279	SU63	410	206	SW64	166	77
ST10	532	278	ST70	683	408	SU17	483	256	SU64	458	234	SW71	116	61
ST11	527	279	ST71	615	326	SU18	175	80	SU65	345	164	SW72	270	127
ST12	557	283	ST72	615	330	SU19	457	233	SU66	320	151	SW73	551	292

Table 1. (continued). Spreadsheet with predicted number of Buzzards per 10-km square in England from the maximum density model (A) and the mean density model (B).

10-km	A	B	10-km	A	B	10-km	A	B	10-km	A	B	10-km	A	B
SW74	421	206	SX67	541	310	SZ38	85	46	TF03	547	270	TF50	273	119
SW75	308	156	SX68	339	183	SZ39	152	69	TF04	327	150	TF51	248	107
SW83	133	66	SX69	369	187	SZ47	18	11	TF05	337	153	TF52	128	55
SW84	446	219	SX73	148	74	SZ48	274	162	TF06	332	150	TF55	45	19
SW85	513	256	SX74	655	330	SZ49	100	50	TF07	253	113	TF56	149	62
SW86	242	114	SX75	584	299	SZ57	64	44	TF08	291	132	TF57	138	58
SW87	91	41	SX76	606	315	SZ58	315	217	TF09	287	133	TF58	15	6
SW93	22	11	SX77	551	295	SZ59	70	37	TF10	243	109	TF60	339	155
SW94	715	387	SX78	484	253	SZ68	39	25	TF11	256	116	TF61	243	107
SW95	339	163	SX79	521	270	SZ69	7	3	TF12	370	174	TF62	233	103
SW96	502	259	SX83	11	5	SZ79	11	5	TF13	376	177	TF63	133	56
SW97	253	120	SX84	282	148	SZ89	124	56	TF14	367	166	TF64	15	6
SX04	94	48	SX85	547	308	SZ99	2	1	TF15	377	168	TF70	243	107
SX05	369	184	SX86	540	262	TA00	242	109	TF16	293	133	TF71	337	153
SX06	574	304	SX87	568	299	TA01	291	133	TF17	291	135	TF72	299	129
SX07	750	436	SX88	402	203	TA02	94	39	TF18	246	113	TF73	312	134
SX08	234	112	SX89	427	213	TA03	178	77	TF19	297	140	TF74	120	51
SX15	512	261	SX95	102	55	TA04	293	138	TF20	312	142	TF80	348	167
SX16	653	377	SX96	29	14	TA05	259	120	TF21	305	138	TF81	345	153
SX17	639	352	SX97	177	86	TA06	262	121	TF22	214	93	TF82	344	154
SX18	411	216	SX98	425	212	TA07	333	154	TF23	241	107	TF83	524	230
SX19	225	111	SX99	450	225	TA08	123	54	TF24	345	155	TF84	153	65
SX25	410	208	SY08	231	108	TA09	25	10	TF25	344	155	TF90	288	131
SX26	648	343	SY09	490	242	TA10	355	165	TF26	241	109	TF91	249	115
SX27	711	411	SY18	64	31	TA11	204	90	TF27	257	117	TF92	248	109
SX28	429	215	SY19	431	214	TA12	87	38	TF28	323	151	TF93	440	195
SX29	472	237	SY28	19	13	TA13	223	99	TF29	358	161	TF94	116	49
SX35	279	140	SY29	750	414	TA14	231	103	TF30	291	130	TG00	269	119
SX36	728	395	SY39	318	157	TA15	199	90	TF31	301	136	TG01	242	105
SX37	631	335	SY49	523	260	TA16	190	86	TF32	295	128	TG02	259	114
SX38	609	310	SY58	306	171	TA17	145	65	TF33	209	91	TG03	268	117
SX39	627	331	SY59	543	282	TA18	5	2	TF34	206	86	TG04	99	42
SX45	71	31	SY67	13	5	TA20	246	107	TF35	305	136	TG10	192	84
SX46	339	158	SY68	637	346	TA21	64	27	TF36	298	134	TG11	192	85
SX47	400	198	SY69	688	374	TA22	229	100	TF37	283	128	TG12	232	104
SX48	383	187	SY78	424	211	TA23	207	92	TF38	241	106	TG13	242	103
SX49	455	233	SY79	702	412	TA24	40	18	TF39	248	110	TG14	48	21
SX54	78	37	SY88	575	308	TA26	2	1	TF40	238	103	TG20	177	77
SX55	343	162	SY89	635	348	TA27	21	9	TF41	260	114	TG21	187	79
SX56	450	239	SY97	126	64	TA30	84	37	TF42	244	105	TG22	254	110
SX57	462	253	SY98	408	204	TA31	30	13	TF43	59	25	TG23	252	109
SX58	272	143	SY99	406	196	TA32	137	59	TF44	57	25	TG24	10	4
SX59	335	167	SZ07	26	12	TA33	8	3	TF45	240	105	TG30	247	109
SX63	9	4	SZ08	62	30	TA41	2	1	TF46	377	169	TG31	255	113
SX64	376	206	SZ09	142	62	TF00	520	253	TF47	419	199	TG32	259	112
SX65	644	330	SZ19	165	73	TF01	413	195	TF48	222	95	TG33	80	34
SX66	391	231	SZ29	165	74	TF02	291	137	TF49	113	49	TG40	234	112

10-km	A	B
TG41	227	99
TG42	110	50
TG50	32	13
TG51	17	7
TL00	247	112
TL01	321	153
TL02	145	65
TL03	291	134
TL04	248	113
TL05	194	86
TL06	393	189
TL07	398	192
TL08	553	280
TL09	483	237
TL10	211	94
TL11	303	143
TL12	434	212
TL13	296	135
TL14	403	186
TL15	282	125
TL16	351	166
TL17	511	247
TL18	461	222
TL19	313	145
TL20	269	124
TL21	264	120
TL22	309	148
TL23	329	153
TL24	363	169
TL25	357	168
TL26	336	156
TL27	293	132
TL28	401	186
TL29	243	108
TL30	203	89
TL31	301	138
TL32	306	147
TL33	399	195
TL34	317	147
TL35	320	149
TL36	294	135
TL37	264	118
TL38	262	118
TL39	281	127
TL40	226	100
TL41	251	115
TL42	362	180

10-km	A	B
TL43	509	251
TL44	385	180
TL45	232	101
TL46	215	95
TL47	335	154
TL48	298	140
TL49	229	100
TL50	269	127
TL51	315	150
TL52	214	100
TL53	412	199
TL54	482	236
TL55	308	143
TL56	306	140
TL57	303	136
TL58	269	119
TL59	260	115
TL60	339	161
TL61	281	129
TL62	303	144
TL63	278	131
TL64	269	128
TL65	305	146
TL66	295	139
TL67	314	141
TL68	291	133
TL69	265	119
TL70	186	82
TL71	283	129
TL72	217	97
TL73	260	122
TL74	253	120
TL75	429	208
TL76	416	195
TL77	428	198
TL78	235	104
TL79	329	149
TL80	200	89
TL81	231	104
TL82	251	114
TL83	280	129
TL84	238	109
TL85	318	149
TL86	231	109
TL87	257	117
TL88	204	91
TL89	371	182

10-km	A	B
TL90	137	62
TL91	238	111
TL92	204	89
TL93	283	134
TL94	274	127
TL95	264	123
TL96	250	113
TL97	303	140
TL98	228	101
TL99	224	100
TM00	73	33
TM01	67	31
TM02	210	94
TM03	287	135
TM04	299	138
TM05	225	102
TM06	268	122
TM07	251	113
TM08	228	105
TM09	242	106
TM11	110	47
TM12	275	123
TM13	171	78
TM14	147	65
TM15	260	120
TM16	244	110
TM17	248	111
TM18	235	104
TM19	217	94
TM21	18	8
TM22	72	32
TM23	96	43
TM24	167	76
TM25	287	133
TM26	252	113
TM27	247	110
TM28	235	107
TM29	252	111
TM33	23	10
TM34	193	88
TM35	258	119
TM36	237	108
TM37	259	114
TM38	228	101
TM39	310	137
TM44	15	6
TM45	111	52

10-km	A	B
TM46	162	75
TM47	208	94
TM48	237	103
TM49	243	111
TM57	9	4
TM58	72	32
TM59	56	24
TQ00	215	98
TQ01	409	197
TQ02	406	200
TQ03	430	211
TQ04	246	116
TQ05	203	90
TQ06	132	53
TQ07	101	39
TQ08	134	55
TQ09	233	104
TQ10	182	86
TQ11	358	171
TQ12	492	248
TQ13	416	206
TQ14	274	132
TQ15	163	73
TQ16	103	41
TQ17	67	27
TQ18	46	17
TQ19	118	49
TQ20	85	41
TQ21	304	149
TQ22	269	130
TQ23	176	83
TQ24	221	104
TQ25	163	73
TQ26	58	23
TQ27	49	19
TQ28	35	14
TQ29	114	50
TQ30	124	58
TQ31	302	152
TQ32	251	117
TQ33	231	108
TQ34	223	106
TQ35	200	86
TQ36	65	27
TQ37	34	13
TQ38	33	13
TQ39	74	30

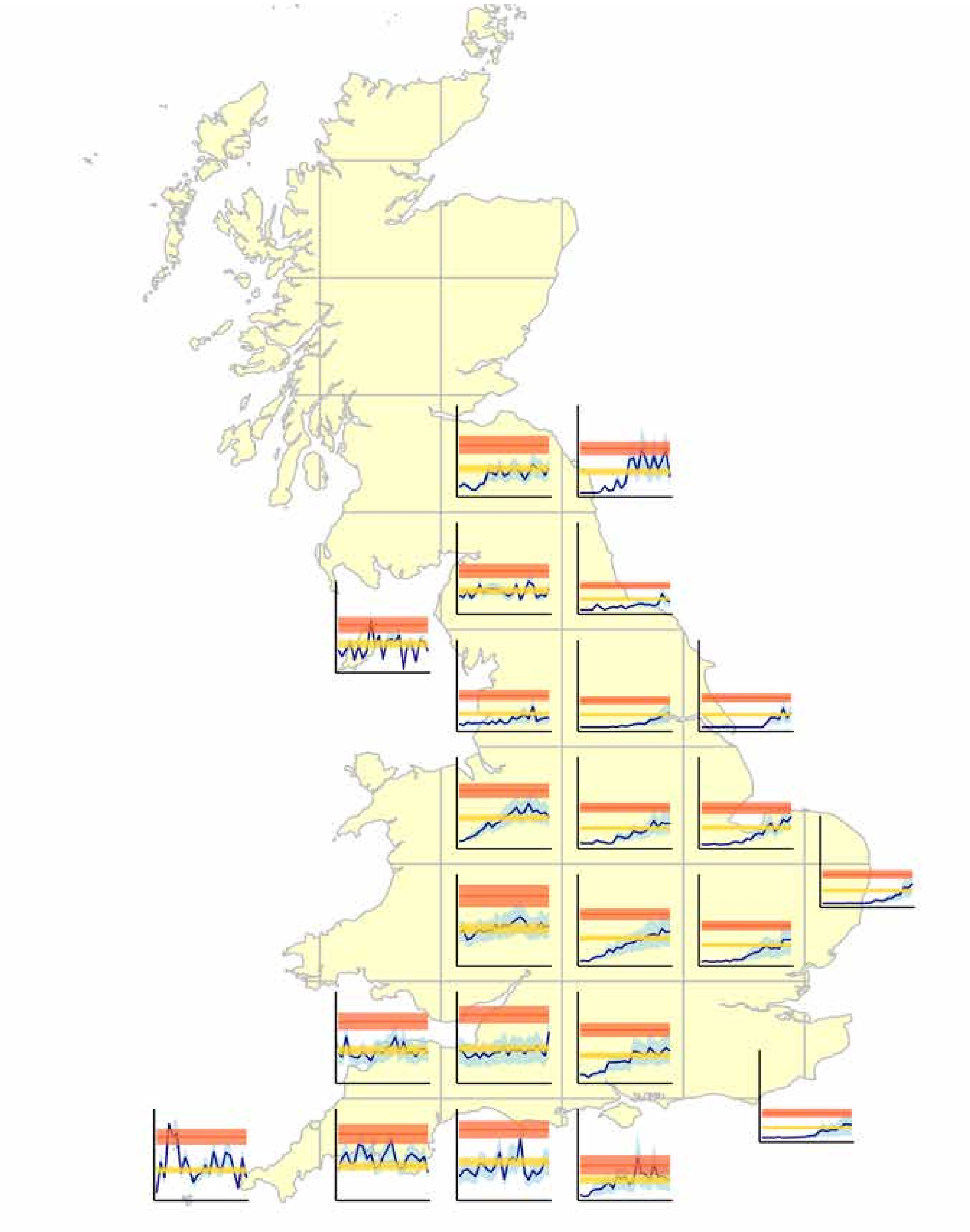
10-km	A	B
TQ40	400	199
TQ41	386	194
TQ42	234	111
TQ43	194	94
TQ44	304	153
TQ45	222	105
TQ46	122	54
TQ47	56	21
TQ48	46	17
TQ49	158	69
TQ50	247	122
TQ51	224	113
TQ52	205	98
TQ53	193	91
TQ54	214	104
TQ55	183	87
TQ56	201	93
TQ57	104	41
TQ58	129	54
TQ59	215	97
TQ60	148	70
TQ61	217	109
TQ62	194	95
TQ63	197	95
TQ64	205	96
TQ65	200	94
TQ66	201	93
TQ67	110	45
TQ68	202	91
TQ69	171	75
TQ70	19	9
TQ71	167	80
TQ72	245	121
TQ73	186	88
TQ74	232	113
TQ75	133	56
TQ76	110	46
TQ77	166	76
TQ78	83	37
TQ79	193	83
TQ81	171	85
TQ82	214	107
TQ83	192	95
TQ84	223	110
TQ85	213	101
TQ86	164	75
TQ87	74	34

Table 1. (continued). Spreadsheet with predicted number of Buzzards per 10-km square in England from the maximum density model (A) and the mean density model (B).

10-km	A	B
TQ88	39	15
TQ89	282	136
TQ91	39	18
TQ92	254	124
TQ93	299	148
TQ94	316	154
TQ95	473	243
TQ96	136	67
TQ97	13	9
TQ98	60	26
TQ99	196	94
TR01	28	13
TR02	205	94
TR03	248	118
TR04	259	124
TR05	238	114
TR06	98	46
TR07	2	2
TR09	52	25
TR13	117	57
TR14	192	94
TR15	177	82
TR16	127	58
TR23	30	14
TR24	258	128
TR25	300	142
TR26	241	112
TR34	117	53
TR35	152	70
TR36	113	50
TR37	1	0
TV49	0	0
TV59	67	33
TV69	1	0

APPENDIX C

Map showing how population trends (blue line and shading) and modelled saturation densities (red line and shading from maximum density model, yellow line and shading from mean density model) vary by 100-km square across England when predictions are averaged only across surveyed squares where Buzzards were reported at least once during the BBS time series and thus contributing to the trend line. Trends, which are all plotted to the same x-axis scale (1994–2017) and y-axis scale (0–7 birds km^{-2}) are based on a simple model of annual Buzzard densities in BBS squares with 95% confidence limits shown by blue shading.



Images: Edmund Fellowes, Edmund Fellowes, Gary Haigh. Cover image: Edmund Fellowes.

Potential future distribution and abundance patterns of Common Buzzards *Buteo buteo*

To contribute towards the definition of Favourable Conservation Status for the Common Buzzard *Buteo buteo*, estimates of local carrying capacity are required throughout England. In this report we aim to assess the potential for future expansion of the Buzzard breeding range in England and forecast potential densities in 10-km squares using species distribution models.

We can be highly confident about the extent of the Buzzards breeding range and its limited scope to expand further. The species distribution models are as robust as we can expect with the data available and they perform comparably to other models of abundance. However, many of the predicted densities are high compared to those in the literature, although it should be noted many of these are quite old and limiting factors may have reduced since then.

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