



Spatial distribution of sarcoptic mange (*Sarcoptes scabiei*) in urban foxes (*Vulpes vulpes*) in Great Britain as determined by citizen science

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Abstract

Urban areas may support high densities of wild carnivores, and pathogens can strongly influence carnivore populations. Red foxes (*Vulpes vulpes*) are hosts of sarcoptic mange (*Sarcoptes scabiei*), which infects numerous species, and transmission can be density dependent. In Great Britain, urban red foxes (*Vulpes vulpes*) have recently increased in population density and undergone range expansions. Here we investigate corresponding changes in urban fox mange prevalence. We predicted a higher prevalence closer to historic epi/enzootics and lower prevalence where urban features reduce fox density and movements, i.e. large areas of public green space, and fragmented habitat, as measured by road length and urban perimeter shape complexity. We visually assessed mange symptoms from georeferenced images of urban foxes submitted online by the public, thus surveying private land on a national scale. We measured the proportion of foxes apparently showing mange and used SATSCAN to identify spatial clusters of high infection risk. Landscape features were extracted from urban layers in GIS to determine associations. Although mange was widespread, we identified a single cluster of high prevalence (37.1%) in Northwest and Central England, which exceeded double mean prevalence overall (15.1%) and mirrors the northward expansion of urban fox distribution. Prevalence was positively correlated with perimeter shape complexity and negatively correlated with distance to the nearest city with mange, although the latter association was weak. Our findings show that citizen science can effectively monitor diseases with highly visible symptoms and suggest that fox movements are influential in explaining spatial patterns of prevalence.

Keywords Citizen science · Mange · Red Fox · Sarcoptes · Urban · Vulpes

Introduction

Land-use changes associated with increasing global urbanization typically lead to detrimental effects on biodiversity (McKinney 2008). However, some wild species such as the red fox (*Vulpes vulpes*) are urban exploiters and may reach higher population densities in towns and cities than in rural areas (Smith and Wilkinson 2003; Baker and Harris 2007; Soulsbury and White 2015). In Great Britain (hereafter termed Britain) urban fox distribution has expanded within the last

30 years (Scott et al. 2014) with an increase in social group density in some cities that can plausibly be extrapolated nationwide (Scott et al. 2018). Rising wildlife densities can heighten the risk of transmission of pathogens, which can affect wild host populations dynamics (Tompkins et al. 2002), increase transmission risk to other host species, and create knock-on-effects on sympatric predators and prey (Lindström et al. 1994). Further, spill-over of disease to domestic animals and humans can occur (e.g. Menzano et al. 2004) therefore it is essential that infectious disease processes in urban wildlife populations are adequately understood.

Red foxes are major hosts of several serious diseases in Europe and globally, some of which are increasing in prevalence (Baker and Harris 2007; Kauhala et al. 2016). Significant veterinary pathogens carried by foxes globally include canine distemper virus (Nouvellet et al. 2013), heartworm (*Dirofilaria immitis*) (Tolnai et al. 2014) and the lungworm *Angiostrongylus vasorum* (Morgan et al. 2008; Taylor et al. 2015). Zoonoses transmitted by foxes include rabies (*Lyssavirus* sp.) (Smith and Wilkinson 2003; Smith et al.

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2003; Singer and Smith 2012), canine roundworm *Toxocara canis*, the tapeworm *Echinococcus multilocularis* (Brochier et al. 2007) and the burrowing mite *Sarcoptes scabiei*. Variants of the latter cause sarcoptic mange in non-human mammals and scabies in humans (Davidson et al. 2008; Plumer et al. 2014; Pisano et al. 2019). Of the pathogens listed, *S. scabiei* and *A. vasorum* are endemic in Britain, and rabies and *E. multilocularis* have the potential to (re)emerge. Sarcoptic mange (hereafter termed mange) is particularly well documented in urban fox populations, (e.g. Newman et al. 2003; Soulsbury et al. 2007; Plumer et al. 2014) and although this may partially reflect the high visibility of both the symptoms and the host species, the disease is nonetheless considered to play a significant role in long-term fox population dynamics (Smith and Wilkinson 2003; Soulsbury et al. 2007). Mange has also been shown to cause negative effects on biodiversity globally (Daszak et al. 2000) including disease-induced mortality of endangered carnivores (e.g. Gakuya et al. 2012; Cypher et al. 2017).

The mange mite is a neglected, re-emerging and widely distributed ectoparasite that infects over 100 mammalian species (Bornstein et al. 2001; Devenish-Nelson et al. 2014; Carricondo-Sanchez et al. 2017). It is highly genetically variable with numerous strains infecting different species including *S. scabiei* var. *vulpes* (fox), var. *canis* (canids), var. *rubicaprae* (Northern chamois *Rubicapra rubicapra*) and var. *hominis* (humans) (Alasaad et al. 2012; Arlian and Morgan 2017). Symptoms include hyperkeratosis, erythema, and intense pruritus with encrusted dermal lesions that can become infected with bacteria and yeast, potentially leading to severe condition loss and emaciation (Alasaad et al. 2012; Niedringhaus et al. 2019). Mange is highly contagious and although symptom severity is variable and not always fatal (Gehrt et al. 2010), it can lead to host fatality in naïve populations in 2–4 months without treatment (Newman et al. 2002). Immune responses of wild mammals to sarcoptic mange are not well-understood (e.g. Bornstein et al. 2001) although the probability of mortality is known to be affected by season, host immune function, co-infections and nutritional status (Nimmervoll et al. 2013; Haas et al. 2018). Mange is transmitted between infected and susceptible individuals and heavy infections can accumulate rapidly (Bornstein et al. 2006) especially in naïve populations. Direct contact is perceived as the primary mode of infection (Devenish-Nelson et al. 2014; Arlian and Morgan 2017) but indirect transmission via fomites (infective objects or materials) also occurs, as all life-cycle stages are viable in the environment for up to 20 days (Arlian and Morgan 2017). Further, any form of contact that leads to transmission is likely to depend on degree of sociality and space use in the host species (Montecino-Latorre et al. 2019).

In Britain, the city of Bristol in Southwest England notably bucks the trend of progressively increasing fox density over

the last 30 years due to a mange epizootic in 1994 that resulted in a population reduction of >95% (Soulsbury et al. 2007). This was apparently exacerbated by extremely high fox density at the time combined with previous lack of exposure. Consequent rapid spread to other, naïve urban populations across Britain resulted in the presence of enzootic infection in most conurbations by 2001 (Soulsbury et al. 2007). Meanwhile, mange-related mortality in the depleted Bristol fox population remained high, indicating frequency (density independent) transmission (Soulsbury et al. 2007; Devenish-Nelson et al. 2014). Similarly, Carricondo-Sanchez et al. (2017) found evidence for frequency-dependent transmission in Norway. However, in Europe and globally, studies report both positive (e.g. Uruguchi et al. 2014) and negative (Gortazar et al. 1998) correlations between mange prevalence and fox density, with the latter also negatively predicting rate of spread (Lindström and Morner 1985). Clearly, the links between prevalence, spread and population density are complex and context specific (e.g. Niedringhaus et al. 2019) although historic infection is likely to play a role.

A definitive diagnosis of mange requires microscopic identification of mites from skin scraping/biopsy or more commonly by sero-diagnosis using an Enzyme-linked immunosorbent assay (ELISA) test supplemented by Western blot (e.g. Fuchs et al. 2016). These procedures, however, are invasive and logistically challenging and require animal capture, reducing the scope for quantifying prevalence over large areas. As mange typically manifests as lesions/alopecia in infected animals, the use of photographs is a promising alternative. Indeed, Carricondo-Sanchez et al. (2017) non-invasively documented spatio-temporal patterns of mange in foxes at the regional scale in Norway by visually determining visible lesions/alopecia from remote camera ‘trapping’ images. Using this approach, they found evidence of enzootic infection via small localized outbreaks, and clusters of high apparent prevalence in peri-urban areas in winter.

Mange prevalence in Britain was investigated in 2001 via questionnaire surveys of the public and animal welfare organizations (Soulsbury et al. 2007). The study found a broad distribution overall, with a peak in prevalence in Central and Southern England, mirroring urban fox distribution at the time, which was in the process of expanding from the South of England to the North and East (Scott et al. 2014, 2018). However, participant perception was liable to have biased the results, and both prevalence and spatial extent may have altered since 2001 following changes in fox distribution and density. Fox movements, particularly juvenile dispersal, are believed to strongly influence mange spread (e.g. Devenish-Nelson et al. 2014). Further, genetic studies reveal high microsatellite diversity and little isolation by distance in fox populations in Britain and parts of continental Europe e.g. Poland (Teacher et al. 2011; Atterby et al. 2015) indicating that there are few barriers to movement. Minimal genetic differentiation

has been found between UK urban and rural populations (Atterby et al. 2015) and very long-distance movements have been documented for individual urban foxes in Britain (e.g. Tolhurst et al. 2016). In striking contrast, differentiation in genetic structuring within and between urban fox populations was documented in the greater Zurich area, Switzerland where both natural barriers (e.g. rivers) and varying anthropogenic infrastructural complexity (e.g. of building density and dimensions) created fragmented subpopulations with limited dispersal between them (DeCandia et al. 2018). Reduced mange spread might be expected to result from correspondingly minimal (direct or indirect) contact between susceptible and infected individuals. This could occur in high density populations where these are distributed within small, stable and contiguous territories with limited movements between them (e.g. White et al. 1996; Baker et al. 2000).

Field investigations of urban foxes on a large scale are constrained by private land ownership and associated barriers to access. However, human populations in urban areas are intrinsically high, presenting opportunities for harnessing observations of engaged citizens to collect large datasets at the regional scale, i.e. citizen science. In this way, access issues can be overcome. Indeed, citizen science data have successfully been used to determine the distribution and density of multiple species across the world (e.g. Van Strien et al. 2013; Scott et al. 2014, 2018; Walter et al. 2018; Okes and O’Riain 2019). We assessed the current distribution and apparent prevalence of mange infection in red foxes in urban areas of Britain using photographic and video images submitted by citizens via a web-based interface as recruited via a national televised program (see Scott et al. 2014). Our objectives were as follows: i) to update estimates of mange distribution and apparent overall prevalence in urban foxes in Britain; ii) to determine whether apparent prevalence currently varies geographically across urban Britain in the form of spatial clusters of high infection risk; or with distance away from a known source epizootic (i.e. Bristol) or other urban populations with mange; and iii) to explore whether prevalence is correlated with urban landscape features putatively affecting fox dispersal and density including city size, length of major roads, proportional public greenspace area, proportional rural area at the urban perimeter, and degree of perimeter habitat fragmentation. We predicted that mange would be widespread, and that frequency-dependent transmission would prevent extreme spatial fluctuations. However, we expected clusters of high risk to occur in the Southwest, North and East of England and in conurbations that are most closely grouped together, reflecting historical epizooty and urban fox distribution expansion. We also hypothesized that, if transmission were predominantly density-dependent, conurbations with extensive landscape features harboring lower densities of foxes (e.g. public greenspace (Scott et al. 2014)) would be associated with lower prevalence, as would highly fragmented environments, the latter as a consequence of restricted fox movements.

Methods

Study area

The target area comprised all conurbations in Britain i.e. towns and cities within England, Scotland and Wales. A conurbation was defined as an urban area with a human population of at least 75,000 (England and Wales) or 50,000 (Scotland) corresponding to a total area of 14,546 km² (Office for National Statistics [ONS] 2004).

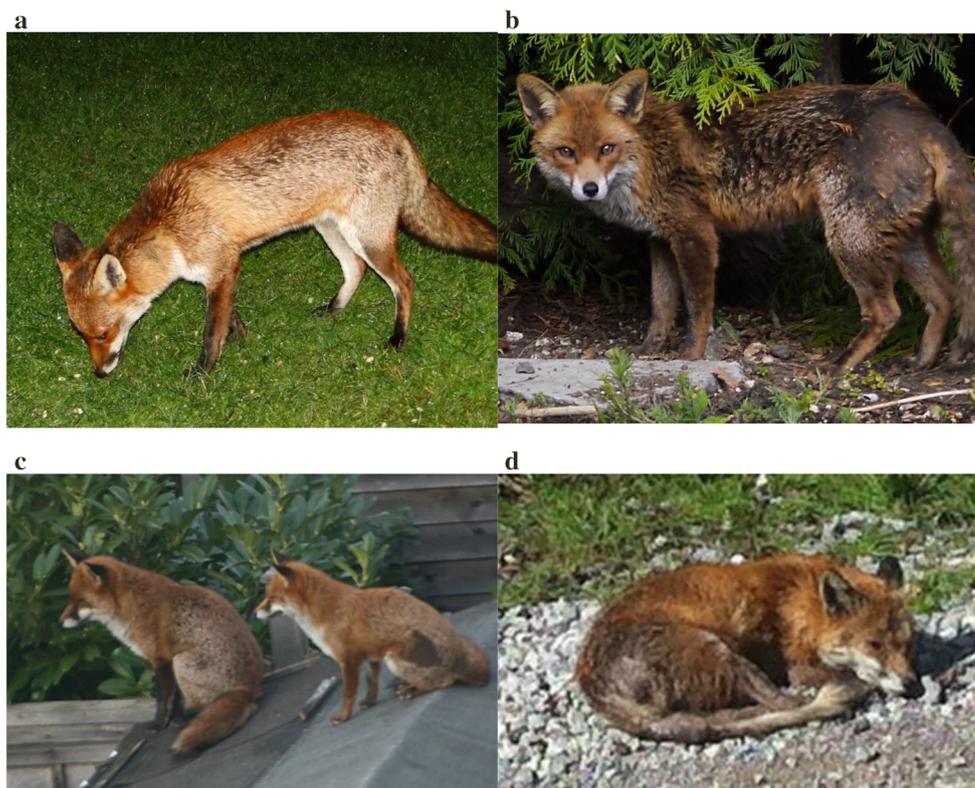
Photographic image collection

Photographic images were collected during April and May 2012, as part of a citizen science recruitment initiative to collate urban red fox sightings records for assessing distribution. Members of the UK public were asked to (anonymously) upload photographs or videos of any foxes photographed between 1st January 2012 and one week after the final broadcast date, together with the date, time and location, to a designated website. The website was produced in association with a nationwide series of television programs called “Foxes live: wild in the city” on Channel 4, which is one of the major publicly accessible terrestrial broadcasters in the U.K. Mange was not mentioned in the request for images, to reduce bias. An interactive link with Google maps enabled accurate georeferencing. Any images/videos with obviously erroneous locations (e.g. offshore) were removed prior to analysis and submitted images were screened for quality (see Scott et al. (2014) for full details of the data collection process). The project was given approval from The School of Pharmacy and Biomolecular Sciences Ethics committee, University of Brighton (Code: 1138). All duplicates were removed and images were excluded if <10% of fox body area was visible, resolution was poor, or the subject was too far away to assess condition.

Assessment of apparent mange prevalence

Mange prevalence was determined as ‘apparent prevalence’ following Carricondo-Sanchez et al. (2017) i.e. proportion of all foxes in images/videos with visible lesions and/or alopecia (considered to be infected) as a proportion of total number of foxes. Alopecia and skin lesions are predominantly visible on the rear of the animal and progress to the face (Baker et al. 2000; Newman et al. 2002; Kido et al. 2013). Mange was therefore determined from visible signs of extensive alopecia, raw skin, scabbing, lesions and hyperkeratosis in these specific areas. Seasonal moult, which is also characteristically visible at the rear, can be confused with mange. To distinguish between moult and mange-related alopecia, visibility of black guard hairs, which are only retained during moult (Maurel et al. 1986), were considered in the assessment. Assessment was conducted for every fox individual in the screened images/videos. Where images had multiple individuals, all

Fig. 1 Examples of submitted images of foxes showing a) good quality image, no mange; b) good quality image with mange (evidence of alopecia and hyperkeratosis on rump); c) poorer quality image with two foxes without mange, right side fox showing evidence of moult on left rear flank; d) poorer quality image with mange (evidence of alopecia and hyperkeratosis on rump, tail and face (copyright for research given when anonymously submitted))



individuals were assessed separately. Figure 1 shows examples of photos of varying quality, showing moult and mange. Following the assessment process, each image was assigned a score of 1,0 (mange present/absent). Where possible, sex was determined from visible sexual characteristics and head shape, age class from size and body proportions (Harris and Baker 2006). All images of juveniles (<3 months old) were consequently removed from the dataset for consistency, due to the progressive nature of mange resulting in greater visibility in adults (Newman et al. 2002; Walton and Currie 2007). A single assessor evaluated all images (NC). Verification was then undertaken by two additional assessors (AT and DS), each independently scoring 20 random individuals, and scores between the three assessors were compared.

Identification of spatial clusters of mange using scan analysis

The scan analysis software SATSCAN (www.satscan.org) Version 9.4.2 was used to identify potential spatial clusters of sarcoptic mange in urban foxes based on the locations of positive occurrence of mange. SATSCAN accounted for the unequal sampling of different areas, which was an inevitable consequence of the citizen science method of recruiting records. The software superimposed circular ‘windows’ over the study area, mapped to a central point, with the size of the

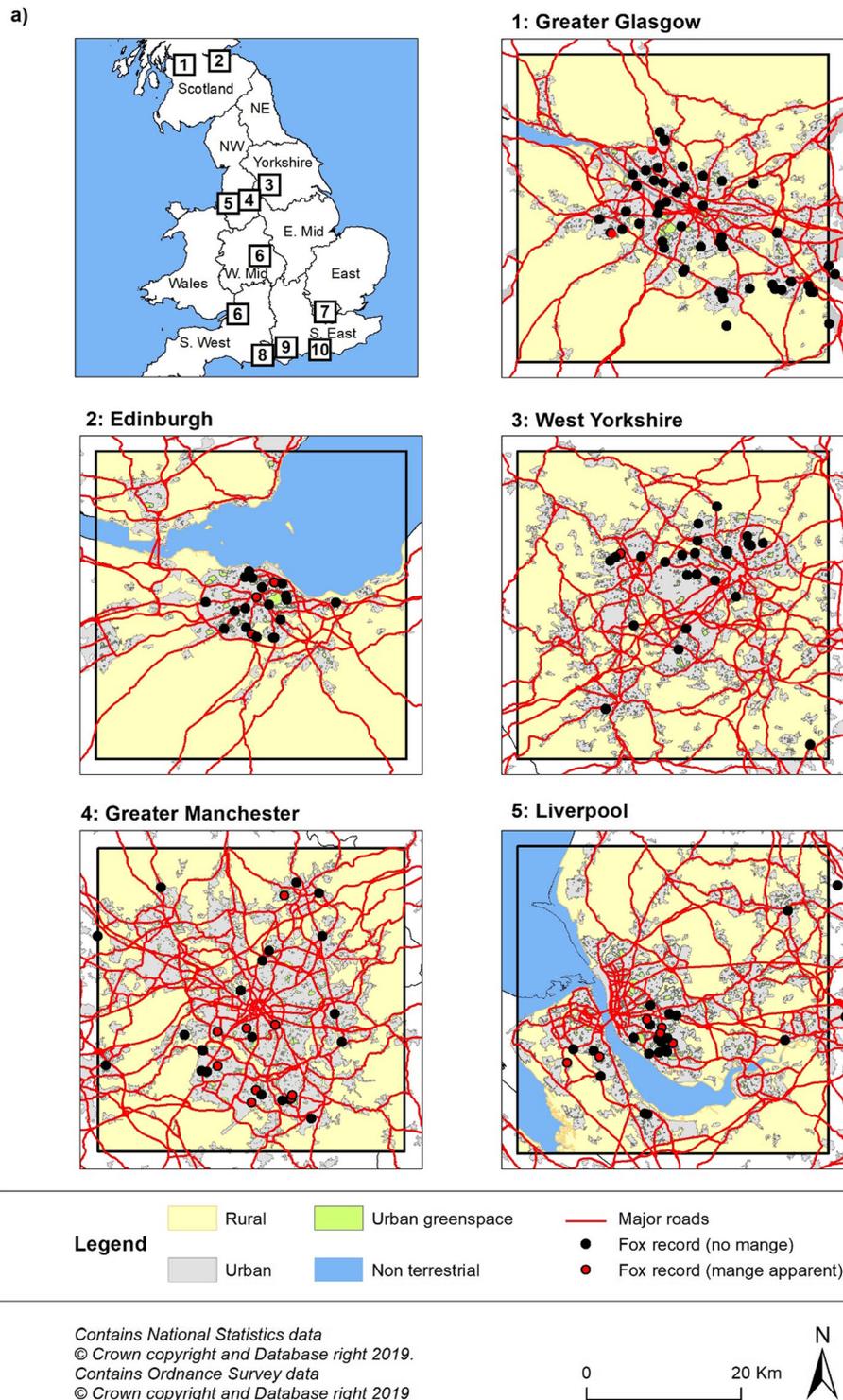
circle varying continuously from zero to a user-defined maximum as it moved across the study area. This created a permutation model, where candidate clusters were the circles and the most likely true clusters were identified using Maximum Likelihood, i.e. clusters least likely to be due to chance, given the underlying sample of the population. Specifically, Maximum Likelihood ratios generated from the data were then compared with those derived from random clusters using Monte Carlo simulations. An initial two-tailed analysis was computed to identify both high risk and low risk clusters of apparent mange, with the alternative hypotheses based on lower or higher risk within each circle as compared to the outside. We extracted significant high-risk clusters at the 0.95 level, using a maximum cluster radius of 100 km, based on an observed urban fox dispersal distance of 70 km (Tolhurst et al. 2016) and a 90 km maximum dispersal distance estimated by Atterby et al. (2015).

Analysis of landscape predictors of apparent mange prevalence

GIS methods

We analysed fox and landscape data from 11 conurbations: London, Bristol, Brighton, Bournemouth, South Hampshire, West Midlands, Liverpool, West Yorkshire, Greater Manchester, Edinburgh and Glasgow (Fig. 2 a and b). The

Fig. 2 a and b: Distribution of focal cities showing overlay of 20km² survey grids and land use categories within each city



cities/urban areas were selected using the criterion of at least 20 images being available for each, which we considered a viable threshold in terms of statistical validity, based on the data. The analysis was carried out in ArcGIS 10.3.1 with open source spatial data (Table 1). A spatial join of the fox and urban boundary datasets were used to select cities with >20

fox records which were then used as “focal cities” for analyses. For each city we generated a 40km² “focal grid” using a 20 km square buffer from each city’s centroid and used this as our study boundary. This size was chosen to enable comparison between cities of different sizes, sample the fox population across the city based on urban fox home range sizes

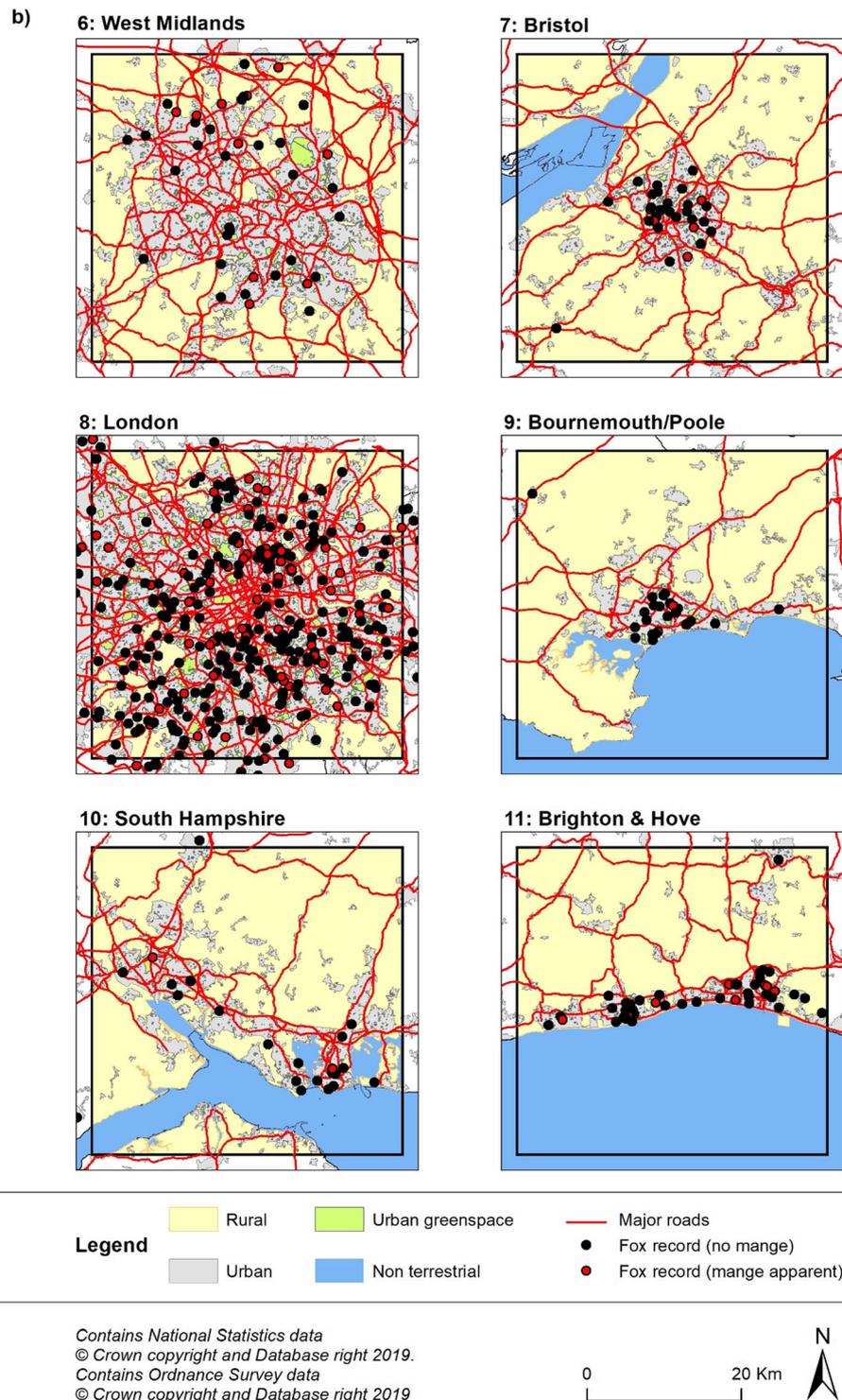


Fig. 2 continued.

(Tolhurst et al. 2016) and provide a sufficient minimum sample size of images per city ($n = 28$ to 382). This buffer size created a grid that encompassed the entire city for each conurbation, whilst also allowing inclusion of bordering rural habitat and therefore peri-urban areas at the interface between

urban and rural. This is important because peri-urban areas were found to be mange hotspots in a previous study (Carricondo-Sanchez et al. 2017). For each focal grid we calculated the percentage of images scoring positive for mange and used spatial overlay to derive explanatory

landscape variables selected a priori to reflect our hypotheses. These variables included: absolute area of the focal city (Focal city area); proportion of the focal city area comprising combined public greenspace (Proportional greenspace area); proportion of the focal grid comprising rural habitat (Proportional rural area), total length of major roads (motorway and A-road combined) in the focal grid; a derived index of perimeter shape complexity at the urban/rural interface called the fractal dimension, which we used as a measure of habitat fragmentation; Euclidean distance to the nearest city with fox mange presence based on our survey (Distance to nearest city) and Euclidean distance to the origin of the most recent large-scale urban mange epizootic in Bristol (Distance to Bristol). Due to its large size and complexity, and the large number of associated images, separate analysis was additionally computed for London only. In this analysis, a 1 km square grid was overlaid to give 14 grid squares (Fig. 3) for which mange occurrence and landscape variables were extracted following an identical method.

Statistical methods

All analyses were computed in the R environment for statistical computing (Version 3.6.1). Putative landscape predictors of apparent mange prevalence were investigated using multiple linear regression models. We ran one analysis for each of two response variables: i) apparent prevalence in focal city for all cities including London ('mangefc'); and ii) apparent prevalence in London only ('mangeL'). Both responses were square root transformed to stabilise variances and thus assume a Gaussian error distribution. Each was then regressed against one or more of the explanatory landscape variables within a Generalised Linear Model (GLM) framework in the package lmer. For mangeL, a reduced set of explanatory variables were used, as appropriate for different areas of a single conurbation; these were Proportional greenspace area and Proportional rural area. We then generated separate models that contained all possible combinations of variables, excluding those which were nested or non-independent. Therefore, as the nearest city with mange could be Bristol, Distance to city and Distance to Bristol were not included in the same model. Likewise, Focal city area and Proportional rural area were not included together as the former was contained within the grid from which the latter was derived. The resulting models were then ranked based on weights derived from information criteria (Symonds and Moussalli 2011) where models associated with delta AICc (ΔAICc) of less than 2 were substantially evidenced and those with AICc of between 2 and 4 were plausible (after Burnham and Anderson 2002). Model-averaged coefficients for the variables in the highest ranked models ($\Delta\text{AICc} < 2$) were then generated. Model selection and averaging were computed using the R package MuMIn (Barton 2018).

Results

Apparent mange prevalence overall

Of the 2808 images submitted, 1521 were considered suitable for analysis (54%) and a total of 1901 individual foxes were assessed, i.e. where multiple foxes were present in images. Of these, 33% were juveniles and therefore excluded, leaving 1274 individuals in total, of which 6.5% were sub-adults and 60.5% adults. 192 images of foxes had visual symptoms of apparent mange (concurred by assessors in >95% of cases) representing 15.1% of the total.

Spatial clusters of mange

1074 spatial locations from 153 (of 201) counties were analysed using SATSCAN. These included the 192 records of mange. One-tailed analysis for high-risk clusters identified 11 clusters, only one of which was significant at the 95% level and encompassed an area that spanned parts of Northwest England (Liverpool and Greater Manchester) and the West Midlands (Fig. 4; Table 2). Apparent mange prevalence in this high-risk cluster was 37.1%, and therefore more than double prevalence overall. Our estimate of mange prevalence in Bristol was relatively high (20%) compared to other areas outside of the high-risk hotspot such as London, and Scottish cities, none of which exceeded 12% prevalence (Table 2).

Landscape predictors of apparent mange prevalence

The highest-ranked models for predicting apparent mange prevalence in focal cities contained the intercept only, Fractal dimension, and Distance to city (Table 3). Mange prevalence was positively associated with Fractal dimension and negatively associated with Distance to city (Table 4). For the London area only, no landscape variables were contained within the highest ranked models, i.e. the intercept only model was substantially better than all other models (Table 5).

Discussion

National distribution of mange prevalence

As predicted, mange was widespread in urban foxes in Great Britain and extreme spatial fluctuations in apparent prevalence were not detected. Mange spatial distribution was non-uniform, and the high-risk hotspot identified in Northwest and Central-west England is partially consistent with predictions based on recent shifts in urban fox distribution and historical epizooty (i.e. north and west of Bristol). However, there was no hotspot in the Southwest or East. Further, we found no association between apparent prevalence and distance to Bristol, although

Table 1 ArcGIS (10.3) layers used in spatial analyses of landscape features, and names and descriptions of features. Proportional rural area was derived from the area within the grid that was outside of the focal city boundary

Land use name	Layers used	Description	Spatial statistic	Landscape variable name
URBAN	Builtup_Areas_December_2011_Boundaries Scottish Settlement boundary data UK Major Towns and Cities dataset for London boundary	Total area of urban extent (including greenspace)	Focal city area (km ²)	Focal city area
GREENSPACE	Ordnance Survey Open Data Greenspace GB Ordnance Survey MasterMap Greenspace topography	Total area of combined accessible public greenspace	Urban greenspace area (km ²)	Proportional greenspace area
UK BOUNDARY	Ordnance Survey Open Data Boundary Line	Outer boundary of sample area		

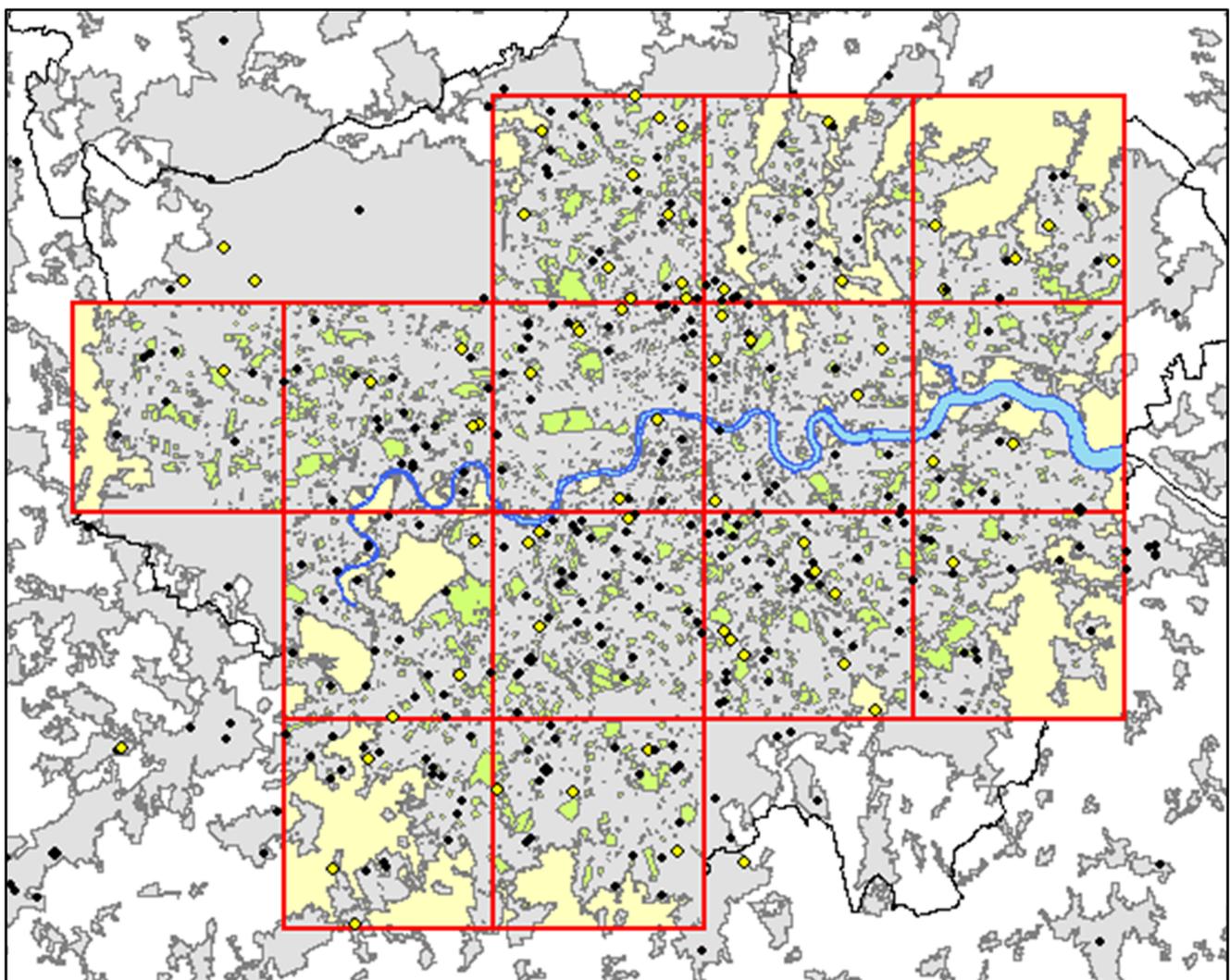
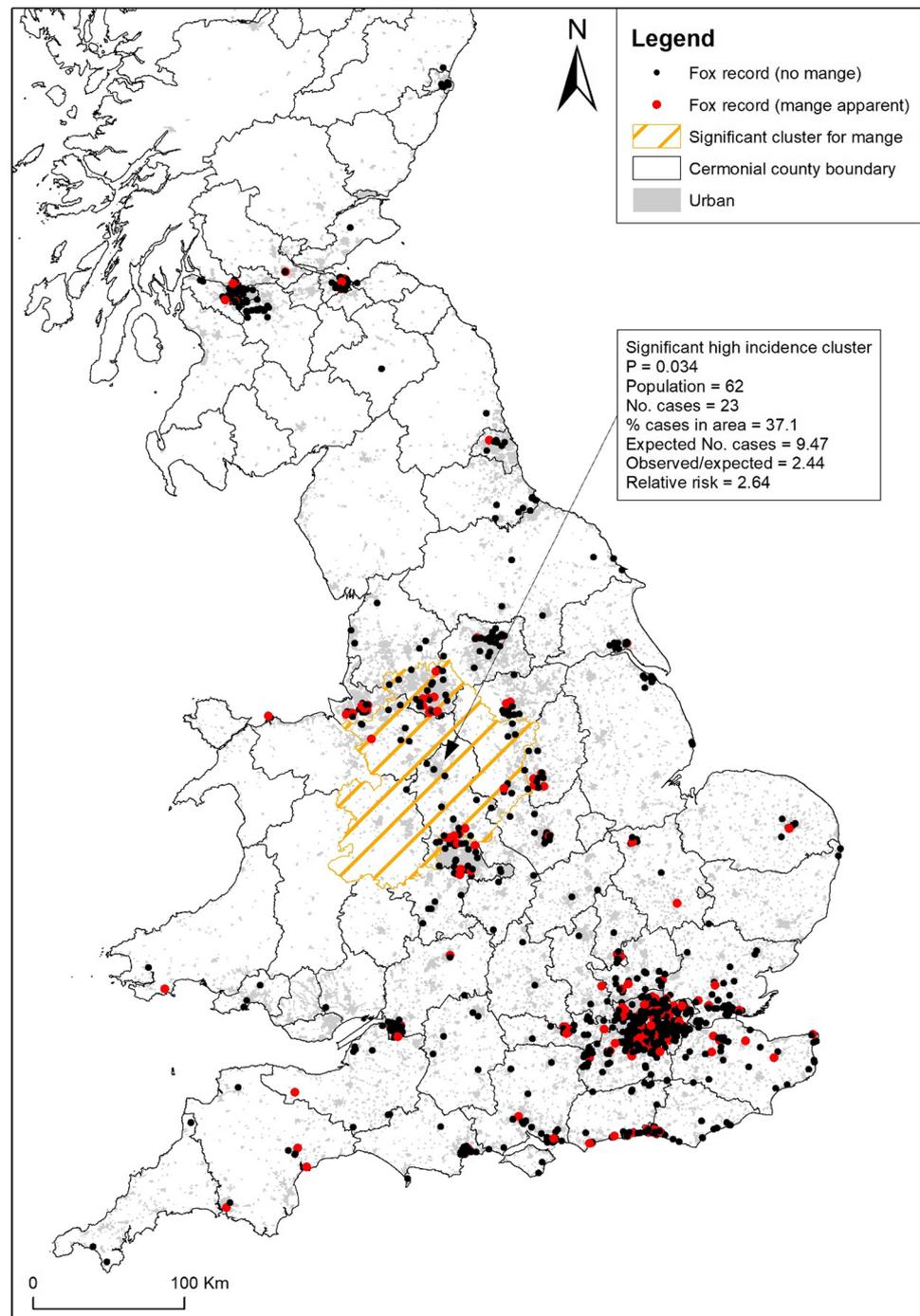


Fig. 3 1 km² grid overlay of London area to explore relationship between mange prevalence and urban landscape. Yellow areas are rural land use, grey areas urban land use. Black dots are records of foxes; yellow dots are records of foxes with apparent mange

Fig. 4 Statistically significant high-risk mange cluster identified using SATSCAN at 100 km radius spatial scale



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we did detect a relatively weak relationship where prevalence decreased with increasing distance from the nearest conurbation with mange. There has not been a largescale mange outbreak in Britain since the Bristol epizootic, which spread rapidly through urban populations nationwide within a few years (e.g. Simpson 2003). It is probable that the consequent absence of naïve populations, and correspondingly widespread enzootic infection, mean that present day prevalence is no more likely to be higher

closer to original source epizootics than anywhere else. We therefore suggest that the weak effect of higher mange prevalence in cities that are closer to other cities (i.e. clustered conurbations) reflects increased fox movements (e.g. dispersal) between adjacent urban areas, rather than variable prevalence between conurbations. Increased dispersal may result from high rates of intra-specific competition where foxes occur at medium-to-high densities.

Table 2 List of the 11 surveyed cities/conurbations used in the analysis, mange percentage values per city, and summary of associated landscape features

City/conurbation	No. of images submitted (N)	% images in focal city with mange	% of images in focal grid with mange	Focal city area (km ²)	Fractal dimension
Bournemouth/Poole	28	7	7	131	1.372
Brighton and Hove	58	18	17	90	1.356
Bristol	30	22	20	144	1.376
Greater Manchester*	35	17	37	631	1.412
Liverpool *	31	38	23	200	1.351
South Hampshire	29	24	17	192	1.404
West Midlands*	47	18	30	599	1.348
West Yorkshire	32	31	6	488	1.416
Edinburgh	25	7	12	123	1.268
Greater Glasgow	65	12	6	267	1.318
London	382	8	17	1243	1.336

Fractal dimension is an index (hence shown to 3 D.P.) of city perimeter shape complexity, used here as a measure of peri-urban landscape fragmentation. NB: some images contained more than one fox. * denotes conurbations included in the Northwest/Centralwest England hotspot from SatScan analysis

The urban landscape and mange

The lack of strong effects of multiple urban landscape features on apparent prevalence was surprising given the generally heterogeneous nature of cities and associated variation in fox habitat quality. Some studies report broad-scale habitat effects on mange prevalence (e.g. higher at the urban periphery, Carricondo-Sanchez et al. 2017) although others show no pattern (e.g. Soulsbury et al. 2007). However, the current study is the first (to our knowledge) to specifically relate mange occurrence to habitat variation within cities rather than comparing essentially homogenous urban environments with wilderness or rural areas. Therefore, we might not expect our results to be consistent with other studies. In addition, in Britain urban foxes are known to positively select residential gardens (yards) where they are generally free from persecution and encounter essential resources including supplementary food, and den/

layup sites e.g. under sheds or in mature vegetation (Saunders et al. 1993; Newman et al. 2003; Scott et al. 2018). Thus, if a difference existed between habitats within a city, we might expect it to be higher mange prevalence in conurbations with greater proportions of private greenspace (i.e. gardens/yards), relative to other areas e.g. public greenspace in which foxes occur at lower density (Scott et al. 2014). Even if transmission was predominantly frequency rather than density-dependent in our study system, the types of behaviours exhibited by resident foxes in private greenspace, such as cross-utilisation of lay-up sites, are likely to facilitate mange transfer (Soulsbury et al. 2007; Montecino-Latorre et al. 2019). Conversely, fox populations in residential gardens tend to be configured within stable territories with limited contact between neighbouring social groups (Baker et al. 2000), such that mange spread within the broader environment would be minimal. We were not able to test these theories, because the inclusion of private greenspace

Table 3 Model selection for predictors of apparent prevalence of mange in foxes in UK focal cities, from photographs

Model	<i>K</i>	AICc	Log Likelihood	Δ AICc	<i>w_i</i>
1 Intercept only	2	-11.7	8.592	0.00	0.263
2 Fractal dimension	3	-11.7	10.548	0.02	0.261
3 Distance to city	3	-10.3	9.889	1.34	0.135
4 Proportional green space area	3	-8.8	9.095	2.92	0.061
5 Distance to city+Fractal dimension	4	-8.2	11.453	3.44	0.047
6 Proportional rural area	3	-7.8	8.624	3.86	0.038
7 Road length	3	-7.8	8.592	3.93	0.037

K = number of parameters (number of explanatory variables +2); Δ AICc = change in AICc between models; *w_i* = Akaike model weight. Light grey shaded = Δ AICc <2 = substantial evidence for models; dark-grey shaded 2–4 = plausible models (after Burnham and Anderson 2002). All values were computed in the 'MuMIn' package (Barton 2018) in R v. 3.6.1

Table 4 Model averaged coefficients using Maximum Likelihood Estimation (MLE) for predictors of apparent prevalence of mange in foxes in UK focal cities, from photographs

Explanatory variable	Estimate (β coefficient)	S.E.	Lower C.I.	Upper C.I.
Intercept only	-0.375	1.368	-3.056	2.306
Fractal dimension	1.508	1.023	-0.497	3.514
Distance to city	-0.006	0.005	-0.015	0.003

Only variables within models for which there was substantial evidence ($\Delta\text{AICc} < 2$) are shown. S.E. = Standard Error; C.I. = Confidence Interval. All values were computed in the 'MuMIn' package (Barton 2018) in R v. 3.6.1

in addition to public greenspace in our GIS analysis would have created a mismatch at the spatial resolution required for meaningful interpretation of the photographic images. Nonetheless, further exploration of this issue is strongly recommended.

We interpret the higher mange prevalence values with increasing urban perimeter shape complexity in terms of increased fox movements at the urban-rural interface relative to the city interior. This contrasts with DeCandia et al. (2018) in Zurich, where limited dispersal occurred between sub-populations within a city. Our findings suggest that there are few barriers to dispersal either within or between UK cities, however further work is necessary to confirm this.

Mange effects and treatment

Mange can affect the feeding and movement behaviour of infected animals (Murray et al. 2015; Carricondo-Sanchez et al. 2017; Suld et al. 2017) and infection is linked to poor body condition and nutritional status, which can alter individual position in dominance hierarchies (Soulsbury et al. 2007) and/or utilisation of habitats and resources (Carricondo-Sanchez et al. 2017). This may lead to an over-estimation of prevalence using our method if mangy foxes access anthropogenic resources more readily than healthy animals, or are less afraid of humans (e.g. Bornstein et al. 2001) and therefore urban residents are more likely to see and photograph them. Prevalence may also be affected by ad hoc treatment administered by rehabilitation centres or members of the public. The extent of such in situ medicating (usually with the parasiticide agent, ivermectin) and whether or how it affects mange prevalence and spread remain unknown. Mange treatment in wildlife is controversial, as there are potential side effects of ivermectin for target individuals and medication may also

inadvertently enter the environment and food chain leading to drug resistance (Niedringhaus et al. 2019). Further research into this area is strongly recommended.

Limitations of the study

The method of image recruitment was necessarily non-random and further studies are recommended to locally validate the results. There may be bias away from photographing animals in poor condition as they are not aesthetically pleasing, hence underestimating the proportion with mange. One approach could collate spatial and temporal records of foxes with apparent mange from the RSPCA and wildlife centres across the UK. The study was conducted in the spring only, the initial focus being to determine the current distribution of the pre-breeding fox population. However, seasonal variation in mortality (Nimmervoll et al. 2013) and group size affecting intra-group contacts (Doming and Harris 2017) mean that our results probably inadequately reflected prevalence across the annual cycle. Additionally, mange manifestation varies depending on mite burden, with 'ordinary mange' predominantly associated with hair loss, and 'crusted mange' presenting with severe hyperkeratosis and sero-cellular crusting (Carricondo-Sanchez et al. 2017). Hair loss is likely to be more apparent in spring due to moult and breeding alopecia (hair loss associated with pregnancy or postpartum period (Novak and Meyer 2009)) so there is a risk of misdiagnosis and consequent over-estimation of prevalence. Opposing bias may have resulted from the variation in symptoms with disease progression such that early-stage symptoms (e.g. small lesions) may have been overlooked. Further under-estimation may have arisen if signs were restricted to 'invisible' parts of the body such as the abdomen (i.e. 'occult' presentations;

Table 5 Model selection for predictors of apparent prevalence of mange in foxes in UK focal cities, from photographs, for London only

	Model	K^*	AICc	LogLik	ΔAICc	w_i
1	Intercept only	2	-20.3	12.680	0.00	0.693
2	Proportional rural area	3	-17.1	12.758	3.15	0.143
3	Proportional green space area	3	-17.1	12.752	3.17	0.142

K = number of parameters (number of explanatory variables +2); ΔAICc = change in AICc between models; w_i = Akaike model weight. Light grey shaded = $\Delta\text{AICc} < 2$ = substantial evidence for models; dark-grey shaded 2–4 = plausible models (after Burnham and Anderson 2002)

Alasaad et al. 2012). It is recommended that future studies compare visual and clinical assessment of mange by combining monitoring of captive animals of known disease status with remotely captured images. However, image selection and appraisal by the assessors was consistent, and all geographical areas were surveyed in the same season, hence we provided a relative measure of mange prevalence that was comparable across the dataset.

Conclusions

We show that citizen science can be an effective method for monitoring wildlife diseases for which symptoms are highly visible; in this case showing that hotspots of mange prevalence have shifted northward since a previous assessment, which partially reflects the expansion in fox distribution in recent decades. Our findings also suggest that fox movements such as dispersal are likely to be influential drivers of mange prevalence in British urban areas.

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