Received: 14 May 2021 | Accepted: 21 December 2021

DOI: 10.1111/1365-2664.14118

Journal of Applied Ecology BRITISH ECOLOGICAL SOCIETY

RESEARCH ARTICLE

Predicting habitat suitability and connectivity for management and conservation of urban wildlife: A real-time web application for grassland water voles

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Funding information
Glasgow City Council; Glasgow Natural History Society; NatureScot; The People's Trust for Endangered Species

Handling Editor: Péter Batáry

Abstract

1. Natural habitats in urban areas provide benefits for both humans and biodiversity. However, to achieve biodiversity gains, we require new techniques to determine habitat suitability and ecological connectivity that will inform urban planning and development.
2. Using an example of an urban population of water voles *Arvicola amphibius*, we developed a habitat suitability model and a resistance-surface-based model of landscape connectivity to identify potential connectivity between areas of suitable habitat. We then updated the environmental variables according to new urban development plans and used our models to generate spatially explicit predictions of both habitat suitability and connectivity.
3. To make models accessible to urban and conservation planners, we developed an interactive mapping tool that provided users with a graphical user interface (GUI) to inform conservation planning for this species.
4. The model found that habitat suitability for water voles was related to the proportion and distance from key environmental variables, such as built-up areas and urban green spaces, while the connectivity model identified important corridors connecting areas of potential distribution for this species.
5. Future development plans altered the potential spatial distribution of the water vole population, reducing the extent of suitable habitat in some core areas. The interactive mapping tool made available suitable habitat and connectivity maps for conservation managers to assess new planning applications and for the development of a conservation action plan for water voles.
6. *Synthesis and applications*. We believe this approach provides a framework for future development of nature conservation tools that can be used by planners to inform ecological decision-making, increase biodiversity and reduce human–wildlife conflict in urban environments.

KEYWORDS
Arvicola amphibius, biodiversity, green infrastructure, shiny, spatial modelling, species distribution models, urban ecology, wildlife management

1 | INTRODUCTION

Natural habitats within cities are increasingly required to tackle the biodiversity extinction crisis (Oke et al., 2021) and to provide benefits for both humans and wildlife in a changing climate (Stafford et al., 2021). However, balancing the needs of humans and nature is especially challenging within these urban environments (Hepinstall et al., 2008). Previous approaches to managing biodiversity in cities have generally involved mapping of green and blue infrastructure and zoning development to avoid important habitats and species. However, to deliver biodiversity benefits, ecological knowledge must be fully integrated into the development of our cities and urban spaces (Apfelbeck et al., 2020). Landscape ecologists and planners have attempted to improve urban biodiversity by protecting core areas of habitat and by increasing connections between patches through corridors and ecological 'stepping-stones' (Lynch, 2019). Therefore, to aid urban design, land managers and planners not only require maps of species distribution but also new techniques to quantify ecological connectivity (LaPoint et al., 2015).

Species distribution models represent one of the most useful tools in wildlife conservation and management, but their use in urban environments has only recently been applied for a few taxa (Gomes et al., 2011; Gortat et al., 2014; Le Louarn et al., 2018; Milanovich et al., 2012; Wellmann et al., 2020). However, the possibility of passing knowledge of species biology or of an environmental system on to the people in charge of management and conservation decision-making is pivotal to successful wildlife management (Pitelka & Pitelka, 1993). This is particularly relevant in an urban context, where planners do not necessarily possess extensive skills in wildlife ecology and conservation.

To date, a wide range of methods for species distribution modelling is available (Elith et al., 2006; Guisan et al., 2017; Guisan & Thuiller, 2005; Matthiopoulos et al., 2020), from regression-based approaches (Guisan et al., 2002) to machine learning, maximum entropy (Phillips & Dudík, 2008) and ecological niche factor analyses (Hirzel & Le Lay, 2008). However, conservation planning based on resource selection and definition of habitat suitability alone is not sufficient if connectivity requirements are not taken into consideration (Abrahms et al., 2017).

Connectivity can be defined in terms of structural connectivity, describing the spatial organisation of habitats throughout the landscape and the physical attributes that may facilitate or impede movement of species. However, individuals or species may respond to these physical features in different ways and we need to consider the functional or behavioural connectivity of landscapes for a variety of species. Ecological connectivity modelling has been used to examine both structural and functional connectivity of urban landscapes and has been highlighted as a means to develop "data-driven and evidence-based biodiversity-friendly infrastructure planning in urban areas" (LaPoint et al., 2015). One of these resistance-surface-based connectivity modelling has become a widespread tool for conservation planning (Wade et al., 2015). Resistance estimation is commonly accomplished by parameterising environmental variables across a 'cost' to movement continuum, where a low resistance denotes ease of movement and a high resistance denotes restricted movement, or is used to represent an absolute barrier to movement (Zeller et al., 2012). Once the resistance surface is defined (often as the inverse of habitat suitability), linkage zones can be mapped by least-cost modelling, or more sophisticated approaches from graph theory, individual-based movement models or electrical circuit theory. The combination of species distribution and connectivity modelling can therefore provide outputs to help implementers focus on conservation through ecological connectivity (Beier et al., 2011).

Although ecological models are valuable tools to understand and predict population dynamics, and test the impact of management strategies, they have become increasingly complex, up to a point where managers can hardly use them (Knight et al., 2008; McNie, 2007). Particularly in an urban context, where changes in land use can happen rapidly, user-friendly tools that provide urban planners with real-time assessment of the effect of planned infrastructures on local biodiversity, offer an opportunity to readily embed robust evidence in the decision-making process (Chapron, 2015).

In Scotland, we have a unique population of one of the UK's most threatened mammals, the European Water Vole, *Arvicola amphibius*, occupying habitats in parks and green spaces in and around the City of Glasgow. This population is unusual as it mainly consists of a burrow-dwelling (fossorial) ecotype found in grasslands which is believed to be rare in the UK (Stewart et al., 2017). Water voles occupying riparian and aquatic habitats are also found within this urban area and these are more common habitats for this species within the UK. Many of the areas occupied by water voles around Glasgow are identified for urban regeneration and many sites will soon be developed. Detailed knowledge of the habitat suitability for this species is required for protection of core areas and also for the identification and/or creation of new receptor sites for relocation of animals (Baker et al., 2003).

The overall aim of this study was to develop a model that could be used by landscape ecologists and planners to predict the habitat suitability and ecological connectivity of a grassland water vole population in North East Glasgow and the Seven Lochs Wetland Park (Scotland's largest urban park, located in the City of Glasgow and North Lanarkshire). The main objectives were to (a) determine the environmental factors (biotic and abiotic) that influenced probability of occurrence of and potential distribution of water voles; (b) identify potential connectivity between suitable areas, (c) evaluate the impact of future planned development on habitat suitability and potential distribution and (d) develop an interactive and user-friendly tool to allow managers and planners to generate real-time prediction of the model outputs under different hypothetical scenarios of urban development. The provision of this model will be used to inform management of water voles, balancing the legal protection of this species, maintaining green amenity space for local people, and planning of housings and infrastructure for the socio-economic development of this area. The approach taken also provides a framework for applying similar practices to the management of other species and habitats in urban environments.

2 | MATERIALS AND METHODS

2.1 | Study area

This study was conducted in an area of approximately 7,600 ha, surrounding North East Glasgow and the Seven Lochs Wetland Park (Scotland) (Figure 1). The main land-use types are residential areas (26.6%), farmland (16.7%), green spaces (grass, parks and recreational grounds) (11.0%), forest (9.6%) and scrub (4.9%). Overall, the area is crossed by approximately 46 km of Motorway (four-lane dual carriageway, with central barrier) and 55 km of A-roads (other major non-motorway roads, mostly two-lane dual carriageway).

2.2 | Data collection

2.2.1 | Water vole presence data

We used an initial dataset consisting of 1,726 GPS-tagged individual records of sightings and signs of water vole presence such as burrows, nests and latrines, provided by different organisations (Glasgow Biological Records Centre, North Lanarkshire Council, Scotland Transerv, Scottish Water and Glasgow City Council). The dataset is the result of one systematic survey in 2014 (Stewart et al., 2017), specific surveys of sites marked for development and citizen science records.

From this dataset, we filtered those collected from 2013 to 2019, to obtain their most recent distribution (Figure 1). Some of the records consisted of area polygons where water voles have been observed, but without precise GPS coordinates. In these

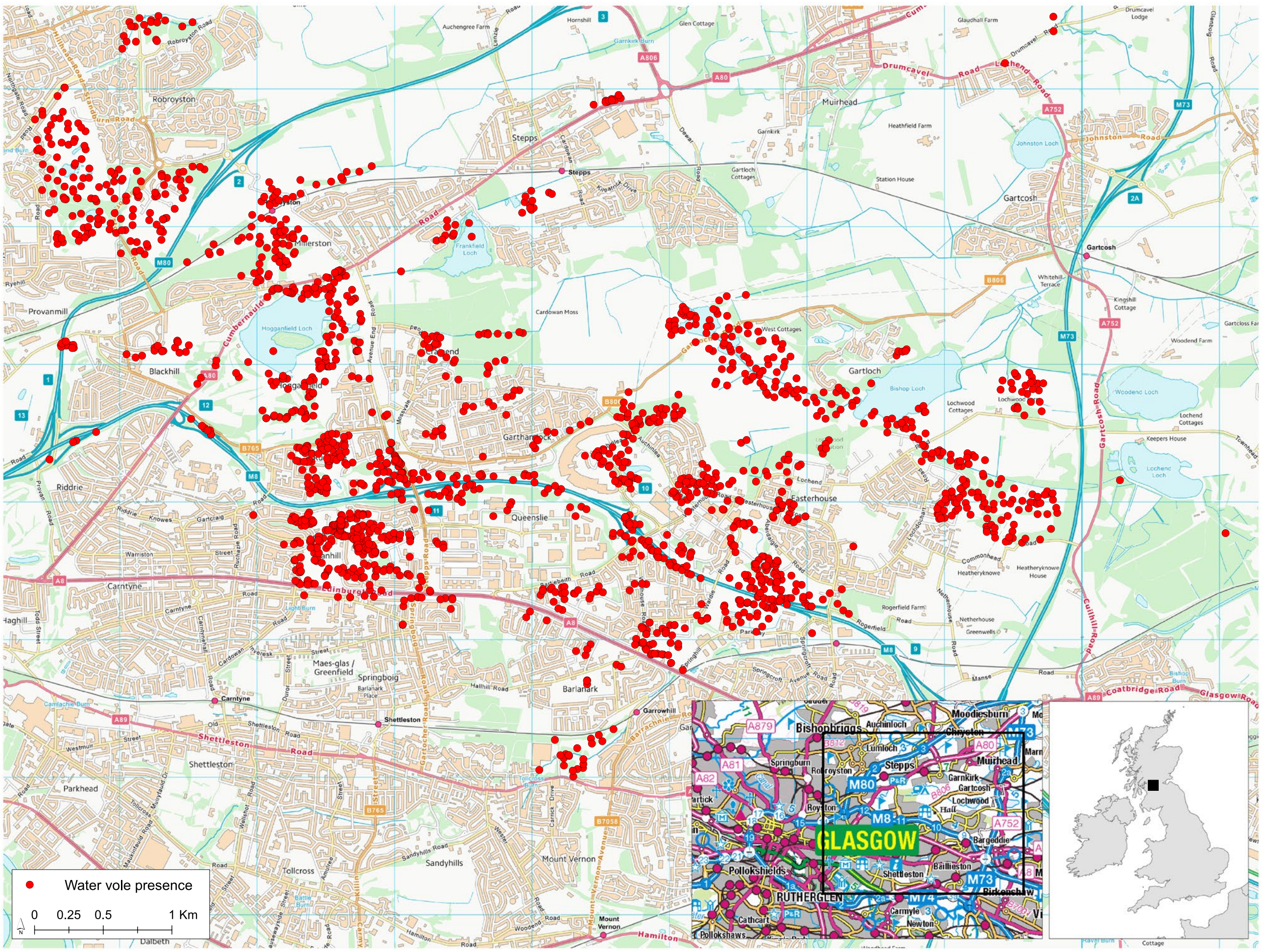

FIGURE 1 Location of the study area (insets) and distribution of water vole records in North East Glasgow and the Seven Lochs Wetland Park. Background images source: Ordnance Survey

cases, we randomly generated pseudo-presence points within the polygons' boundaries. The number of these points was proportional to the size of the polygons, with a density of 93 points/ha, according to the estimated average density of water voles in the same area (Stewart et al., 2019). The final dataset consisted of 799 records (182 sightings, 159 burrows, 10 latrines, 448 pseudo-presence); of these, 185 came from surveys of sites marked from development, 263 from surveys in other areas not directly affected by development, 65 from the Stewart et al. (2017) systematic survey and the rest from the other sources previously mentioned (see also Acknowledgements).

No animal has been captured or manipulated for this study. Ethical approval and fieldwork were not required.

2.2.2 | Environmental predictors

As candidate environmental predictors, we considered variables related to land use, terrain and soil, as these are known to affect water voles in urban ecosystems (Stewart et al., 2017). We initially considered a set of covariates related to land use, obtained from Open Street Map data (OpenStreetMap contributors, 2020) and Ordinance Survey Open Data (www.ordnancesurvey.co.uk), and created raster surfaces of the distance from the nearest patch of key features such as woodland, buildings, green spaces and main roads. In addition, we calculated the proportions of each land-use category in a circular buffer of 75 m radius around each point, corresponding to an approximation of an average home range for both males and females (Strachan & Moorhouse, 2006).

Using a digital elevation model with a spatial resolution of 10 m, we calculated slope (°) and northness. This latter variable was calculated as the cosine-transformation of aspect (Zar, 1999), and it ranges from −1 (completely south-exposed) to +1 (completely north-exposed; Nelli, 2015).

Finally, we considered soil data including features of lithology, texture and structure, derived from the British Geological Survey (BGS) 1:50,000 Geological Map of Great Britain (DiGMapGB-50) (British Geological Survey, 2020). The full list of candidate predictors and their description is presented in Table 1.

2.3 | Data analysis

To evaluate habitat suitability for the species, we formulated a resource selection probability function (RSPF) following a use versus availability design (Boyce et al., 2002), using a series of generalised linear mixed effect models with binomial distribution. As response variable, we used water vole presence points (1) and a set of 10x random points (0) (Legendre & Legendre, 1998; Zuur et al., 2007). As water vole presence points could be biased towards close proximity to certain features such as roads, being more accessible than woodlands of open farmlands, we minimised the effect of observation-bias, by generating random points with a different intensity according the density of presence points. In particular, using the ADEHABITATHR package in R, we created a two-dimensional kernel density estimate based on the occurrence points, and used that surface as a probability density function to generate the coordinates of the pseudo-absences.

To account for annual fluctuation in the baseline probability of presence, we included the year as a random intercept.

We started from a full model considering all the variables (presented in Table 1), with the continuous variables including both a linear and a quadratic effect. We standardised all the variables by subtracting the mean and dividing the result by the standard deviation, to compare the effect size of the model coefficients. To select the habitat variables for inclusion in the final model, we have used a backward stepwise approach (Venables & Ripley, 2013) based on Akaike's information criterion (AIC). To validate the selected model, we used a twofold cross-validation (Roberts et al., 2017) and split the full dataset into a training subset (75%) and a test subset (25%). Models were developed using the training subset, and validated on the test subset by calculating Tjur's R^2, which has an upper boundary of 1.0 and can be interpreted similar to R^2 values from linear regression (Tjur, 2009), and area under the curve (AUC) receiver operating characteristics (ROC) (Hosmer Jr et al., 2013).

We then created a 5 m resolution grid, covering the entire study area. For each centroid of the grid, we calculated the same environmental variables that were retained by the best model and we used them to predict the habitat suitability for water voles. We defined the potential distribution of water voles by considering all the continuous areas with a habitat suitability higher than 0.50. By increasing this threshold to 0.75 and 0.90, we also defined the 'core areas' (defined here as areas with the highest habitat suitability for the species).

We created a model of landscape connectivity based on circuit theory (McRae et al., 2008; McRae & Beier, 2007), calculating pairwise resistance values between areas of potential distribution and defining all the possible pathways. The resistance map for this analysis was calculated as the inverse of the habitat suitability map.

To evaluate how future development plans would affect habitat suitability and potential distribution, we updated the environmental variables according to the proposed changes in the land use, in particular in terms of new buildings, residential areas and industrial areas (and consequent changes in the other land-use categories). Using the updated land-use map, we re-calculated the distances between the centroids of the grid and the environmental variables, and we re-generated the maps of habitat suitability and connectivity. We then calculated the differences between the current land-use scenario and the future scenario under the proposed development, to highlight changes in habitat suitability and connectivity and loss of areas of potential distribution, including core areas.

Preliminary manipulation of environmental layers was undertaken using the software QGIS (QGIS Development Team, 2021). The model fitting was carried out in the statistical environment R version 4.1.1 (R Development Core Team, 2021) via the package

TABLE 1 List of candidate predictors used in the generalised linear models of water vole presence vs. environmental variables in in North East Glasgow and the Seven Lochs Wetland Park

Source	Variable	Description	Values/range in presence points
Open Street Map and Ordnance Survey	D_A_roads	Distance from nearest A road	0.2–2,443 m
	D_M_roads	Distance from nearest motorway	0.2–2,532 m
	D_building	Distance from nearest building	1.0–755 m
	D_green	Distance from nearest green area	4.0–1,250 m
	D_industrial	Distance from nearest industrial area	9.0–3,166 m
	D_residential	Distance from nearest residential area	4.1–1,626 m
	D_farmland	Distance from nearest farmland area	9.0–4,620 m
	D_scrubland	Distance from nearest scrubland area	5.1–1,753 m
	D_water	Distance from nearest surface water	0.7–1,168 m
	D_woodland	Distance from nearest woodland	4.5–643 m
	P_building	Proportion of built-up areas	0.00–0.40
	P_green	Proportion of green areas	0.00–0.40
	P_industrial	Proportion of industrial areas	0.00–1.00
	P_residential	Proportion of residential areas	0.00–1.00
	P_farmland	Proportion of farmland areas	0.00–1.00
	P_scrubland	Proportion of scrubland areas	0.00–1.00
	P_water	Proportion of surface water	0.00–1.00
	P_woodland	Proportion of woodland	0.00–1.00
10 m digital elevation model	ALT	Altitude a.s.l.	19.9–109 m
	SLOPE	Slope	1.5–8.3°
	NORTH	Northness	−1.0–1.0
British Geological Survey	VARIATION	Classification of soil variability	**Low**: the parent is spatially uniform across a wide area (uniform over 100's metres). **Mod**: medium indicates variability at a local scale (uniformity at 10's of metres) **High**: high variability at a metre scale.
	DOM_GRAIN	Qualitative classification of the most common (dominant) grain size to be expected from the parent material	**Mud**: 0–0.006 mm (particle diameter) **Sand**: 0.006–0.2 mm **Medium**: 0.2–2.0 mm
	GRAV_CNTN	The parent material may contain gravel or is capable of weathering into a soil that will contain gravel	**Yes**/**no**

LME4 (Bates et al., 2015). For the connectivity model, we used the software Circuitscape v. 4.0.5 (McRae et al., 2013).

2.4 | Web application

To illustrate how our model can be used to explore habitat suitability and connectivity under different development scenarios, we created an interactive mapping tool using the packages LEAFLET (Cheng et al., 2019) and SHINY (Chang et al., 2020) in R. The tool is a user-friendly graphical user interface (GUI), that enables the user to interactively explore the model outputs (as presented in this paper), and to update them by uploading new shapefiles of proposed residential and industrial areas, and green spaces. The tool is hosted by an online server currently hosted by the 'Boyd Orr Centre for Population and Ecosystem Health' (University of Glasgow), that generates predictions based on the model presented here and real-time updates with the uploaded shapefiles from the user. This returns the outputs (expected habitat suitability, potential distribution and core habitat areas) via an interactive mapping tool (in the form of a web-GIS software) that allows download of the updated maps in the form of raster and shapefiles.

3 | RESULTS

3.1 | Habitat suitability and connectivity models

The final selected model had a AUC value of 0.81, indicating good accuracy (Hosmer Jr et al., 2013), and $R^2 = 0.34$.

The strongest effect on habitat suitability was shown by the proportion of built-up areas in the 75 m buffer around the points

(Table 2), indicating that habitat suitability for water voles decreases quickly to zero, when the proportion of built-up areas are >0.5 (Figure 2). Interestingly, the distance from the nearest building showed a negative effect, although with a lower effect size. This indicates that although areas containing greater proportions of buildings have a negative impact on voles, where they do occur animals appear to be distributed in areas near buildings.

The second ranked variable based on effect size was the proportion of farmland areas. This variable showed a similar negative effect as with built-up areas, although with a minor slope (Figure 2), and indicating a constant decrease in habitat suitability when the proportion of farmland increases. The proportion of industrial areas showed a similar negative pattern on habitat suitability, although with a relatively lower effect size.

Areas along the motorway were more likely to be occupied by water voles, and the model indicated that the highest probability of occurrence was between 0 and 750 m from the motorway (Figure 2).

The coefficients for distance from scrubland and green areas showed that the proximity with these features were associated with a relatively higher habitat suitability, whereas the proximity of water surfaces was negatively associated with the presence of the species. However, the effect size of the latter was weaker than with the other variables. In terms of soil characteristics, areas with the highest variability at 1 m depth were associated with the highest suitability (Table 2).

By applying this model to the 5 m grid covering the entire study area, we obtained a continuous surface of habitat suitability (Figure 3a). While most of the population was concentrated around a central area, apparently semi-isolated to fully isolated patches of suitable habitat were present surrounding this. Overall, the potential distribution of water voles (areas with habitat suitability >0.5) was 2,786 ha, corresponding to 43.4% of the study area (Figure 3b). The core areas with a habitat suitability higher than 0.75 were 644 ha (9.5% of the study area) and the areas with the highest suitability (>0.9) were 46 ha (0.7% of the study area).

The connectivity model based on circuit theory, indicated some clear corridors connecting the isolated areas of potential distribution of the species, particularly on the north-eastern side of the study area (Figure 4).

3.2 | Impact of new developments

The inclusion of future development plans altered the potential spatial distribution of the water vole population, reducing the extent of suitable habitat in some areas of high suitability (Figure 5a). Quantitative estimates of the loss of suitable habitat due to future development plans were calculated for the areas of potential distribution and the core areas (Figure 5b). We estimated a loss of 441 ha of areas of potential distribution (corresponding to 14% of the current area), a loss of 147 ha of core habitat areas with >0.75 habitat suitability (corresponding to 20% of current area) and a loss of 9 ha of core habitat areas with >0.90 habitat suitability (corresponding to 17% of current area).

Finally, we created the new connectivity map under the future development scenario and calculated the differences with the current one (Figure 6). This highlighted a major loss of connectivity between suitable habitat in the south-east region and in a number of other smaller regions within the study area.

3.3 | Web application

The most updated version of the interactive tool can be found at http://boydorr.gla.ac.uk/lucanelli/watervole/. The interface consists of different boxes and panels (Figure 7). The box in the top-right corner is a map viewer in the form of a Web-GIS interface, where the user can navigate, zoom in/out, change the background layer

TABLE 2 Results of the generalised linear mixed-effect model of water vole presence vs. environmental variables in North East Glasgow and the Seven Lochs Wetland Park (β, standardised regression coefficient, *SE*, standard error; LCI, lower 95% confidence interval; UCI, upper 95% confidence interval). Only fixed effects are shown

Variable	β	*SE*	LCI	UCI	*p*
(Intercept)	−1.14	0.208	−1.550	−0.732	<0.001
D_building	−0.26	0.062	−0.382	−0.140	<0.001
D_GREEN	−0.15	0.050	−0.248	−0.051	0.003
D_M_roads	−0.19	0.071	−0.329	−0.049	0.008
D_M_roads^2	−0.14	0.045	−0.228	−0.052	0.002
D_scrubland	−0.28	0.047	−0.374	−0.189	<0.001
D_water	−0.21	0.067	−0.337	−0.075	0.002
D_water^2	0.15	0.048	0.058	0.245	0.002
P_building	−1.34	0.082	−1.502	−1.182	<0.001
P_farmland	−0.37	0.053	−0.479	−0.271	<0.001
P_industrial	−0.28	0.075	−0.433	−0.138	<0.001
VARIATION (LOW)	0.97	0.228	0.521	1.417	<0.001
VARIATION (MOD)	0.98	0.205	0.586	1.390	<0.001
VARIATION (HIGH)	1.16	0.214	0.746	1.586	<0.001

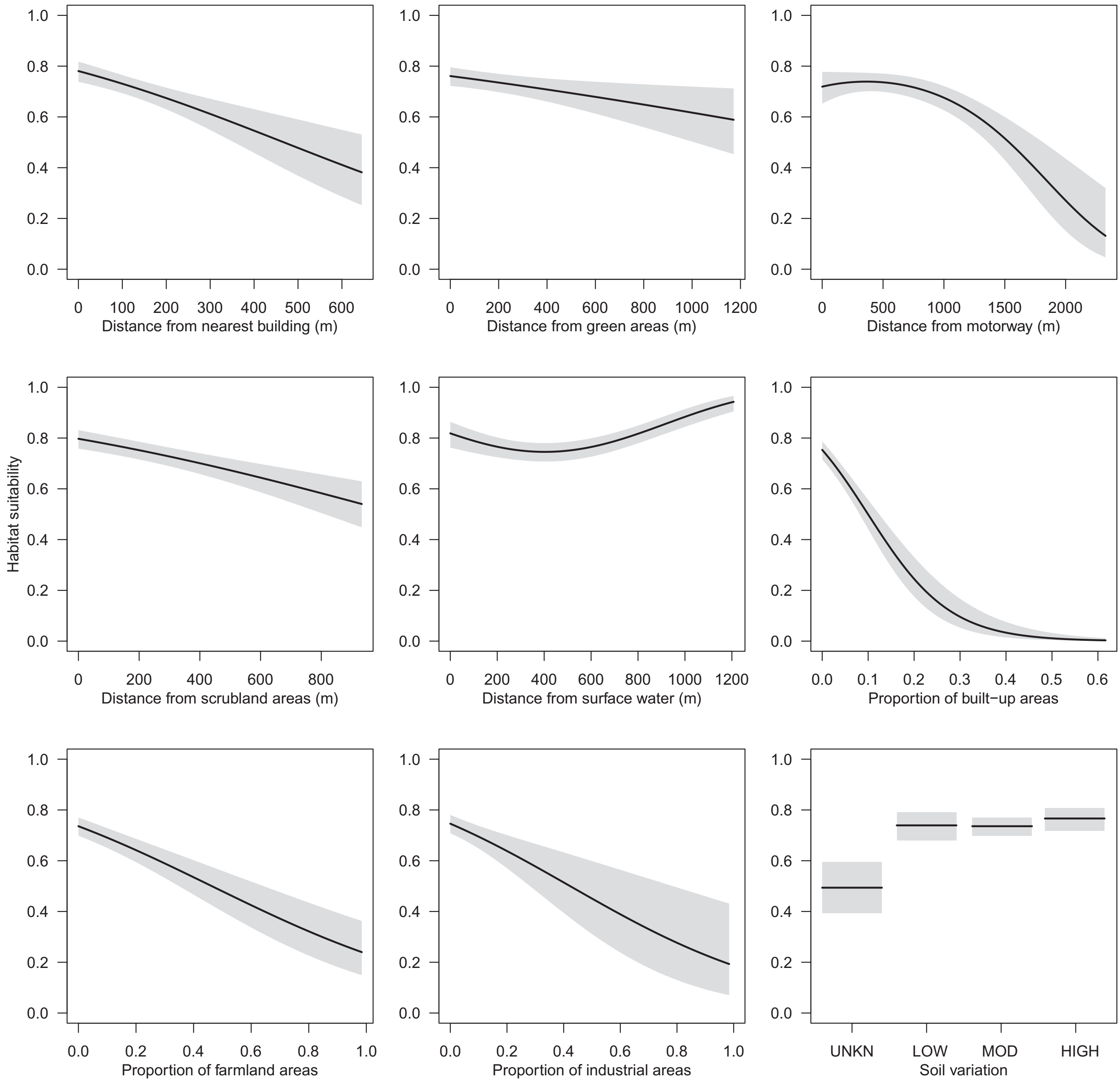

FIGURE 2 Effects (black line), and 95% confidence intervals (grey ribbons), of environmental variables on habitat suitability for water voles in North East Glasgow and the Seven Lochs Wetland Park

and select which model output to show (e.g. continuous surface of habitat suitability or the core areas under different habitat suitability thresholds). The user can then upload the shapefiles of the new environmental variables (i.e. proposed new residential areas, industrial areas and green spaces), and a new habitat suitability map with different resolutions can be generated for the new land-use scenario (shown in the box in the bottom-right corner in Figure 7). The new environmental variables are also shown on the map. Finally, the user can download the current view of the Web-GIS window, and the files of the updated habitat suitability maps. The general habitat suitability comes as a GeoTiff format, whereas the core habitat areas will be stored as ESRI Shapefile into compressed folders.

4 | DISCUSSION

4.1 | Management tool

One of the many challenges of increasing biodiversity in cities is finding ways for ecologists to work together with planners to bring about suitable development that minimises impacts on species. Planning decisions are complex and ecologists are tasked not only with making planners aware of species distributions and habitat requirements, but also how ecological connectivity can be part of urban design to increase biodiversity across our cities and urban environments. Our management tool therefore offers a user-friendly

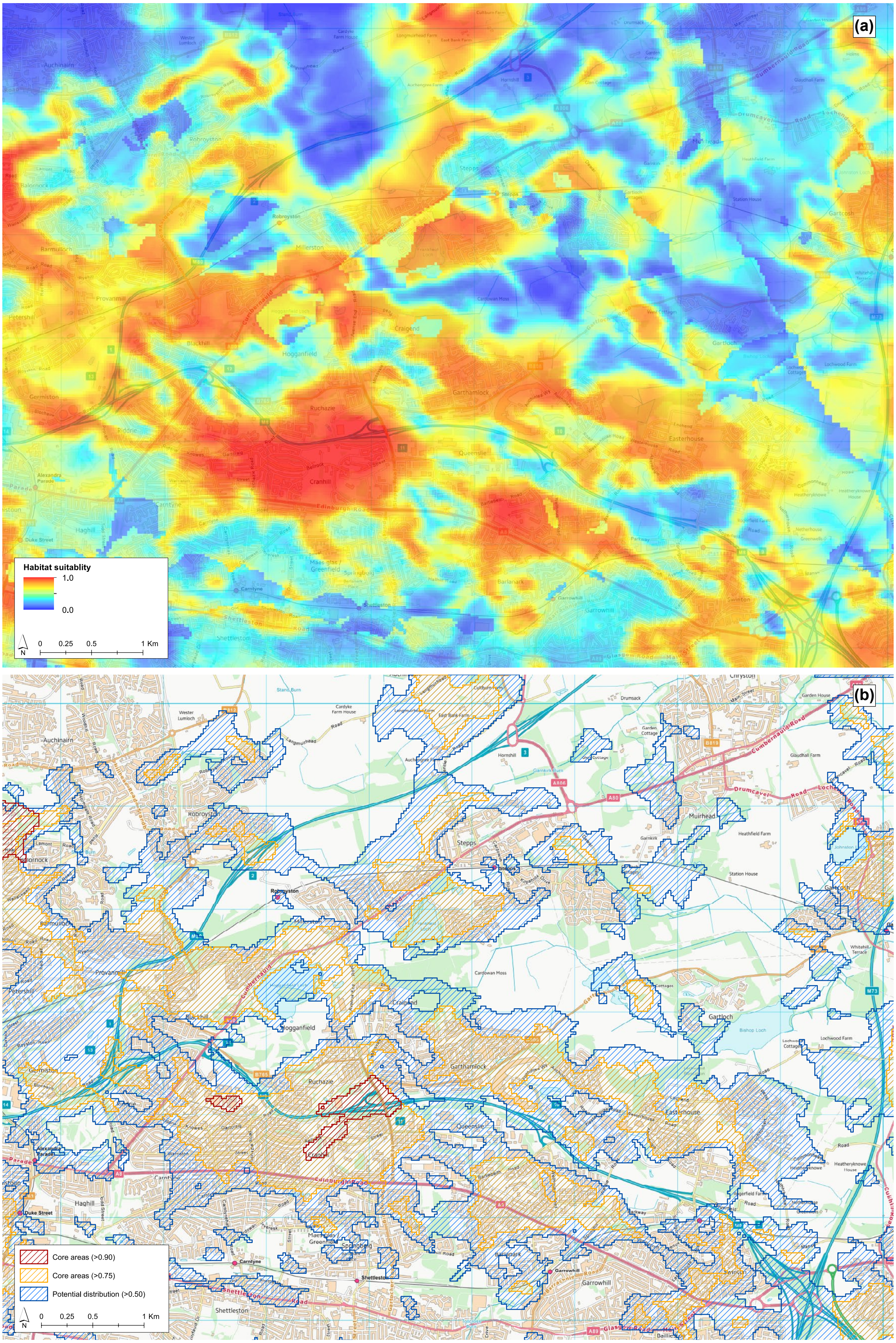

FIGURE 3 Habitat suitability model showing the probability of occurrence (a) and potential distribution and core areas under different thresholds of probabilities (b), for water voles in North East Glasgow and the Seven Lochs Wetland Park. Background images source: Ordnance Survey

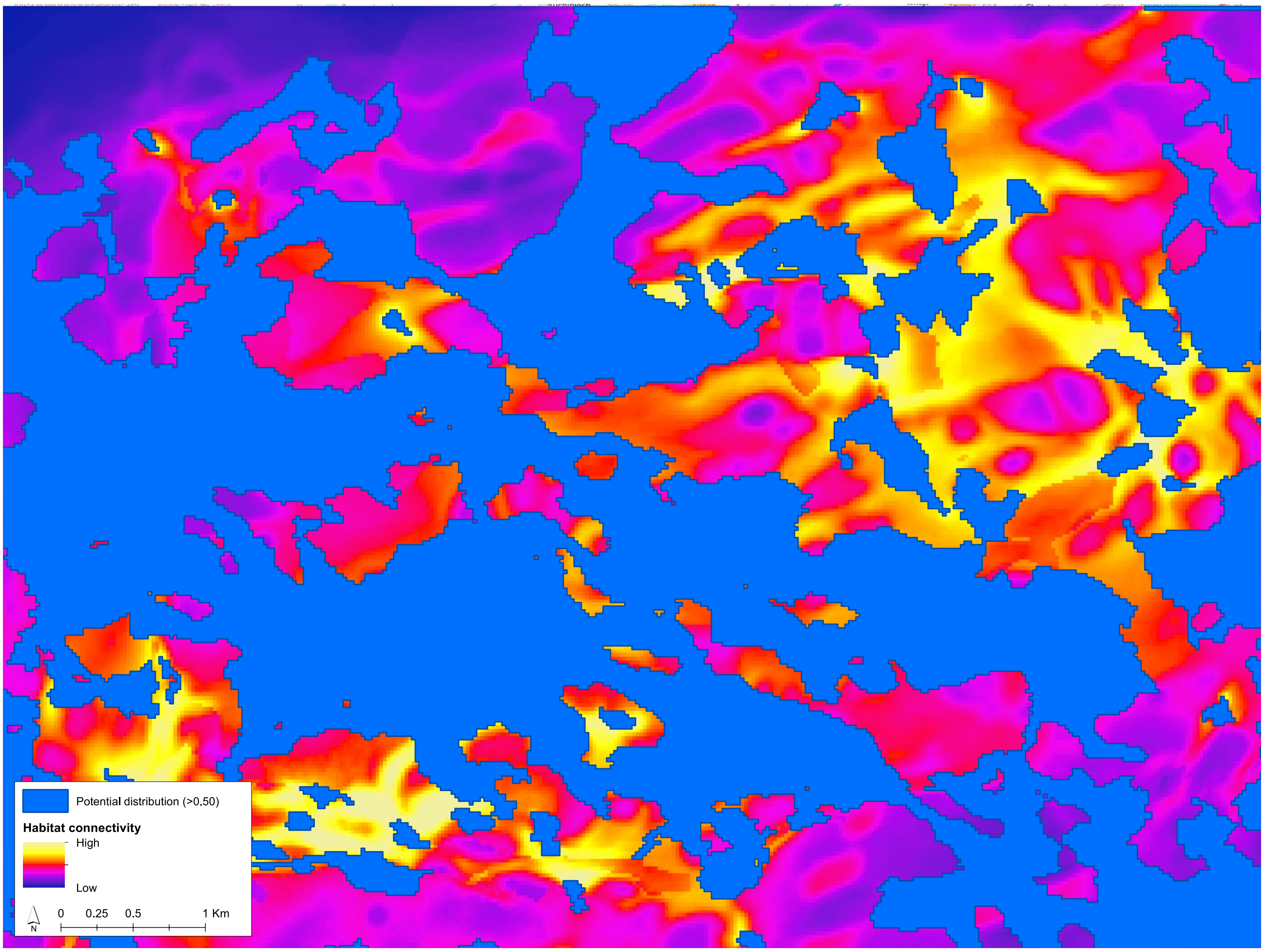

FIGURE 4 Circuit model of habitat connectivity between areas of potential distribution for water voles in North East Glasgow and the Seven Lochs Wetland Park

web application that can be used by biodiversity managers and planners to obtain a real-time picture of the implications of urban development. This tool has already been used in the scrutiny of planning applications and is currently being used by ecologists to develop a Conservation Action Plan for a species of high conservation concern. Such an approach is an example of its potential, and has wider applicability beyond the specific system, scale and data available in our case study.

4.2 | Habitat suitability

Habitat suitability for water voles increased with distance from water indicating that this population was largely non-riparian, in agreement with previous research that has focused survey effort in these habitats (Stewart et al., 2017). Although riparian habitats are important urban refuges with abundant and layered vegetation acting as natural wildlife corridors along fragmented habitats (Mahan & O'Connell, 2005), these habitats are also highly suitable for American mink *Neovison vison* that predate water voles (Wijas et al., 2019). There is some evidence that mink may avoid habitats where there is increased human disturbance (Brzeziński et al., 2018) and this may possibly explain water vole occurrence away from water in this urban area.

Not surprisingly, habitat suitability for water voles increased with proximity to green spaces. Urban green space may contain remnants of native vegetation, for which native wildlife have a preference (Mahan & O'Connell, 2005). However, the quality of the habitat is highly dependent on how managed these zones are and their level of human disturbance (Mahan & O'Connell, 2005). Residential areas (as opposed to farmland areas) were more likely to be occupied by water voles. Gardens form a large part of urban habitats and residential areas tend to have a higher connectivity with a number of different green spaces around them (Gomes et al., 2011) which could benefit water voles. To confirm this hypothesis, our model indicated that areas in close proximity with buildings had a relatively higher suitability for water voles. Habitat suitability decreased in areas with a higher proportion of industrial areas. Industrial disturbance may negatively affect wildlife that is sensitive to noise and light pollution. However, for small mammals noise coming from these sites could impair the efficiency of predators that rely on acoustic cues from prey (Shonfield &

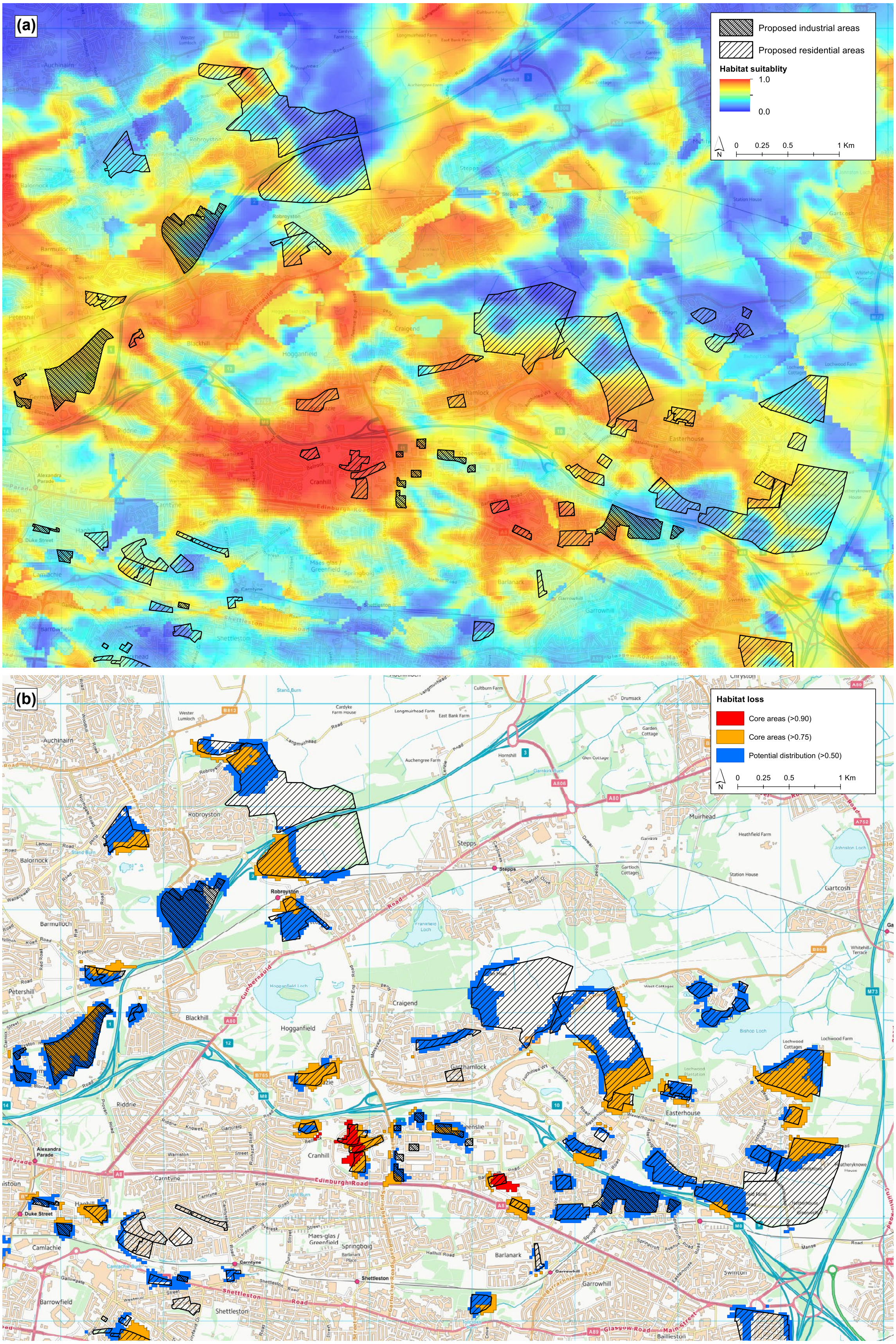

FIGURE 5 Expected habitat suitability for water vole in North East Glasgow and the Seven Lochs Wetland Park under the future development plans (a). Estimate of loss of suitable habitat due to the future development plans (b). Background images source: Ordnance Survey

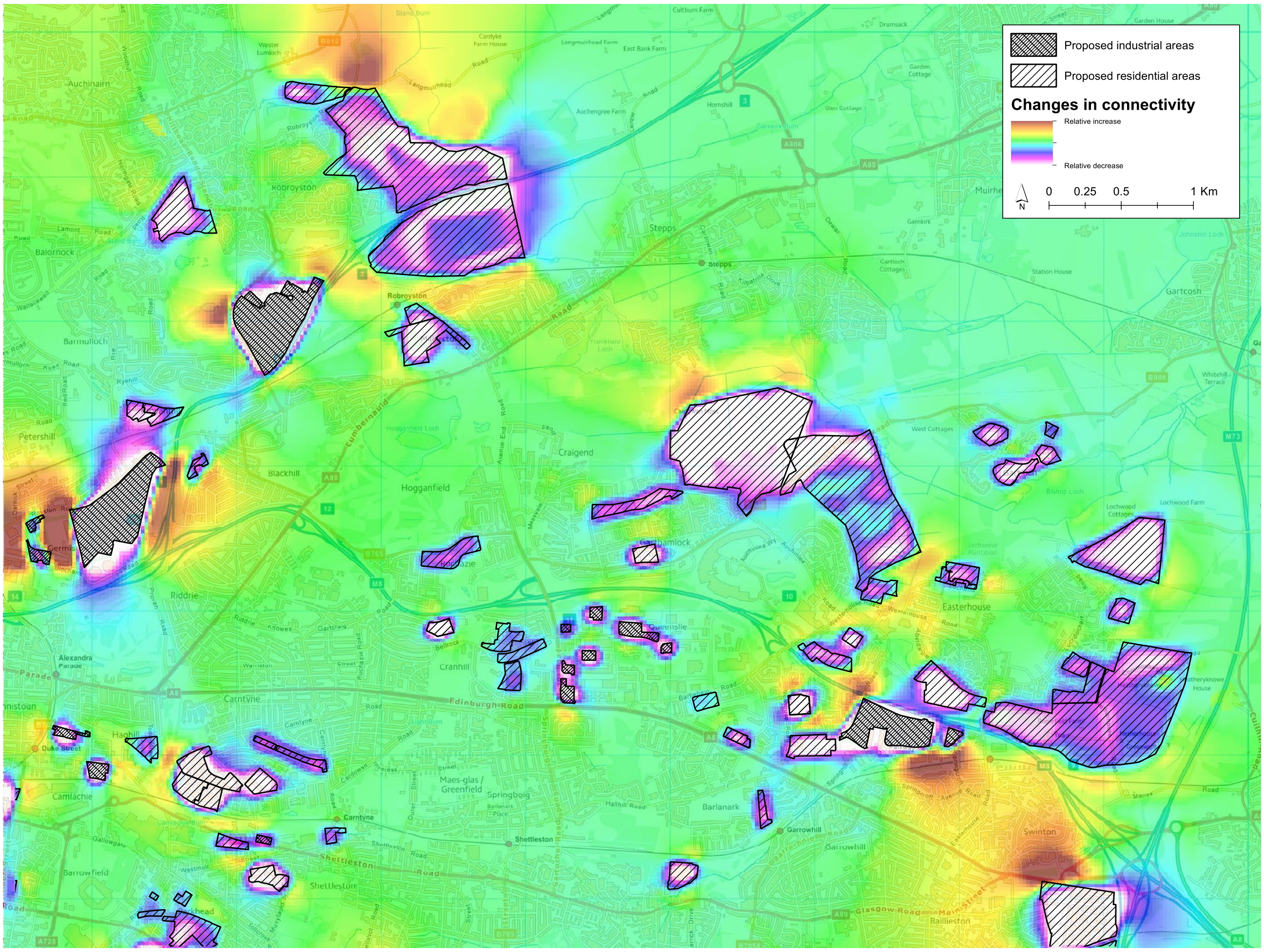

FIGURE 6 Differences of habitat connectivity for water vole in North East Glasgow and the Seven Lochs Wetland Park between future and current scenario. White areas indicate a decrease in connectivity. Background images source: Ordnance Survey

Bayne, 2019). Water voles are subject to predation by a range of avian and mammalian species but it is not known the extent to which predation varies between residential and industrial areas.

An interesting finding of the model was to highlight that water vole habitat suitability decreased with distance from the motorway but not with distance from the main primary A-roads, as the latter were not retained by the best model. This difference is likely due to the fact that the motorway edge has large areas of grassland while verges of A-roads are normally mown to short sward height. Road traffic causes wildlife mortality and roads also form a barrier to animal movement (Galantinho et al., 2017), causing habitat fragmentation by reducing their available habitats (Downing et al., 2015). Therefore, roads may have positive or neutral effects on species with small territories that avoid crossing roads, and are capable of maintaining viable populations between roads (Downing et al., 2015). Road verges are especially important for small mammals within urban or intensively farmed areas and where predators may be at greater risk of being killed by traffic (Bellamy et al., 2000).

From a burrowing perspective, small mammals generally have a preference for unsaturated freely draining soils that are soft and lacking in larger stones that may prevent tunnelling (Blank et al., 2011). Water voles appear to require uncompacted soil that facilitates burrowing activities (Bonesi et al., 2002). Perhaps due to the spatial resolution of data, soil characteristics did not clearly explain habitat suitability. Soils with the highest variability at 1 m depth were associated with the highest habitat suitability. Soil tillage could be an important factor influencing water voles as habitat suitability was low in farmland areas on the edges of the study area. Montane water voles *Arvicola scherman*, with similar fossorial ecology can have major agricultural impacts in grasslands and root crops during peak population cycles, although appear to avoid grain fields (Meylan, 1977). This may suggest that water voles have the potential for future range expansion if agricultural practices allow.

4.3 | Impact of future planned development on potential distribution

We estimated a decrease of 14% of the current potential distribution due to planned housing and industrial developments. However, the model also predicted that habitat suitability would increase in some areas, for example, where farmland will be impacted by development.

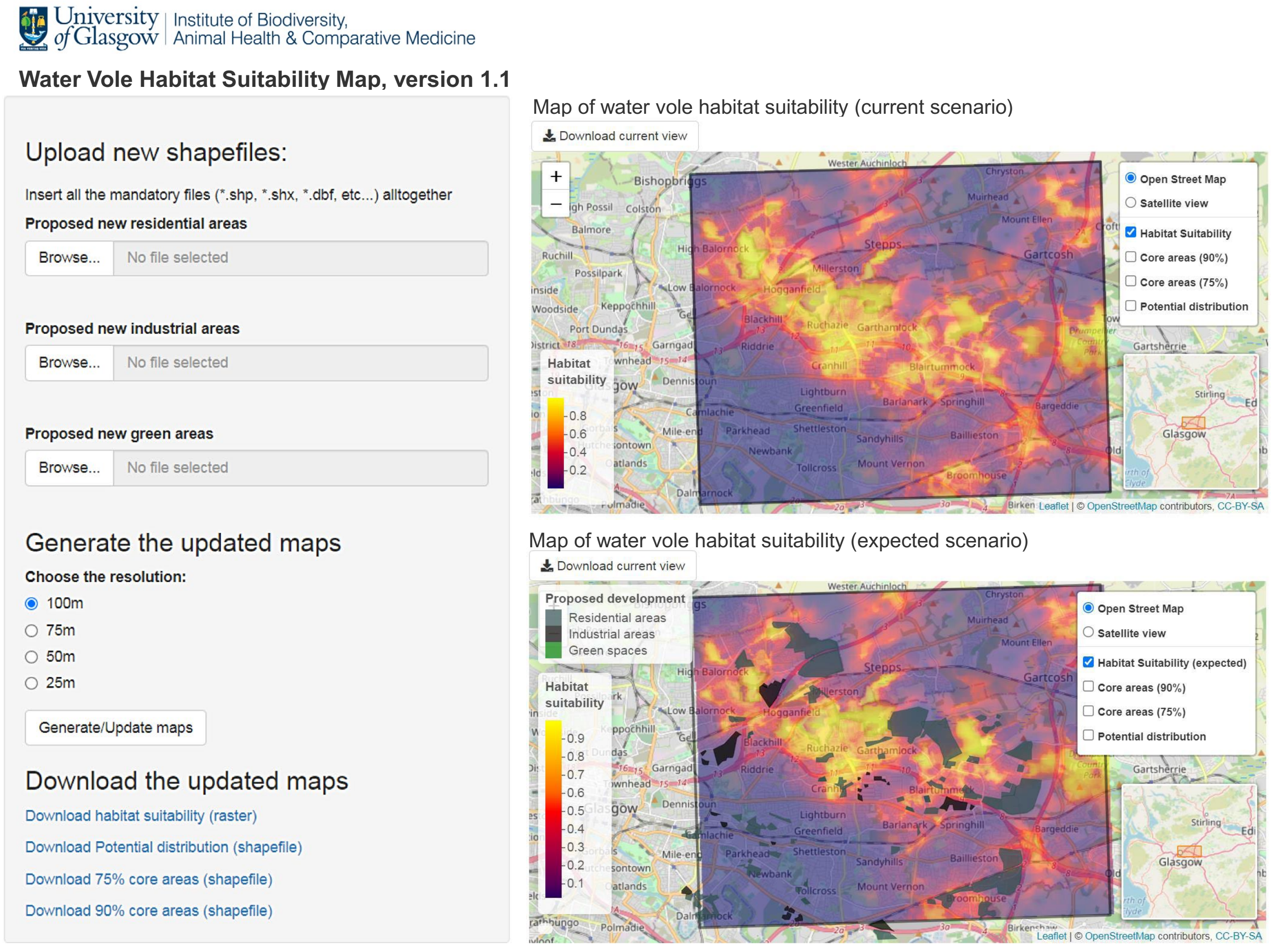

FIGURE 7 Graphical user interface of the interactive online tool (available at http://boydorr.gla.ac.uk/lucanelli/watervole/) for investigating the habitat suitability of water voles, and to assess the impact of future urban development

The development was predicted to have a major impact on connectivity along one of the motorway corridors. Animal populations in fragmented habitats can be more susceptible to local extinction due to isolation (Carter & Bright, 2003) and because habitat patches often have a low degree of connectivity between them (Baker et al., 2003). However, despite a highly fragmented urban habitat our connectivity models indicated a number of clear corridors for water voles in the study area. Previous studies of water voles showed that metapopulations often occur in areas where there are suitable patches surrounded by unsuitable habitats (Telfer et al., 2001). Even though habitats can be favourable they can be unoccupied due to low connectivity with nearby colonies (Telfer et al., 2001). Unoccupied but suitable habitat patches are just as important to study as used habitats, as they may become occupied when neighbouring colonies disperse in the future (MacPherson & Bright, 2011). Smaller populations are generally at higher risk of extinction because they are more vulnerable to the impacts of stochastic events (Telfer et al., 2001) and rely heavily on immigration from nearby colonies (Lawton & Woodroffe, 1991). Because of the importance of connectivity between suitable habitats, preserving and developing connectivity is important for conservation (McRae et al., 2008) and this was fully highlighted in our connectivity modelling.

4.4 | Conclusions and future applications

Our aim was to design an ecological modelling tool that allows ecologists and urban planners to evaluate together the impact of proposed developments on habitat suitability and connectivity for a particular species. The tool was developed by ecologists working with conservation managers and is now being used mostly by these personnel to scrutinise planning applications for housing and infrastructure development. Importantly, this approach is based on a detailed understanding of habitat suitability, allowing the opportunity for longer term management of a given species and associated habitats. The final and ongoing step in this project is to fully implement this model within the planning system so that urban planners can use this model to inform their decision-making. The web application can be further developed to iteratively update habitat models in real time. For example, the predictions that are generated after uploading the new environmental variables are based on a model that was fitted on previously collected data. However, as new data of species presence are reported, the model itself may require updating. This process of real-time model updating can of course be embedded in the tool and it would bring citizen science to a higher level, moving from simple data reporting to automatically modelling species distribution. In addition, a multi-species approach could be developed for spatial analysis of a range of species, allowing for more effective design and management of green infrastructure and biodiversity in urban areas.

AUTHORS' CONTRIBUTIONS

L.N., R.A.S., C.S., S.F., S.M. and D.J.M., conceived the ideas and L.N. designed the methodology; L.N. and B.S. analysed the data; L.N. and D.J.M. led the writing of the manuscript. All authors contributed to drafts and gave final approval for publication. We declare no competing interests.

ACKNOWLEDGEMENTS

The work was funded by NatureScot, Glasgow City Council, the People's Trust for Endangered Species and Glasgow Natural History Society. We are grateful to the Glasgow Biological Records Centre, North Lanarkshire Council, Scotland Transerv, Scottish Water and Glasgow City Council for sharing water vole records.

DATA AVAILABILITY STATEMENT

Data of water vole sites are sensitive and may be available in certain circumstances from the corresponding author on reasonable request. All the model outputs (maps, raster, shapefiles) are available and downloadable at the author's page on University of Glasgow server via http://boydorr.gla.ac.uk/lucanelli/watervole_appendix/. The source code of the interactive software is available via the Dryad Digital Repository https://doi.org/10.5061/dryad.ghx3ffbqq (Nelli et al., 2021).

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How to cite this article: Nelli, L., Schehl, B., Stewart, R. A., Scott, C., Ferguson, S., MacMillan, S. & McCafferty, D. J. (2022). Predicting habitat suitability and connectivity for management and conservation of urban wildlife: A real-time web application for grassland water voles. *Journal of Applied Ecology*, *59*, 1072–1085. https://doi.org/10.1111/1365-2664.14118