Predicting future distributions and dispersal pathways for precautionary management of human-raccoon dog conflicts in metropolitan landscapes

Qianqian Zhao1, Yixin Diao1, Yue Weng1, Zixin Huang2, Bojian Gu1, Yiqian Wu3, Yihan Wang1, Qing Zhao4 and Fang Wang1∗

1 School of Life Sciences, Fudan University, No. 2005 Songhu Rd, Shanghai 200438, People’s Republic of China
2 School of Environmental and Forest Sciences, University of Washington, Seattle, WA 98195, United States of America
3 Shan Shui Conservation Center, Beijing 100871, People’s Republic of China
4 Bird Conservancy of the Rockies, Fort Collins, CO 80603, United States of America

∗ Author to whom any correspondence should be addressed.
E-mail: wfang@fudan.edu.cn

Keywords: species distribution model, circuit model, urban ecology, urban wildlife management, habitat suitability, habitat connectivity, raccoon dog

Supplementary material for this article is available online

Abstract

Human-wildlife conflicts in cities are becoming increasingly common worldwide and are a challenge to urban biodiversity management and landscape planning. In comparison to compensatory management, which often focuses on addressing emergency conflicts, precautionary management allows decision-makers to better allocate limited resources on prioritized areas and initiate long-term actions in advance. However, precautionary approaches have rarely been developed or applied in biodiversity conservation. Since 2020, human-raccoon dog conflicts in Shanghai, one of the largest cities in the world, have tripled in reported number due to the rapid spread of the species in the city from 70 residential districts in 2020 to 249 residential districts in 2022. Here, we use ensemble and circuit modeling to predict suitable raccoon dog habitat and identify their potential dispersal pathways to aid the development of precautionary management strategies. We find that raccoon dog distribution is positively associated with several anthropogenic factors, including residential buildings and nighttime light, which could be signs that the species’ foraging behavior has adapted to the urban environment. We find that raccoon dogs only occupy 10.1% of its suitable habitat, and thus there is a high potential for the expansion of the raccoon dog population and more frequent human-raccoon dog conflicts in the near future. We predict 60 potential dispersal pathways across Shanghai, seven of which cross densely human populated areas and are likely to trigger excessive conflicts. Based on our findings, we propose priority areas where precautionary management strategies, such as constraining stray animal feeding and wildlife-vehicle collision prevention, would potentially alleviate human-raccoon dog conflicts. We present the first study on the precautionary approach of human-wildlife conflict in China’s major cities, and provide a practical example of how comprehensive modeling approaches can be used as the foundation of precautionary management in urban landscapes.

1. Introduction

Currently, 55% of the world’s human population live in cities, and the proportion is predicted to increase to 68% by 2050 (UN-Habitat 2020). While urbanization negatively influences many species, certain species expand their distributions into cities due to their ability to adapt to the urban environment (Schell et al 2021). One consequence of such change is increases in human-wildlife conflicts, including direct (e.g. aggression and nuisance) and indirect conflicts (e.g. spread of parasites or infectious diseases)
(Treves et al 2006, Collins et al 2021). In urban areas, there are four main types of human-wildlife conflicts: property damage, injuries/attacks, disease transmission, and vehicular collisions (Soulsbury and White 2015, Schell et al 2021). In terms of property damage, the destruction of infrastructure or buildings (Lee and Miller 2003), damage to lawns or fences (Washburn and Seams 2012), and rummaging in garbage bins (McKinney 2011) are frequently reported. Urban wildlife attacks on humans have become more frequent due to increases in wildlife populations (Bombieri et al 2018). Species living in urban areas tend to have high population densities, which, combined with the high density of humans and companion animals, allows for the transmission of disease from wildlife to humans or from wildlife to pets (Bradley and Altizer 2007, Lindahl and Magnusson 2020). Therefore, zoonotic and vector-borne diseases in urban areas pose a considerable risk to human health and urban economies. Last but not least, wildlife-vehicle collision has become more common as wildlife populations increase (Ng et al 2008, Hager 2009). Consequently, enormous resources are expended to mitigate human-wildlife conflict in urban areas (Soulsbury and White 2015, Schell et al 2021) due to the high cost of repairing damaged buildings, preventing or treating zoonotic diseases (Davison et al 2011, Soulsbury and White 2015), and trapping, removing, and sterilizing wildlife (Hegglín and Deplazes 2013, Schell et al 2021).

Despite the high demand for precautionary management strategies that aim to prevent human-wildlife conflict, most management practices have focused on responding to emergencies after the conflict occurs (e.g. compensation after conflict or mortality) (Fontaine 2011, Wu 2014, Soulsbury and White 2015). Conflict management that only targets contemporary circumstances and ignores future shifts in species distributions could be costly and inefficient (Soulsbury and White 2015). For example, red foxes (Vulpes vulpes) in Britain and coyote in the USA have adapted to anthropogenic interference and greatly expanded their range in the past decades, and management decisions that ignored the shifts in the distributions of these species populations were ineffective (Webbon et al 2004, Lewis et al 2015). In addition, wildlife managers found that removing attractants (e.g. food and water) provides better long-lasting conflict alleviation than simply removing animals, and incorporating species forecast can better help decision-makers find the most critical areas to implement such solutions (Spencer et al 2007, Baruch-Mordo et al 2013). However, the implementation of precautionary management also has challenges. Animal data collection in cities is difficult and there is no standardized methodology (van Bommel et al 2020). Administrators involved in wildlife management in cities often do not have the zoological expertise to perform data analysis and model optimization, and have limited understanding of wildlife management and ideas for precautionary management approaches (Messmer 2000, Merkle et al 2011). Overall, knowledge on a species’ future distribution and dispersal pathways allows precautionary management strategies to better allocate limited resources to prioritized areas and actions, and promote a sustainable coexistence between humans and wildlife in urban environments (van Bommel et al 2020).

Shanghai, China’s largest city and one of the super metropolises of the world, is in urgent need for precautionary management strategies to mitigate human-wildlife conflict, which has become much more frequent. While most large and medium-sized native mammals, such as the Asian badger (Meles leucurus), small Indian civet (Viverricula indica), and leopard cat (Prionailurus bengalensis), have been extirpated due to their inability to adjust to urbanization. On the contrary, raccoon dogs (Nyctereutes procyonoides) are growing in numbers and are rapidly expanding their urban ranges after decades of population decline (Shanghai Municipal Bureau of Agriculture and Forestry 2004). As a native species, raccoon dogs may have important functions in urban ecosystems, such as seed dispersal and pest control (Oerlemans and Koene 2007, Mulder 2012). However, according to the official human-wildlife conflict database, various forms of human-raccoon dog conflicts were reported across most districts, resulting in 180 million heated discussion threads on China’s main social media platforms (Shanghai Forestry Bureau 2021). Although the authorities have succeeded in addressing conflicts in a few communities, new cases continue to emerge, including some severe cases that involve raccoon dog attacks and retaliatory killings, and have kept most communities concerned (NetEase News 2021).

One promising opportunity to introduce precautionary management plans is the newly announced Shanghai 2035 City Planning, in which the city authorities plan to redesign greenspace to sustainably support urban biodiversity (Zepp et al 2021). It is critical to address the knowledge gap of how raccoon dogs respond to the changing urban environment, and develop precautionary management strategies to alleviate the growing frequency of human-raccoon dog conflicts. To address this challenge, we sought to understand raccoon dog habitat association and predict their dispersal pathways during population expansion in Shanghai. More specifically, we aimed to (a) assess the association between raccoon dog distribution and urban environmental characteristics, (b) predict future raccoon dog distributions and potential dispersal pathways, and (c) identify areas of precautionary management priority. Our findings contribute immediately to urban biodiversity management in Shanghai, and can be easily adapted for other systems where rapid changes in urban...
species distributions have challenged human-wildlife coexistence.

2. Material and methods

2.1. Study area

Our study was conducted in Shanghai (120°52′–122°12′E, 30°40′–31°53′N), a metropolis in the Yangtze River Delta located on China’s east coast (figure 1). The study area covers approximately 6340.5 km², with a population of 24 million residents (National Bureau of Statistics 2020). It has a sub-tropical monsoon climate with an average annual temperature of 17.3 °C and annual precipitation of 1409 mm (National Bureau of Statistics 2020).

2.2. Data collection

2.2.1. Species data

During 2019–2021, we first conducted online questionnaire surveys in China’s most widely used social media platforms (Weibo and WeChat). Link and quick response (QR) code of our questionnaires were posted on the official accounts of the Shanghai Forestry Bureau (SFB) and reposted by many non-governmental organizations and social media users. Participants reported the location and time of raccoon dog sightings and uploaded photos using the online portal. The questionnaire was approved by the Ethics Review Committee of Fudan University. In addition to online questionnaire surveys, human-raccoon dog sighting information, including the conflict type, location, date, and time were also reported to the SFB’s official human-wildlife database.

We combined our online questionnaire survey results with the SFB database to produce the most comprehensive raccoon dog data set for Shanghai. We then verified each record by conducting field surveys at each reported location. Upon arrival at a reported location, we first interviewed residents about raccoon dog sighting history, and visually verified signs of their presence with their help. For the locations where we did not find signs of raccoon dogs, we transected the area to survey for hair, feces, dens, and raccoon dogs. We recorded the latitude and longitude coordinates with a handheld global positioning system (GPS) unit when we discovered evidence of the presence of raccoon dogs. Upon receiving reports of raccoon dog presence, we conducted field surveys at each reported location to search for evidence of their presence. We used the sign transect method and searched for raccoon dogs or signs within 10 m on both sides of the transects. We kept only verified raccoon dog reports for habitat modeling, as verified reports represented the best information on raccoon dog distribution from any possible source.

2.2.2. Environmental variables

We reviewed previous raccoon dog studies (Mulder 2012, Duscher and Nopp-Mayr 2017, Mitsubishi et al 2018, Osaki et al 2019) and identified six environmental variables (water coverage, distance to water, grass coverage, trees coverage, road density, and normalized difference vegetation index (NDVI)) and three anthropogenic variables (building area, human density, and the intensity of nighttime light) that have been reported to affect raccoon dog habitat selection in the urban environment (Okabe and Agetsuma 2007, Duscher and Nopp-Mayr 2017, Mitsubishi et al 2018, Osaki et al 2019). We extracted water, grassland, woodland, and building area from the 2020 Shanghai land use map (Karra et al 2021) and confirmed its accuracy using ground truthing (Olofsson et al 2013).

We conducted our field trips in the communities where raccoon dogs were reported. For locations where we did not locate any raccoon dogs or signs of their presence, we expanded and repeated the survey into neighboring communities to avoid false reports. We obtained road data from OpenStreetMap (www.openstreetmap.org), nighttime light data from Google Earth Engine (https://earthengine.google.com), and population density data from WorldPop (www.worldpop.org). NDVI was extracted from the moderate resolution imaging spectroradiometer (MODIS) vegetation product (Huete and Didan 2002). The MODIS vegetation indices, which span the years 2019–2020, were provided at 250 m resolution every 16 d. We calculated mean annual NDVI, and used mean interannual variability as the standard deviation value for each pixel (Huete and Didan 2002). All data layers (table S1) were resampled to 300 m × 300 m resolution in ArcGIS 10.8 to fit the raccoon dog home range (Mitsubishi et al 2018). Before constructing the models, we used the variance inflation factor (VIF) to test for potential multicollinearity among candidate variables (Salmerón Gómez et al 2016). We found that no variable had a VIF value greater than 10, which indicated weak multicollinearity between our covariates (O’Brien 2007).

2.3. Modeling approaches

2.3.1. Modeling habitat suitability

Habitat suitability models apply ecological niche principles by using environmental variables to predict species’ presence/absence with the primary aim of identifying key variables that determine species distributions (Hirzel and Le Lay 2008). We used an ensemble modeling approach to model raccoon dog associations with environmental and anthropogenic variables (Breiner et al 2015). Because the surveys yielded presence-only data, we generated random pseudo-absent locations to meet the data requirements of specific statistical algorithms (Iturbi et al 2015). Pseudo-absent locations were generated at a distance larger than 1 km from verified raccoon dog locations, a distance that was adapted from the previously reported size of raccoon dog range in urban environments (approximately 17.6 ± 13.0 ha; Mitsubishi et al 2018).
We then used the R-package ‘biomod2’ (Thuiller et al. 2009) to conduct the analysis with a five-fold cross validation. We used six modeling algorithms, which included flexible discriminant analysis, generalized additive model, generalized boosting modelGBM, generalized linear model, multivariate adaptive regression splines, and Random Forest (Singh and Milner-Gulland 2011, Hao et al. 2019). We then used two cross-validation metrics, the area under curve of the receiver operating characteristic (AUC) (Fielding and Bell 1997) and the true skill statistic (TSS) (Allouche et al. 2006), to evaluate model performance (Guisan and Zimmermann 2000). We selected the two best performing models with the highest AUC and TSS values, and used a weighted average method to construct a final ensemble model (Ray et al. 2021). Our hypothesis assumed that the raccoon dog population will continue to grow until it occupies most of its suitable habitat. Such assumptions have been found to be true for species that are able to adapt well to urban environments. For example, studies on Northern Raccoon (Procyon lotor) found that their densities in urban and suburban areas are much higher than rural populations and that they occupied most suitable urban patches (Dodge and Kashian 2013, Elliot et al. 2016). Lastly, we extrapolated the species-environment associations from the model ensemble and predicted the habitat suitability of raccoon dogs throughout Shanghai to represent their potential future ranges.

2.3.2. Modeling dispersal pathways
We conducted Circuit Models (Circuitscape 4.0; McRae and Shah 2011) to identify potential dispersal pathways for raccoon dogs. Circuit Models are widely used to predict the dispersal pathways and quantify the degree of connectivity between habitat patches, biological population, or protected areas (Mcrae et al. 2008). We generated the minimum bounding geometry at points in the range of 300 m (the boundary length of one grid) with a 300 m buffer to represent their potential home ranges and used it as a focal node. A total of 30 focal nodes were generated in Shanghai.

We then generated a map with the inverse of the habitat suitability value as a resistance surface (McRae and Shah 2011). Since continuous diffusion patterns require explanatory or complementary models to determine where the best connections might be, we used a linkage mapper to further identify the pathways with the highest dispersal probabilities (McRae et al. 2012, Wang et al. 2018). We used the ratio of cost-weighted distance to reflect the quality of each dispersal pathway (Gustas and Supernant 2017). This
value represents the average resistance encountered by individuals on the best path chosen when migrating between a pair of adjacent core habitat patches (Chen et al. 2019).

2.3.3. Identifying precautionary management areas
We established rules that combine raccoon dog habitat suitability and dispersal pathway modeling results with human densities to identify precautionary habitat patches and dispersal pathways. To identify precautionary habitat patches, we first overlaid our habitat suitability map with the human density layer, and then categorized the result into three levels: habitat patches that require high precaution (habitat suitability > 0.75 and human density > 100), moderate precaution (habitat suitability > 0.75 and human density 25–100), and low precaution (habitat suitability 0.50–0.75 and human density > 100).

Among the precautionary habitat patches, some overlapped with potential dispersal pathways and thus can support raccoon dog distribution as well as facilitate their expansion (i.e. precautionary dispersal pathway). To identify such precautionary dispersal pathways, we further overlapped potential raccoon dog dispersal pathways with high precautionary habitat patches, and calculated the percentage of high precautionary habitat patches in each pathway. Potential dispersal pathways with high (>75%), moderate (50%–75%), and low (25%–50%) overlap with precautionary habitat patches were identified as precautionary dispersal pathways.

3. Results

3.1. Raccoon dog habitat suitability
We received a total 665 valid questionnaires from 191 residential district, among which 145 residential districts were reported to have raccoon dog sightings. The SFB received 324 reports about raccoon dogs from 2020 to 2021 from 89 residential districts. By combining the two data sources, we identified 215 non-duplicate raccoon dog locations in eight districts.

The best-fit algorithm was RF (AUC: 0.95 ± 0.02 and TSS: 0.83 ± 0.02) and GBM (AUC: 0.95 ± 0.03 and TSS: 0.81 ± 0.02) (figure S2). Using these two algorithms, we found that raccoon dog occurrence probability was positively associated with high building area coverage and moderate human and road density. Raccoon dog occurrence probability was highest when the nighttime light index was 40 lux, and decreased when nighttime light index exceeded 80 lux. Raccoon dog occurrence probability was highest at locations with moderate NDVI values between 0.4–0.6. As the distance to a water source increased, raccoon dog occurrence probability decreased (figure S3).

Based on species-environment associations, we identified 1279.89 km² of suitable raccoon dog habitat, which accounted for 26% of the entire area of Shanghai (figure S4). The distribution area of raccoon dogs was 129.49 km², which represented 10.1% of its suitable habitat. The distribution of suitable habitat varied among districts: areas with a habitat suitability value higher than 0.5 (17.5% of the entire area) were mainly located in Minhang and Pudong near residences, roads, and water sources. The most developed areas, such as Hongkou, Huangpu, and Xuhui, had less suitable habitat (figure 1). Pudong and Minhang had large, suitable habitats but were not yet occupied by raccoon dogs at the time of our study (figure 1).

3.2. Potential dispersal pathways
We identified 60 potential dispersal pathways and their length varied between 1.5 km and 45.7 km. Pathways shorter than 5 km were mainly in Songjiang and Minhang, and pathways longer than 10 km were mainly in Pudong and Jiading. The mean ratio of the cost-weighted distance for all dispersal pathways was 0.27, with a standard deviation of 0.21, and ranged from 0.03 to 0.98 (figure 2, table S5).

3.3. Precautionary management areas
High, moderate, and low precautionary habitat patches was distributed in clusters across Shanghai (figures 3, 4 and table S6). The three districts with the largest areas of high level precautionary habitat patches were Minhang (27.45 km²), Pudong (20.79 km²), and Baoshan District (14.94 km²). Two districts, Pudong (316.98 km²) and Minhang (221.58 km²), had the largest total areas of precautionary habitat patches, while Hongkou (17.26 km²) and Huipu (0.27 km²) had the smallest total areas of precautionary habitat patches (table S5).

We identified seven dispersal pathways with a high precautionary level. These pathways had an average length of 4.5 ± 2.8 km and were all in Minhang District. We also identified ten dispersal pathways with a moderate precautionary level, with an average length of 6.9 ± 5.3 km. Moderate precautionary pathways were mainly located in central Shanghai in Putuo, Jing’an, Changning, and Hongkou District. There were 43 dispersal pathways with a low precautionary level; they had an average length of 14.6 ± 11.6 km and were located in Jiading, Qingpu, Songjiang, Minhang, Pudong, Huipu, Hongkou, and Yangpu District (figure 5).

4. Discussion
Here we presented the first study on raccoon dog habitat suitability and potential dispersal pathways in China’s metropolitan landscape, Shanghai. We found that raccoon dog distribution was positively associated with several anthropogenic variables, such
as building area and night-time light, which indicated that raccoon dogs can adapt to the urban environment. Based on species-environmental associations, we further predicted raccoon dog distributions and identified potential dispersal pathways, which can inform precautionary management strategies.

4.1. Raccoon dog habitat suitability and dispersal pathways in Shanghai

We found that raccoon dogs respond positively to residential areas. We believe they respond positively because food sources are abundant and it is easy for them to travel via trails in urban residential areas. Our on-site observations found that raccoon dogs regularly visit dumping grounds or private gardens to search for discarded human food. We found that an abundance of cat food and wet garbage was accessible to raccoon dogs in most communities, and we observed raccoon dogs foraging on fish and frogs in private courtyards (ThePaper 2021). While our observations differed from previous findings that raccoon dogs avoid road traffic or other human activities in suburban landscapes in Japan (Mitsuhashi et al. 2018), they were consistent with a few urban bird and mammal studies that found that some species can change their foraging behavior, dietary habits, and temporal activity patterns to adapt to urban environments (Ditchkoff et al. 2006, Neumann et al. 2013).

In addition to food sources, the availability of dispersal pathways could also greatly contribute to raccoon dog rapid expansion in Shanghai, represented by the increase in the number of communities with raccoon dogs from 70 in 2020 to 249 in 2021. Meanwhile, the number of human-raccoon dog

Figure 2. Potential dispersal pathways for raccoon dogs. Darker color indicates higher dispersal probability. Red polygons represent focal nodes. The districts of Shanghai are abbreviated (BS: Baoshan, CN: Changning, EX: Fengxian, HK: Hongkou, HP: Huangpu, JA: Jing’an, JD: Jiading, JS: Jinshan, MH: Minhang, PD: Pudong, PT: Putuo, QP: Qingpu, SJ: Songjiang, XH: Xuhui, and YP: Yangpu District).
conflicts has also increased (table S7). We found that the raccoon dog range was only 10.1% of its suitable habitat, which indicated that the raccoon dog population could greatly expand and lead to more frequent human-wildlife conflicts. Most of the potential dispersal pathways that we identified were close to residential areas with relatively high vegetation coverage and road density. Canines, such as coyotes and foxes, have been reported to be more attracted to human settlements as the density of human settlements increases, and we speculate that raccoon dogs may be exhibiting a similar change (Brooks et al 2020). Our study provided a preliminary but vital prediction of how raccoon dogs disperse along roads and residential areas in Shanghai’s urban environment, and we advocate that future studies use GPS tracking devices and other techniques to thoroughly understand the mechanisms that drive the dispersion of this species and its spatial patterns.

4.2. Precautionary management strategies

For areas that have different environmental characteristics and human-wildlife conflict intensity, we suggest city authorities to develop different strategies to meet the diverse management needs. According to our findings, Pudong and Minhang District had the largest precautionary habitat patches, which indicated that there is an urgent need to regulate abnormal raccoon dog population growth and excessive expansion in these districts. Because raccoon dog distribution is positively associated with human-related food and stray cat feeding, we strongly suggest constraining stray animal feeding and strengthening wet waste management in these areas to minimize the availability of human-related food to raccoon dogs.

A study of black bears (Ursus americanus) found that bears forage for both natural and human food in an urban area in Aspen, Colorado, USA, with 77% of feeding events being anthropogenic (Lewis et al 2015). Overwhelmingly, garbage was the primary
Figure 4. Areas with different precautionary levels of human-raccoon dog conflict in Shanghai districts (BS: Baoshan, CN: Changning, FX: Fengxian, HK: Hongkou, HP: Huangpu, JA: Jing’an, JD: Jiading, JS: Jinshan, MH: Minhang, PD: Pudong, PT: Putuo, QP: Qingpu, SJ: Songjiang, XH: Xuhui, YP: Yangpu).

Figure 5. The locations of high, moderate, and low levels of precautionary dispersal pathways. The districts of Shanghai are abbreviated (BS: Baoshan, CN: Changning, FX: Fengxian, HK: Hongkou, HP: Huangpu, JA: Jing’an, JD: Jiading, JS: Jinshan, MH: Minhang, PD: Pudong, PT: Putuo, QP: Qingpu, SJ: Songjiang, XH: Xuhui, YP: Yangpu).
anthropogenic food source used by bears, which led to a strategy of using bear-resistant garbage containers in this area from 2007 to 2010. However, the strategy had limited success due to the difficulty in the proper use of bear-resistant garbage containers and the continued use of non-resistant containers. Similarly, the widespread stray cat feeding sites in Shanghai likely provide a large amount of human-sourced food for raccoon dogs.

Because raccoon dogs have a poor ability to jump and climb, one potential solution is to elevate cat food atop climbing frames to prevent raccoon dogs from accessing cat food. During our study, we observed that raccoon dogs adjusted their foraging behavior according to changes in their surrounding environment. For instance, after a two-week experiment in which cat feeding and wet garbage was controlled, raccoon dogs increased their avoidance of humans and were sighted less frequently around residential buildings. Because we found that all high precautionary dispersal pathways were located in Minhang, we urge wildlife authorities in this district to closely monitor raccoon dog movement corridors and new colonies, and identify factors that can limit or slow raccoon dog dispersal.

Critter control measures, such as ultrasound or flashlight, could be installed at key corridors to slow down the rapid expansion of raccoon dogs. Also, we suggest that transportation departments establish warning signs to reduce raccoon dog-vehicle collisions at the locations suggested by our circuit modeling. Areas with low- to-moderate precautionary levels may have less urgent management challenges, but these areas need proper strategies to prevent future human-wildlife conflict escalation nonetheless. Education could raise awareness among residents about the ecological value of urban wildlife, and teach the public how to properly handle wildlife encounters to avoid potential risks of conflict (Konig 2008, Soulsbury and White 2015, Collins et al 2021).

4.3. Adaptive management with citizen science
Citizen science has emerged as a powerful tool for addressing many of the challenges faced by conservationists (McKinley et al 2017). For instance, research on urban coyotes demonstrated the effectiveness of using citizen science to understand urban wildlife (Mowry et al 2021) through the collection of a large amount of data from citizen scientists, which can be used to implement adaptive management. Precautionary management has the potential to be implemented in an adaptive management approach to deal with the uncertainties that arise from environmental changes, improvements in sampling methods, or species adaptations (Richardson et al 2020). We advocate that an adaptive management strategy should be applied, and the management plans should be revised and updated with modeling results annually.

Using up-to-date species and environmental information, decision-makers can adjust their management strategies and remain flexible and responsive to changes in the urban environment and the species they monitor. For instance, when high precautionary habitat patches become low precautionary habitat patches, then the warning signs can be removed and the frequency of educational activities can be reduced.

The frequent collection of data by citizen scientists is particularly useful when human-wildlife interactions and conflicts become increasingly common. As a result of our study, we are optimizing data collection pathways and attempting to create a residential district information collection network that can cover all of Shanghai. Each residential district regularly reports information on the loci of human-wildlife interactions (including interaction types, photos, latitude and longitude) to the district forestry station each month, which is then aggregated by each district forestry station and submitted to the SFB. The establishment of a long-term data network can be applied in adaptive management to achieve precise precautionary and control of conflict occurrence.

4.4. Limitations of presence-only data
Both of our data sources, questionnaires and field surveys, yield presence-only data. Presence-only data are often spatially dependent due to differences in the observation rate in different landscapes and citizen scientists' tendency of reporting sightings of target animals (Bonney et al 2009, Hecht and Cooper 2014, McKinley et al 2017). To reduce the potential negative impacts of such spatial dependency on our modeling results, we conducted additional field surveys to verify each reported sighting. We believe our approach was adequate in interpreting and predicting the rapid expansion of raccoon dogs. However, we encourage future researchers to consider systematic sampling designs (e.g. distance sampling (Royle et al 2004)) and adopt integrated modeling approaches to jointly analyze systematic survey and citizen science data (Miller et al 2019).

4.5. Conclusions
By modeling suitable habitat and potential dispersal pathways, we identified precautionary management areas and proposed strategies to alleviate human-raccoon dog conflict in Shanghai. Our study provides a practical example of using comprehensive modeling approaches as the foundation of precautionary management in urban landscapes. Our findings and approach will make immediate contributions to urban biodiversity management in Shanghai, and the approach can be easily adapted for other systems where rapid changes in urban species distributions have brought challenges to the coexistence of humans and wildlife.
Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Acknowledgments

We thank Shanghai Forestry Bureau helped us in logistical details and permit applications. We thank staff of Shan Shui Conservation Center and Shanghai citizen volunteers that participated in online and field surveys. Funding for this study was provided by the National Natural Science Foundation of China (Grant No. 32270543), ‘One Yangtze’ Project of Huatai Foundation (Grant No. WTL-A000081), and Shanghai Forestry Station (Grant No. YBZX202235).

ORCID iDs

Qianqian Zhao  https://orcid.org/0000-0001-8546-8689
Yixin Diao  https://orcid.org/0000-0002-6090-5683
Yue Weng  https://orcid.org/0000-0002-1926-700x
Bojian Gu  https://orcid.org/0000-0002-6361-6246
Yihan Wang  https://orcid.org/0000-0002-0225-4915
Qing Zhao  https://orcid.org/0000-0003-2759-1114
Fang Wang  https://orcid.org/0000-0002-3922-5851

References

Allouche O, Tsoar A and Kadmon R 2006 Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS) J. Appl. Ecol. 43 1223–32
Baruch-Mordo S, Webb C T, Breck S W and Wilson K R 2013 Use of patch selection models as a decision support tool to evaluate mitigation strategies of human-wildlife conflict Biol. Conserv. 160 263–71
Bombieri G, Delgado M D M, Russo I F, Garrote P I, López-Bao J V, Fedriani J M and Penterian V 2018 Patterns of wild carnivore attacks on humans in urban areas Sci. Rep. 8 1–9
Bonney R, Cooper C B, Dickinson J, Kelling S, Phillips T, Rosenberg K V and Shirk J 2009 Citizen science: a developing tool for expanding science knowledge and scientific literacy BioScience 59 977–84
Bradley C A and Altizer S 2007 Urbanization and the ecology of wildlife diseases Trends Ecol. Evol. 22 95–102
Breiner F T, Guisan A, Bergamini A and Nobis M P 2015 Overcoming limitations of modelling rare species by using ensembles of small models Methods Ecol. Evol. 6 1210–8
Brooks J, Kays R and Hare B 2020 Coyotes living near cities are bolder: implications for dog evolution and human-wildlife conflict Behaviour 157 289–313
Chen Q, Li M, Wang X, Qamer F M, Wang P, Yang J, Wang M and Yang W 2019 Identification of potential ecological corridors for marco polo sheep in taxkorgan wildlife nature reserve, Xinjiang, China Biodivers. Sci. 27 186–99
Collins M K, Magle S B and Gallo T 2021 Global trends in urban wildlife ecology and conservation Biol. Conserv. 261 109236
white-faced Capuchins (Cebus capucinus) Am. J. Primatol. 73 439–48
Mcrae B H, Dickson B G, Keitt T H and Shah V B 2008 Using circuit theory to model connectivity in ecology, evolution, and conservation Ecology 89 2712–24
Mcrae B H, Hall S A, Beiear P and Theobald D M 2012 Where to restore ecological connectivity? Detecting barriers and quantifying restoration benefits PLoS One 7 e52608
Mcrae B H and Shah V B 2011 CIRCUTSCAPE User Guide (Santa Barbara, CA: University of California) (available at: www.circuitscape.org)
Merkle J A, Krausman P R, Decesare N J and Jonkel J J 2011 Predicting spatial distribution of human-black bear interactions in urban areas J. Wildl. Manage. 75 1121–7
Messmer T A 2000 The emergence of human-wildlife conflict management: turning challenges into opportunities Int. Biodeterior. Biodegrad. 45 97–102
Miller D A W, Pacifici K, Sanderlin J S and Reich B J 2019 The recent past and promising future for data integration methods to estimate species’ distributions Methods Ecol. Evol. 10 22–37
Mitsushashi I, Sako T, Teduha M, Koizumi R, Saito M U and Kaneko Y 2018 Home range of raccoon dogs in an urban green area of Tokyo, Japan J. Mammal. 99 732–40
Mowry C B, Lee A, Taylor Z P, Hamid N, Whitney S, Heneghen M, Russell J and Wilson L A 2021 Using community science data to investigate urban Coyotes (Canis latrans) in Atlanta, Georgia, USA Hum. Dimens. Wildl. 26 163–78
Mulder J L 2012 A review of the ecology of the raccoon dog - (Nyctereutes procyonoides) in Europe (available at: www.zoogdiervereniging.nl/)
National Bureau of Statistics 2020 Land use change and wildlife conservation-case analysis of LULC change of pench-satpudawildlife corridor in Madhya Pradesh, India (available at: www.stats.gov.cn/)
NetEase News 2021 More than 100 neighborhoods in Shanghai went to Jiading to solve the public’s panic about the raccoon dog (available at: http://fhr.sh.gov.cn/)
Shanghai Municipal Bureau of Agriculture and Forestry 2004 Shanghai Terrestrial Wildlife Resources (Shanghai: Shanghai Science and Technology Press) pp 125–48
Singh N J and Milner-Gulland E J 2011 Conserving a moving target: planning protection for a migratory species as its distribution changes J. Appl. Ecol. 48 35–46
Spencer R D, Beausoleil R A and Martorell D A 2007 How agencies respond to human-black bear conflicts: a survey of wildlife agencies in North America Ursus 18 217–29
ThePaper 2021 Raccoons have activity records in more than 30 neighborhoods in Songjiang! Expert: reducing feeding will solve it (available at: www.thepaper.cn/newsDetail_forward_1348603)
Thuiller W, Lafourcade B, Engler R and Araújo M B 2009 BIOMOD—a platform for ensemble forecasting of species distributions Ecology 32 369–73
Treves A, Wallace R B, Naughton-Treves L and Morales A 2006 Co-managing human–wildlife conflicts: a review Hum. Dimens. Wildl. 11 383–96
UN-Habitat 2020 World cities report 2020: the value of sustainable urbanization (available at: https://unhabitat.org/World%20Cities%20Report%202020)
van Bommel J K, Badry M, Ford A T, Columbia T and Burton A C 2020 Predicting human-carnivore conflict at the urban-wildland interface Glob. Ecol. Conserv. 24 e01322
Wang F, McShea W J, Li S and Wang D 2018 Does one size fit all? A multispecies approach to regional landscape corridor planning Divers. Distrib. 24 415–25
Webbon C C, Baker P J and Harris S 2004 Faecal density counts for monitoring changes in red fox numbers in rural Britain J. Appl. Ecol. 41 768–79
Wu J 2014 Urban ecology and sustainability: the state-of-the-science and future directions Landsc. Urban Plan. 125 209–21
Zepp H, Falke M, Günther F, Gruenhagen L and Dong N 2021 China’s ecosystem services planning: will Shanghai lead the way? A case study from the Baoshan district (Shanghai) Erdkunde 75 271–93