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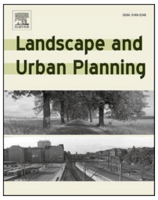

Research Paper

Urban bat occupancy is highly influenced by noise and the location of water: Considerations for nature-based urban planning

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HIGHLIGHTS

- The surrounding urban landscape is rarely considered in habitat planning for wildlife.
- Noise, water, and canopy cover influenced the distribution of urban bats in Chicago.
- Building height, density, and complexity had little to no influence on urban bats.
- Increasing noise levels will quickly outweigh the benefits of water for bats.
- Cities can provide bat-friendly habitat, especially when thoughtfully designed.

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ABSTRACT

Nature-based green infrastructure projects have become a common consideration in cities for the benefits they provide to humans. However, the co-benefits provided to wildlife are often assumed but not critically assessed. The value of green infrastructure for wildlife likely depends on the habitat requirements of a species and the spatial context of that habitat within the landscape. We examined the influence of both natural characteristics and those of the built environment, including noise, on bat species distribution in the Chicago, Illinois metropolitan area. Occupancy rates for four of the eight species in our study responded positively to the proximity of water sources, and three species responded negatively to increasing urban noise. When noise and water were examined in association with one another, the benefits of being adjacent to water quickly diminished as noise levels increased. These results illustrate the importance of considering both natural elements and the built environment in urban habitat design. Our findings demonstrate that cities - when carefully planned and designed - can provide important habitat for bats, a taxa of high conservation need.

1. Introduction

In the face of a changing climate and expanding urbanization, nature-based green infrastructure like natural green spaces, street trees, rain and pollinator gardens, and green roofs are increasingly prioritized in urban planning for the myriad ecosystem services they provide (Aronson et al., 2017). For example, green infrastructure can improve stormwater management, enhance water, soil, and air quality, increase carbon sequestration, and reduce urban heating (Demuzere et al., 2014; Gill, Handley, Ennos, & Pauleit, 2007; Tzoulas et al., 2007). More recently, urban greening has been recognized for its numerous benefits to overall human health and wellness by promoting relaxation and providing space for recreation (Tzoulas et al., 2007).

Because green infrastructure often includes natural, vegetated elements, it is generally assumed that it also provides habitat for wildlife. However, the utility of green infrastructure for wildlife likely depends on the needs of the species and the design, management, and spatial context of the habitat (Lepczyk et al., 2017; Levin, 1992; Manly,

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McDonald, & Thomas, 1993). Habitat needs for wildlife are complex, and we have a limited understanding of species-specific habitat requirements for wildlife in cities (Gallo et al., 2018). Therefore, we cannot take a "one size fits all" approach to urban habitat design. To maximize the co-benefits of green infrastructure for wildlife, we need a deeper understanding of the complex habitat needs of wildlife in urban areas.

Bats are one such taxa that could benefit from improved green infrastructure design. Bats are known to inhabit cities, but it is unclear what aspects of the urban environment influence their distributions. For example, city parks, green spaces, and residential street trees can provide forest canopies and edge habitat that likely support foraging, roosting, and movement across the landscape (Dixon, 2012; Hale, Fairbrass, Matthews, Sadler, & Fenton, 2012; Krauel, LeBuhn, & Bersier, 2016). The presence of buildings, however, may reduce available green space and restrict bat movement across the landscape, both in the two-dimensional (impervious cover) and three-dimensional (impervious clutter) space. Yet, buildings increase the amount of roosting habitat for some bat species that use human-made structures for roosting (Brigham, 1991). Thus, the relationship between bats and the built environment is less clear and likely depends on the structure and composition of buildings on the landscape. Finally, water is a key habitat requirement for bats for drinking, foraging, and navigation (Dixon, 2012; Krauel et al., 2016; Straka, Lentini, Lumsden, Wintle, & van der Ree, 2016), and may be more abundant in cities due to the increased presence of both human-made ponds that are associated with parks, golf courses, and residential neighborhoods (Fidino, Lehrer, & Magle, 2016).

In addition to habitat structure and availability, there may be less tangible determinants of urban habitat quality for bats. Sensory pollutants, such as anthropogenic noise and artificial light are increasingly recognized as a conservation threat to wildlife due to their numerous impacts on health, social and foraging behavior, and reproduction (Barber, Crooks, & Fristrup, 2010; Francis & Barber, 2013; Senzaki, Barber, & Phillips, 2020; Shannon et al., 2016). Less is known about bat responses to noise in cities, but in developed and experimental settings bats exhibited limited movement behavior (Bennett & Zurcher, 2013), modified echolocation calls (Jiang, Wu, & Feng, 2015), decreased foraging efficiency (Luo, Siemers, & Koselj, 2015), and habitat avoidance (Bunkley, McClure, Kleist, Francis, & Barber, 2015) when encountering noise. Although often synonymous with urbanization, the spatial variation of urban noise is typically overlooked when planning for wildlife habitat in cities (Parris et al., 2018), and its impact on urban bats is unknown.

The goal of this study was to inform bat-supportive green infrastructure design by determining which aspects of the urban environment influence the spatial distribution and habitat use of urban bats in Chicago, Illinois, USA. We examined three facets of the urban environment: 1) natural features, namely proximity to water, canopy cover, and forest edge, 2) the built environment, specifically building height, building density, and spatial complexity, and 3) urban noise. We predicted that bats would more likely occupy areas that were closer to water, and areas with more surrounding canopy cover and forest edge (Hale et al., 2012; Krauel et al., 2016). We also predicted that bats would avoid areas with higher impervious clutter, represented by taller buildings, greater building density, and increased spatial complexity (similar to birds; Pellissier, Cohen, Boulay, & Clergeau, 2012) as these areas would require more effort to navigate and may present a mortality risk, similar to wind turbines (Cryan et al., 2014). Furthermore, we predicted that bats would avoid areas with higher levels of urban noise because they may mask prey sounds, social calls, or may simply be aversive (Bunkley et al., 2015). Bats are currently under severe conservation threat across the United States, largely due to the spread of white-nose syndrome and expanding wind energy development that have caused staggering mortality (Blehert, Hicks, Behr, Meteyer, Berlowski-Zier, Buckles, Coleman, Darling, Gargas, Niver, Okoniewski, Rudd, & Stone, 2009; Frick et al., 2017). Bats are also important indicators of ecosystem health, and provide ecosystem services, including natural pest control (Boyles, Cryan, McCracken, & Kunz, 2011; Kunz, Braun de Torrez, Bauer, Lobova, & Fleming, 2011). Thus, understanding how cities can better support bats through improved habitat design is both beneficial to humans and critical to the long-term conservation of bats.

2. Methods

2.1. Study area

The Chicago Metropolitan area is a densely populated region of approximately 9 million people distributed across 28,120 km^2 (. Annual Estimates of the Resident Population: April 1, 2010, 2019). While the Chicago region is highly urbanized, the area contains a patchwork of green spaces in the form of city parks, golf courses, cemeteries, protected forests, and restored or recreated prairies that provide habitat for wildlife (Magle, Lehrer, & Fidino, 2016; Moskovits et al., 2004). The surrounding rural area is a human-modified system of intense row-crop agriculture with little forest canopy. Our sampling sites were located in Cook County, where the city of Chicago is located (average population density of 7355 people/km^2), suburban Lake County (average population density of 612 people/km^2), and exurban Kane County (average population density of 383 people/km^2).

2.2. Recording bat echolocation calls

Beginning in 2013, we deployed passive acoustic recorders at 9 sites in urban/suburban Cook and Lake Counties and 9 sites in exurban Kane County (Fig. 1). While maintaining the 9 original exurban sites, we added new urban sites annually, up to 16 by 2017, for a total of 28 total sites. Sites included forest preserves (n = 14), golf courses (n = 4), rooftops (n = 3; 4–7 stories), and city parks (n = 7) that were selected from the available green spaces in the Chicago area in a stratified random design to maximize variation in landscape heterogeneity and spatial distribution. Within each site, we placed one SM2BAT+ recorder (Wildlife Acoustics, Maynard, MA). To reduce factors that could obscure the recording of bat calls, we secured recorders to trees or existing structures with little to no overhead canopy and placed them away from areas of high human activity along trails, forest edges, or rooftops. To record bat echolocation calls, we attached an SMX-US (2013–2015) or SMX-U1 (2016–2017) omnidirectional, ultrasonic microphone that was fixed to a pole and extended roughly 3 m above the ground or rooftop.

Recorders were deployed for three sampling seasons per year, in May, July, and September (except in 2013, when sites were only sampled in July and September), to sample both residents and migrating bats in the spring and fall. Due to equipment limitations, we grouped sites and randomly rotated available recorders through each grouping such that every site was sampled for an approximately one-week session within the three-week sampling season. Each grouping consisted of a minimum of 3 urban sites and 3 exurban sites, and the order of sampling for each grouping varied per season. Due to logistical constraints and equipment malfunction, sites were not sampled equally. We excluded sampling sessions that had fewer than 4 active nights (the minimum standard for acoustic sampling; Loeb, Rodhouse, Ellison, & Lausen, 2015) and limited the session length to a maximum of 8 nights (median nights active = 6). During each night of deployment, recorders were set to detect high frequency sounds (i.e., bat echolocation calls) for 6 h beginning at sunset. Recordings were triggered to begin when sound above 18 khz was detected, the minimum frequency at which bats were expected to echolocate in our study area. To identify bat species present in the recordings, we used the SonoBat Scrubber Utility version 5.5 (Szewczak, 2013) to remove any non-bat recordings or recordings of poor quality. We identified bat species in the remaining files using SonoBat nMW version 3.2.1 (Szewczak, 2013). We excluded Indiana bat (*Myotis sodalis)* as a reference species as it has not been captured in our study area in over 90 years (Illinois Department of Natural Resources.

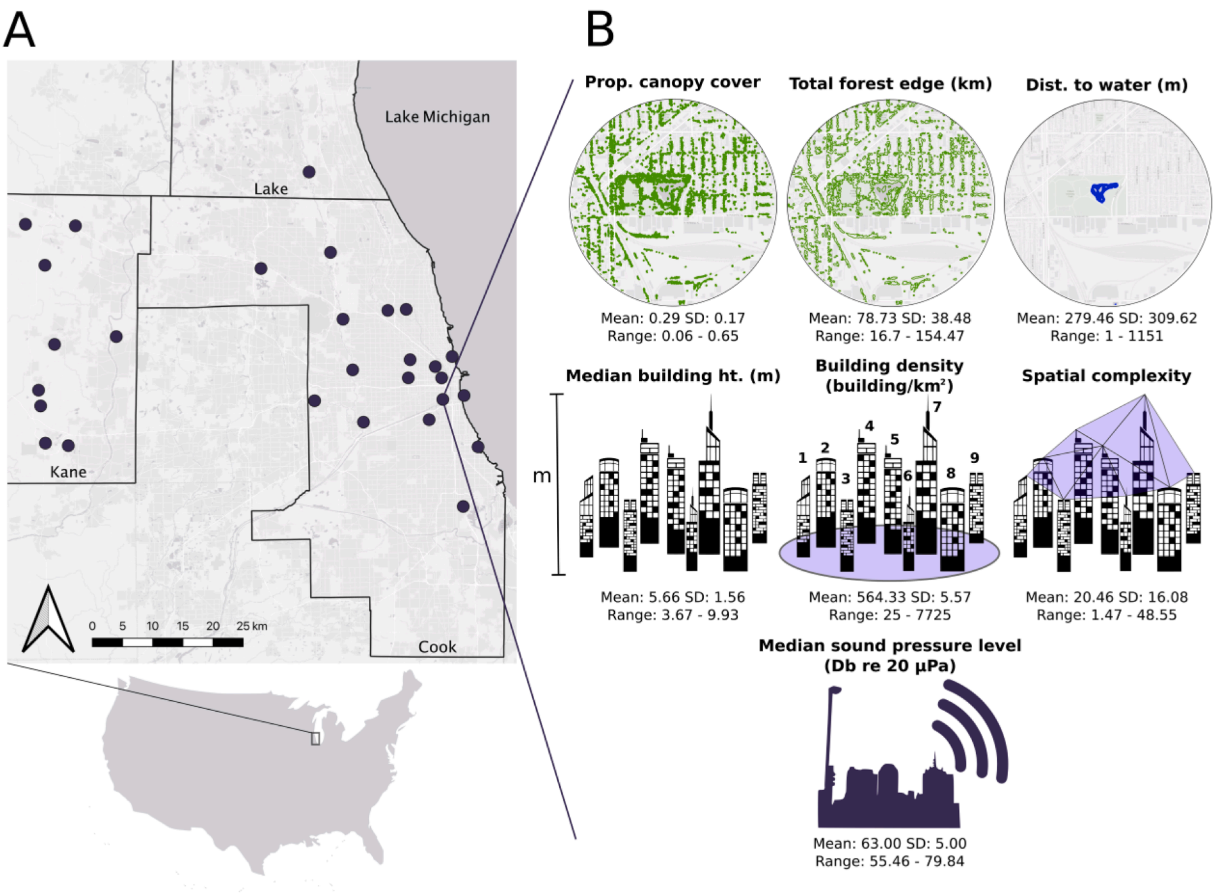

Fig. 1. Locations of passive acoustic recorders in the Chicago, Illinois USA metropolitan area (A) deployed to record bat echolocation calls. Features of the natural and built environment were measured at each location (B).

https://www2.illinois.gov/dnr/conservation/NaturalHeritage/Pages/NaturalHeritageDatabase.aspx, 2018). Thus, any calls identified as *Myotis* were categorized as either *Myotis lucifugus* or *Myotis septentrionalis,* as appropriate. To manually vet the automated process, EWL visually confirmed a subset of the species identifications generated by SonoBat, including all calls identified as *Myotis*.

2.3. Measuring the urban soundscape

In 2016 and 2017, we recorded urban noise during each deployment by fixing an additional SMX-U1 microphone to the recorder at approximately 1.5 m above ground, and cleared any surrounding vegetation that could block the microphone. We scheduled the recorder to record urban noise (3–17 khz) for one full minute every 20 min during the 6-hour nightly sampling period. Thus, each sampling night resulted in 18 1-minute clips of urban noise during the sampling night.

Urban noise files were batch processed using the PAMGuide package (Merchant et al., 2015) in R ver 3.4.3 (R Core Team, 2016) and the median value across all seasons was calculated for each site. To calibrate the data, we used the manufacturer's technical specifications (Wildlife Acoustics, 2011) for the SMX-U1 microphone and a user-defined gain setting of 48 dB (settings can be found in Appendix A).

2.4. Landscape-level predictor variables

To assess the influence of both built and natural environmental features on the presence of each bat species, we calculated predictor variables within a 1 km fixed-radius buffer around each recorder location. We chose this distance as it is considered a general foraging distance for bats and is often used in the literature for landscape analyses (Dixon, 2012; Pauli, Zollner, & Haulton, 2017; Weber & Sparks, 2013). We evaluated the following site-level predictors:

Building density, height, and complexity – To assess how morphology and composition of the built environment may influence bat occupancy we calculated 1) building density, 2) median building height and 3) the complexity of building heights within a 1-km buffer of each site (Fig. 1). We used two data sources to develop a building footprint dataset. First, we isolated raster cells categorized as "building" from the 2010 High-Resolution Land Cover data set for northeast Illinois and northwest Indiana (Chicago Metropolitan Agency for Planning, 2016). Second, we used an available dataset from the City of Chicago (City of Chicago, 2015) that contained building footprints for all buildings within the administrative boundaries of the city of Chicago. To calculate building density we took the log of the total number of buildings within a 1-km buffer of each sampling site. The distribution of building density around each site was highly skewed, therefore we log-transformed this covariate to help with model convergence. To calculate building height we used LIDAR data available from Cook, Lake, and DuPage counties. Following a procedure outlined by Czoli (2014), building height was measured by taking the lowest point located within a 2 m ring around a building footprint, but separated from the building edge by 1 m, and subtracting this value from the average height within a building footprint. We then calculated the median height of buildings within each 1-km buffer.

To calculate building height complexity we applied the Zenner (2000) metric for measuring forest complexity to our building data layers. This measure of complexity takes into consideration the interaction between building height and the spatial location of each building. More specifically, all buildings within the 1-km buffer were represented as 3-dimensional data points with the x and y coordinates representing the horizontal locations, and the z coordinate representing building height (Zenner, 2000). We then used the *delaunayn* function (Barber, Dobkin, Dobkin, & Huhdanpaa, 1996) in the R package *geometry* (Habel, Grasman, Gramacy, Mozharovskyi, & Sterratt, 2019) to connect the three nearest neighbors in the x, y, z space and form a network of non-overlapping triangles. The complexity index was then defined as the sum of the surface areas of the non-overlapping triangles (Zenner, 2000). Higher index values indicate greater variation in building height around a site (i.e. height complexity). See Appendix A for a detailed description and R scripts for this procedure.

Canopy cover – To calculate tree canopy cover around each sampling site, we again used the 2010 High-Resolution Land Cover dataset (Chicago Metropolitan Agency for Planning, 2016) to determine the proportion of raster cells categorized as ‘tree’ within each 1 km buffer (Fig. 1).

Forest edge – To assess how forest edge influenced bat occupancy we used the LecoS (Jung, 2016) tool in QGIS ver. 2.18 (QGIS Development Team, 2009) to convert all adjacent ‘tree’ raster cells in the 2010 High-Resolution Land Cover dataset to individual ‘forest patches’ (Fig. 1). We then converted this raster into a vector and calculated the area of each individual forest patch. We could not find any information in the literature to help define a suitable size habitat patch for urban bat species. However we assumed that the circumference around a single residential tree would not constitute “forest edge”. Therefore, we removed patches that were less than 99 m^2 to eliminate single or small clusters of what we considered single residential or street trees. We converted our reduced vector back to a raster, and increased each patch by 5 m to fill in potentially insignificant gaps. Since our raster layer was 1-m resolution we summed the number of edge cells of each patch that was within the 1-km buffer to calculate the total edge length within each buffer.

Distance to Water – Using the 2010 High-Resolution Land Cover data set, we calculated the Euclidean distance (m) between each sampling site and the nearest raster cell that was categorized as ‘water’ (Fig. 1). Open water sources included rivers, streams, lakes, and natural or human made (e.g. golf course ponds) water sources.

2.5. *Statistical analysis*

To assess how landscape characteristics of the urban environment influenced bat species occupancy, we used a Bayesian single season occupancy model that contained a random effect on sampling season (Appendix A). By modeling the sampling season as a random effect, we allowed partial pooling across seasons, which improves estimates (Gelman & Hill, 2006), and makes explicit the assumption that occupancy between consecutive sampling seasons was not wholly independent. For each species, we fitted a single model including all predictor variables and used Bayesian lasso regression to estimate the occupancy probabilities of each species. We modeled the detection probability of each species as a function of the average daily precipitation at each site during each sampling session, as precipitation could affect the microphone’s recording quality and the activity of bats. We also included the individual detector used during each sampling session at each site ($n = 12$) as a covariate on detection since devices could vary in their microphone quality. We did not expect the detectors to vary in their ability to detect individual species so this parameter was kept constant across species (Appendix A; Wildlife Acoustics, 2020).

All predictor variables were tested for correlation (r) among variables. We found moderate correlation ($r > 0.7$) between impervious cover and length of roads ($r = 0.80$), impervious cover and sound pressure levels ($r = 0.77$), and length of roads and distance to water ($r = 0.75$). Although correlation among predictor variables can result in high variability in regression coefficients, our implementation of lasso regression is a well-established method to reduce this variability when multicollinearity exists (Oyeyemi, Ogunjobi, & Folorunsho, 2015). All parameters were given vague Laplace priors (Appendix A). The Laplace distribution shrinks values for variables that have low explanatory value toward 0 based on the tuning parameter λ and reduces the variability of estimates when multicollinearity exists (Oyeyemi et al., 2015).

Predictor variables were standardized prior to model fit and posterior distributions of model parameters were estimated using a Markov chain Monte Carlo (MCMC) algorithm implemented in ver 4.2.0 of JAGS (Plummer, 2003) using the *runjags* package (Denwood, 2016) in R ver 3.4.3. Six parallel chains were run from a random starting value with a thinning rate of 5 for 25,000 iterations after burning in 15,000 samples. Model convergence was assessed by checking that the Gelman-Rubin diagnostic statistic for each parameter was <1.1 (Gelman & Rubin, 1992) and by visually inspecting the MCMC trace plots for each parameter. We considered any parameter to have evidence of a significant effect if the 95% Bayesian credible intervals (BCI) did not overlap zero.

3. Results

Based on 56,051 ultrasonic call files recorded over 1725 sampling nights, we detected eight bat species in the Chicago area: big brown bat (*Eptesicus fuscus;* 939 nights detected and detected at 93% of sites), little brown bat (*Myotis lucifugus;* 88 nights detected and detected at 57% of sites), Northern long-eared bat (*Myotis septentrionalis;* detected 1 night at 1 site (3%)), Eastern red bat (*Lasiurus borealis;* 502 nights detected and detected at 96% of sites), silver-haired bat (*Lasionycteris noctivagans*; 923 nights detected and detected at 100% of sites), hoary bat (*Lasiurus cinereus;* 440 nights detected and detected at 93% of sites), evening bat (*Nycticeius humeralis;* 390 nights detected and detected at 79% of sites), and tricolored bat (*Perimyotis subflavus;* 146 nights detected and detected at 68% of sites). Only 2 calls were identified as Northern long-eared bat, thus we excluded this species from our analysis.

3.1. *Influence of urban noise*

Median sound pressure level had a significant, negative effect on the occupancy rates of two species in our study: silver-haired bat ($\beta = -0.71$, 95% BCI $= -1.24$ – -0.23), and big brown bat ($\beta = -0.94$, 95% BCI $= -1.62$ to -0.36); Fig. 2. We also found a moderate negative effect of sound pressure level on evening bat ($\beta = -0.39$, 90% BCI $= -0.82$ – -0.02).

3.2. *Influence of building density, height, complexity*

We did not observe a significant effect of building density, height, or complexity on the occupancy rates of any species in our study (Fig. 2). However, we did find a moderate negative effect of building height on hoary bat ($\beta = -0.31$, 90% BCI $= -0.65$ – -0.02).

3.3. *Influence of natural features*

There was a positive effect of canopy cover on tricolored bat occupancy ($\beta = 0.56$, BCI $= 0.19$ – 0.98). Distance to water had a negative effect on the occupancy rates of tricolored bat ($\beta = -0.58$, BCI $= -1.31$ – -0.02), evening bat ($\beta = -0.57$, BCI $= -1.05$ – -0.14), hoary bat ($\beta = -0.63$, BCI $= -1.10$ to -0.20), and big brown bat ($\beta = -0.77$, BCI $= -1.24$ – -0.34; Fig. 2). These results indicate that being closer to water increased the probability of occupancy for these 4 species. Parameter estimates revealed no significant effects of total forest edge on the occupancy of any of the eight bat species analyzed (Fig. 2).

3.4. *Predicting the relationship between urban noise and water*

Both distance to water and median sound pressure level had significant effects on the occupancy rates of several species (Fig. 2). For species in which urban noise and distance to water had a significant or moderate effect, we calculated the median sound pressure levels at

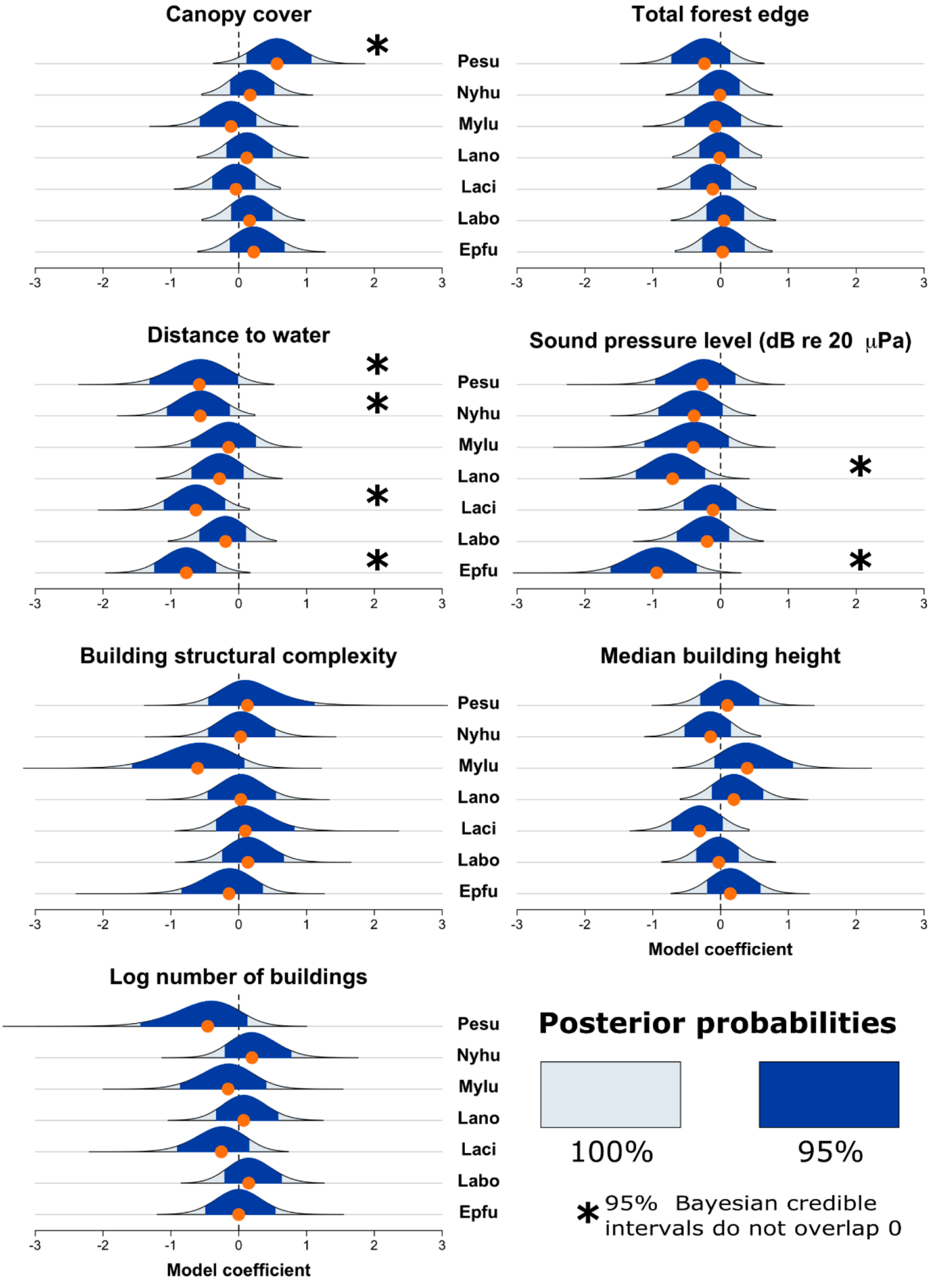

Fig. 2. Posterior distributions of model coefficients quantifying the effects of the natural and built environment on the occupancy probability of urban bats, based on echolocation calls recorded at sites across the Chicago, Illinois, USA metropolitan area. Red dots along the bottom of each distribution represent the median coefficient value. 95% Bayesian credible intervals that do not overlap 0 indicate a significant relationship (either positive or negative), as indicated by the asterisk. Species include, tricolored bat (*Perimyotis subflavus;* Pesu); evening bat (*Nycticeius humeralis;* Nyhu); little brown bat (*Myotis lucifugus;* Mylu); silver-haired bat (*Lasionycteris noctivagans;* Lano); hoary bat (*Lasiurus cinereus;* Laci), Eastern red bat (*Lasiurus borealis;* Labo), and big brown bat (*Eptesicus fuscus;* Epfu). Bat occupancy was influenced by canopy cover, distance to water, and sound pressure level. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

which the positive effect of being directly adjacent was 0 ($\frac{\beta_{water} {}^{*} x_{water=0}}{-1+\beta_{spl}}$). We found that the benefits of being 0 m from water dissipated at 66.68 db (BCI 64.33 – 74.34 db) for big brown bat, 64.79 db (BCI 62.59 – 71.17 db) for silver-haired bat, and 69.12 db (BCI 30.07–129.61 db) for evening bat (Fig. 3a). At these sound pressure levels, the benefit of being adjacent to water was outweighed by the negative impact of urban noise. Additionally, we predicted the probability of occupancy at a site 0 m from water as a function of median sound pressure levels, which illustrates how patterns of bat occupancy may change near water if

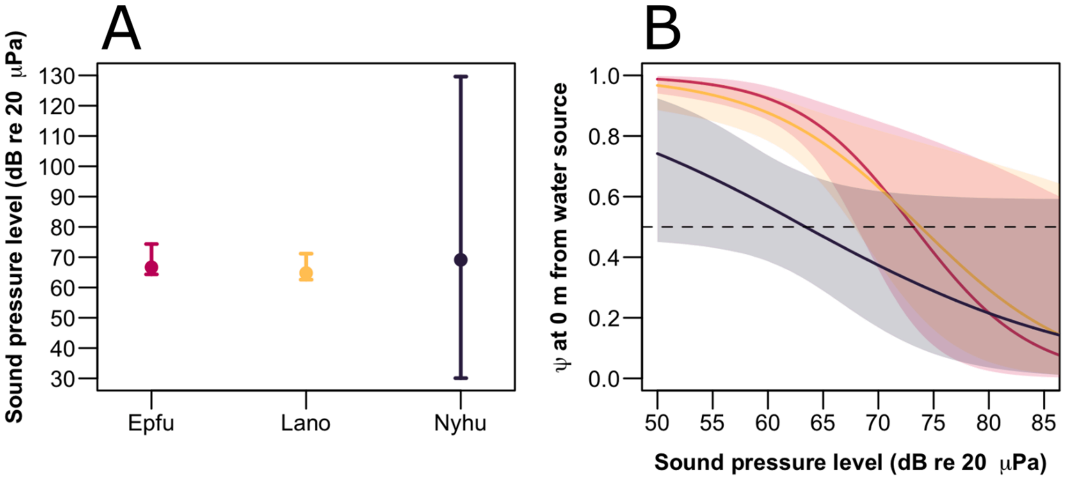

Fig. 3. Distance to water and chronic urban noise influenced the occupancy of 3 urban bat species: big brown bat (*Eptesicus fuscus;* Epfu), silver-haired bat (*Lasionycteris noctivagans;* Lano), and evening bat (*Nycticeius humeralis;* Nyhu), as determined by echolocation calls recorded at sites across the Chicago, Illinois, USA metropolitan area. (A) Median sound pressure levels at which the negative effect of noise begins to outweigh the positive benefits of being located adjacent to water. Error bars represent the 95% BCI (B) occupancy probabilities (ψ) decrease as sound pressure levels increase even when sites are located 0 m from water. Shaded areas represent the 95% BCI. Colors associated with each species in panel (A) correspond to the same species in panel (B).

sound levels were increased. Sound pressure levels ranged from 55.46 to 89.84 dB across our study, which are equivalent to conversational speech and a freight train at a 30 m distance, respectively (OSHA, 2013). Therefore, we began our predictions at 50 db – 5 db below the lowest median sound pressure level in our study. All other variables were held at their mean. The probability of occupancy at 0 m from water decreased at different rates for each species as a function of sound pressure levels (Fig. 3b). The probability of occupancy dropped below 50% at 73.19 db (BCI 68.04 – 91.90 db) for big brown bat, 73.81 db (BCI 67.82 – 98.59 db) for silver-haired bat, and 63.40 db for evening bat (Fig. 3b). The lower bounds of the BCI for evening bat was 50.00 db, however the upper bound did not cross 0.5 at a realistic decibel level (Fig. 3b).

4. Discussion

As expected, both natural elements and the built environment influenced occupancy for several bat species in our study area. Specifically, we predicted that bats would favor areas closer to water, with more forest edge and canopy cover. Of the natural elements we examined, distance to water had the strongest effect on occupancy rates for 4 species; bats were more likely to occupy sites that were closer to water. Contrary to our predictions, building features did not influence occupancy for any species in our area, however, urban noise had a negative influence on occupancy rates of 3 species that we detected. When we examined the interplay between water and urban noise, we found that the benefits of water for bats were quickly diminished by increasing noise. These results emphasize the importance of considering the synergies between natural features and the built environment when planning for bat habitats in green infrastructure design. This study also provides the first evidence that bats avoid areas due to urban noise.

We measured the built environment using building density, height, and complexity, instead of standard, coarser metrics like impervious surface (e.g., Dixon, 2012, Hale et al., 2012, Gili, Newson, Gillings, Chamberlain, & Border, 2020). Impervious surface fails to capture the three-dimensional form of the built environment, which has been shown to be highly relevant to birds (Pellissier et al., 2012). Contrary to our predictions, we failed to detect a significant effect of median building density, height, or complexity on bat occupancy. Bat species may vary in their responses to different landscapes based on foraging strategy and wing morphology (Denzinger & Schnitzler, 2013; Haddock, Threlfall, Law, & Hochuli, 2019). For those species that are more adapted to flying in open spaces (e.g., hoary bat, big brown bat; Menzel et al., 2005), our inability to detect an effect of impervious clutter could be explained by a difference in the “scale of clutter” between forests and buildings. Dense forests are likely more cluttered and complex than the smooth, non-natural surfaces of the built environment, and therefore the three-dimensional built environment may not present navigational challenges for the species in our area. Moreover, our results suggest that these bat species are not avoiding urban core areas, and thus, these areas may present unique opportunities to create novel habitat for wildlife.

We found a positive effect of canopy cover for the tricolored bat, and this is likely reflective of their life history and ecology, as they are known to roost in tree foliage (Perry, Thill, & Leslie, 2007; Veilleux, Whitaker, & Veilleux, 2003) and are considered to be clutter-adapted (Menzel et al., 2005). For those species that are more adapted to flying in open spaces or along forest edges (e.g., big brown bat (Menzel et al., 2005), little brown bat (Broders, Findlay, & Zheng, 2004)), it is possible that urban areas provide alternate sources of roosting habitat (e.g., older buildings; Kubista & Bruckner, 2015) and concentrations of foraging opportunities (e.g., street lights; Jung & Kalko, 2010) such that bats in cities are less dependent on finding areas with continuous forest cover. Similarly, we failed to detect an effect of forest edge on any species occupancy, even though this variable has been shown to have an effect on the distribution of bats in other studies (Krauel et al., 2016; Pauli et al., 2017). The concept of urban forest edge and its contribution to habitat for urban wildlife is rarely examined and worth further exploration.

Many bat species forage over and drink from open water (Li & Kalcounis-Rueppell, 2018). Of the environmental variables we examined, we found that distance to water had the strongest effect on bat species occupancy. These results align with previous research that show positive relationships between bat foraging and water sources (Dixon, 2012; Krauel et al., 2016; Straka et al., 2016), and recent work from Chicago that predicted hotspots of bat activity along Chicago area waterways (Gallo et al., 2018). Blue-green corridors are often considered in urban planning for their importance with stormwater management, improved water quality, and groundwater recharge (Brears, 2018). Our results show that water sources strongly influence the presence of urban bats and suggest that blue-green corridors could provide important habitat for bats as well. The connectivity that these corridors provide may be especially important for bats in cities where habitat is often fragmented and disconnected.

As predicted, our results demonstrated a significant, negative effect of urban noise on the occupancy probabilities of urban bats. Sites that had higher sound pressure levels were less likely to be occupied by evening bats, silver-haired bats, and big brown bats (Fig. 2). Noise is increasingly recognized as a detrimental disturbance with numerous impacts on wildlife (Shannon et al., 2016). Although most bat species in our study area forage by catching prey during flight, and thus primarily use ultrasonic echolocation to forage and navigate the environment, bats can hear frequencies far below ultrasound, and often use the full acoustic frequency spectrum to acquire key information for social communication and foraging (Bunkley et al., 2015; Feldhamer, Carter, & Whitaker, 2009; Gillam & Fenton, 2016; Hackett, Korine, & Holderied, 2014; Poussin & Simmons, 1982). In noisy environments, social communication could be entirely or partially masked (Barber et al., 2010), or sounds produced by prey could be dampened (Morley, Jones, & Radford, 2014), thereby reducing foraging efficiency for bats (Bunkley, Barber, & Foster, 2015; Siemers & Schaub, 2011). Despite these and known impacts on other species (Shannon et al., 2016), noise is rarely considered in the context of urban planning and habitat design for wildlife (Parris et al., 2018). Our results suggest that surrounding noise levels need to be strongly considered when designing habitat with wildlife in mind, especially when targeting bats.

Although water was important for many bat species, our results demonstrated that its benefits can be dramatically compromised by noise (Fig. 3). Once solely considered as modes for transportation and wastewater diversion, urban waterways are increasingly recognized for their value as a natural resource, and many cities have undertaken major waterway revitalization projects in the last ten years (e.g., City of Los Angeles, 2007; Metropolitan Planning Council, 2016; Houston Parks Board, 2020). A shifting view of urban waterways brings competing demands including ecosystem services, commercial and residential development, and recreational opportunities (Metropolitan Planning Council, 2016). As water quality improves, urban waterway revitalization presents an opportunity for expanded habitat and connectivity for urban bats. However, for these spaces to act as valuable bat habitat, we must consider both the composition of the habitat and the amount of anthropogenic noise associated with other competing demands. Without these considerations, wildlife may avoid a site completely, wasting limited funding and resources dedicated toward these conservation efforts.

Solutions for noise mitigation, especially those applying to a broad source, are challenging (Shannon et al., 2016). Ideally, the impact of noise on wildlife could be reduced by prohibiting noisy commercial or industrial development such as factories, outdoor music venues, and athletic stadiums adjacent to natural areas. If such development is unavoidable or already present, mitigation may be possible using sound absorbing or sound blocking panels around the site, or by directing a noise point source away from natural areas. Unfortunately, these solutions may be expensive, aesthetically undesirable, and could reduce connectivity by impeding wildlife movement (Shannon et al., 2016). Thus, we suggest careful weighing of the benefits and drawbacks of noise mitigation options to avoid unintended consequences for wildlife.

Using acoustics to identify bat species occupancy can present some challenges. Various factors (e.g., the recording conditions, length of the call, proximity of the bat to the microphone), can cause overlap in call characteristics, which can result in false positives, even with the use of automated call classification software. To account for this uncertainty, our classification approach was conservative in several ways: 1) we examined occupancy rather than a metric of activity that would rely on accurate identification of every call, 2) we visually confirmed all calls that were classified as species that are rare in our area or rare for a particular site, 3) we excluded all call files that were not of good quality, and 4) we did not attempt to differentiate Myotis species that are known to have substantial acoustic overlap (Szewczak, 2020). Furthermore, we do not expect that false positive rates would vary among sites, since we followed the same protocol and used the same automated call classification software. Additionally, we measured chronic sound pressure level at each study site, thus, our results capture spatial variation in noise levels across sites, but fail to capture temporal variation in noise levels. However, we did not expect noise levels to have varied substantially across the time frame of the study. We also did not attempt to categorize the source of noise from the recordings. Understanding the sources of noise that are influencing bat presence would further inform bat-supportive design efforts. Finally, our results focus on nocturnal bat occupancy, but diurnal roosting habitat in the form of live and dead trees is likely an equally important, yet limited resource for urban bats as the urban tree canopy is reduced and often managed to remove dead or decaying trees in the interest of human safety (Carpaneto, Maria, Adriano, Giorgia, & Luca, 2010; Stagoll & Lindenmayer, 2012). Bat-supportive green infrastructure should seek to provide roosting habitat by retaining snags in various stages of decay, maintaining mature trees and tree cavities, or by installing artificial roosting habitat such as bat houses when natural roosts are unavailable or have to be removed (Mager & Nelson, 2001; Taylor, 2006; White, 2004).

Nature-based infrastructure can increase resiliency for cities grappling with the consequences of urbanization and the pressure of climate change by providing ecosystem services and health benefits for humans (Demuzere et al., 2014). These efforts can also contribute to valuable habitat for urban wildlife. If not thoughtfully designed, however, these efforts can be ineffective at best and aversive to wildlife at worst. In order to maximize the value of green infrastructure for wildlife, we must consider species-specific habitat requirements, and continue to think beyond habitat structure and composition to consider more invisible elements, such as noise. Our results suggest that noise is an important consideration for bat habitat, particularly along urban waterways. If carefully planned, cities can provide valuable habitat for wildlife, even those that are facing extreme conservation threats.

CRediT authorship contribution statement

Elizabeth W. Lehrer: Conceptualization, Methodology, Investigation, Data curation, Writing - original draft, Project administration. **Travis Gallo:** Conceptualization, Methodology, Data curation, Formal analysis, Writing - original draft, Visualization. **Mason Fidino:** Conceptualization, Data curation, Formal analysis, Writing - review & editing. **R. Julia Kilgour:** Conceptualization, Methodology, Investigation, Writing - review & editing. **Patrick J. Wolff:** Conceptualization, Investigation, Writing - review & editing. **Seth B. Magle:** Conceptualization, Writing - review & editing, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.landurbplan.2021.104063.

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