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Variation in Bird Vocalizations across a Gradient of Traffic Noise as a Measure of an Altered Urban Soundscape

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It is evident that widespread land use and land cover change, including increasing urbanization, are altering ecological processes. One modification gaining attention is increased anthropogenic noise associated with cities. To examine potential impacts of rising anthropogenic noise, we conducted an acoustic analysis of Brown-headed Nuthatch (*Sitta pusilla*) and Eastern Towhee (*Pipilo erythrophthalmus*) vocalizations in Greenville Co., South Carolina as a function of a gradient of increasing traffic noise. Our data demonstrate that even moderate levels of noise may alter the structure of avian vocalizations. In particular, the minimum frequency of the Brown-headed Nuthatch vocalization shifted upward to avoid acoustic overlap with the noise associated with vehicular traffic. Understanding the impacts of noise created by urbanization on songbird vocalizations provides insight into the altered soundscape as well as ecosystem health. Thus, it is essential that we monitor and understand the impacts of anthropogenic noise and implement effective city planning strategies to improve urban ecosystems. In addition, the evidence of birds' response to increased traffic noise serves as a starting point to begin dialog between researchers and practitioners across environmental and public health fields.

Keywords

Anthropocene, Brown-headed Nuthatch, Patch, Piedmont, Public Health

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INTRODUCTION

The scope and scale of human influence over physical processes and ecological patterns of the Earth has prompted many to describe this era as the Anthropocene (Ellis 2011; Kareiva & Marvier 2012). Yet one under-discussed (e.g., Brown & Graham 2015), though increasingly evident, aspect of this disruption is an increase in anthropogenic noise, or sound generated from human activity, such as automobiles, aircrafts, construction, etc. (Blumstein et al. 2011). In particular, decisions made regarding transportation in city development are altering the soundscape and changing the acoustic makeup of ecosystems by adding non-natural, human produced noises to the environment (Blumstein et al. 2011). Much of this added noise can be attributed to urban roads and vehicular traffic. Indeed, 83% of the continental United States is within 1 km of a road and effects of traffic noise may extend over 300 meters from both sides of roads (Forman & Deblinger 2000; Ritters & Wickham 2003). Thus, it is not surprising that 30% of Americans made formal noise complaints in 2000 U.S. Census (Goines & Hagler 2007) nor that there is accumulating evidence of impacts of noise on human health (Goines & Hagler 2007, Shephard et al. 2013) and cognition (Benfield et al. 2010).

In addition to its impact on human systems, the accumulated impacts of anthropogenic noise on natural systems is becoming evident, including reduced species abundance or occupancy (Francis et al. 2009), altered age structure, behavioral changes (e.g., Meillère et al. 2015), and decreased reproductive success (Katti & Warren 2004; Francis et al. 2009, Ortega 2012, Francis and Barber 2013). In particular, studies have shown negative consequences of traffic (Forman et al. 2002) and road noise on birds (Ortega 2012), which are recognized as an indicator species to monitor environmental change (Järvinen & Väisänen 1979). In particular, the energy of traffic noise can interfere with avian vocalizations, a phenomenon described as acoustic masking. Negative consequences of acoustic masking include impaired communication (Halfwerk et al. 2011a), behavioral changes in foraging (Francis et al. 2012), and incorrectly copied vocalizations leading to variation in songs (Ortega 2012). Because of acoustic masking, birds may adapt by shifting songs (Parris & Schneider 2008) and calls (Oden et al. 2015) to vocalize at higher frequencies or amplitude or changing the timing of their vocalization (Fuller et al. 2007). When a species does change its vocalization there are measured costs including lowered attractiveness of song (Halfwerk et al. 2011a), difficulty communicating with a potential mate (des Aunay et al. 2014), risk of being cheated on (Halfwerk et al. 2011a), and overall lower reproductive success (Halfwerk et al. 2011b). Not all species, however, respond to acoustic interference (e.g., Grace & Anderson 2015). In a recent review, just over half of monitored bird species were found to have differences in measured frequency (Brumm & Zollinger 2013), suggesting a need for species specific data across taxa. Furthermore, while differences in bird vocalization have been shown between sites with high and low noise (e.g., Slabbekoorn & den Boer-Visser 2006; Oden et al. 2015), less is known as to how bird vocalizations may vary along a gradient of traffic and road noise produced within and around urban areas.

In this study, our objective was to measure the effects of a gradient of traffic and road noise on bird vocalizations in a rapidly urbanizing environment (Terando et al. 2014). Traffic noise is characterized as a low frequency band of noise between 1 and 4 kHz (Parris & Schneider 2008). Specifically, we tested whether Brown-headed Nuthatch (*Sitta pusilla*) and Eastern Towhee (*Pipilo erythrophthalmus*) minimum vocalization frequency shifted upward, compressed in vocalization frequency range, or if the entire vocalization shifted upward in response to a gradient of increasing levels of road noise. We hypothesized the former hypothesis was more likely as the lower frequency portions of a vocalization have the greatest likelihood of being masked by traffic noise (Ortega 2012, Brumm & Zollinger 2013, Parris & McCarthy 2013).

We chose the Brown-headed Nuthatch and Eastern Towhee because each commonly inhabits city environments including parks, back-yards, golf courses, and other areas likely to be found near where humans live and recreate. Each reflects an ecosystems embedded in urban and peri-urban landscapes; pine and successional shrub respectively. Each is considered a wildlife species of conservation concern in the southeastern United States. The Brown-headed Nuthatch forages in the canopy of pine patches. A cooperatively-breeding species, inter-flock communication between breeding pairs and helpers is important; perhaps even more so as its habitat becomes increasingly fragmented and disturbed. This species is known to give a loud vocalization in response to attempted predation (Slater et al. 2013). In contrast the Eastern Towhee is in general a solitary species commonly found in early successional shrub. Males will defend territory with singing and aggressive behavior, including responding to playback of recordings. Vocalizations are used to secure mates, a process that naturally quickly occurs. Indeed, these is evidence of extensive communication within a pair before nest building. Like the nuthatch, the towhee responds to predators with alarm calls (Greenlaw 2015). Lastly, we discuss these data to suggest the use of the response of birds to increased traffic noise as a starting point for discussion between disciplines interested in urban sustainability on the potential impacts of noise on both human and environmental health.

METHODS

Study Sites

We located pine patches within and adjacent to Greenville Co. in northwestern South Carolina, USA (Figure 1). Sites were centered on the city of Greenville, SC (34°50′40″N 82°23′8″W). The population size, in 2013, of Greenville county was 474,000 (U.S. Census 2013) but density varies spatially in the county. The county is at the center of the rapidly growing Southern Megalopolis (Terando et al. 2014). The county has had a 1.9 percent growth rate over the last 10 years, with an estimated population increase of over 5% during the last four years alone (U.S. Census 2013). The major biome type of the Southern Piedmont ecoregion is temperate deciduous forest. However, much of the forested area is second or third growth forest, including pine plantations as a forest commodity crop. Current urbanization is rapidly replacing existing forest and agricultural systems that dominated land use in the region over the last 200 years (Napton et al. 2010).

We selected forty-one study sites for acoustic sampling based on land use, intensity of road and traffic noise, habitat suitability, and accessibility (Figure 1). Consequently, study sites were located within municipal boundaries, low-density residential, protected areas, and a gradient of land use in between; thus our sites spanned urban, peri-urban, and extra-urban areas (MacGregor-Fors 2011). All sites included pine patches, the preferred habitat of the Brown-headed Nuthatch, while the Eastern Towhee is commonly found in early successional shrub cover within and adjacent to forest patches (Slater et al., 2013; Greenlaw, 2015). Study sites were widely spaced (≥ 400 meters apart) to ensure that individuals sampled were unique to each study site. Breeding territories of the Brown-headed Nuthatch and of Eastern Towhee are less than 2.5 ha and 1.5 ha respectively (Slater et al., 2013; Greenlaw, 2015)

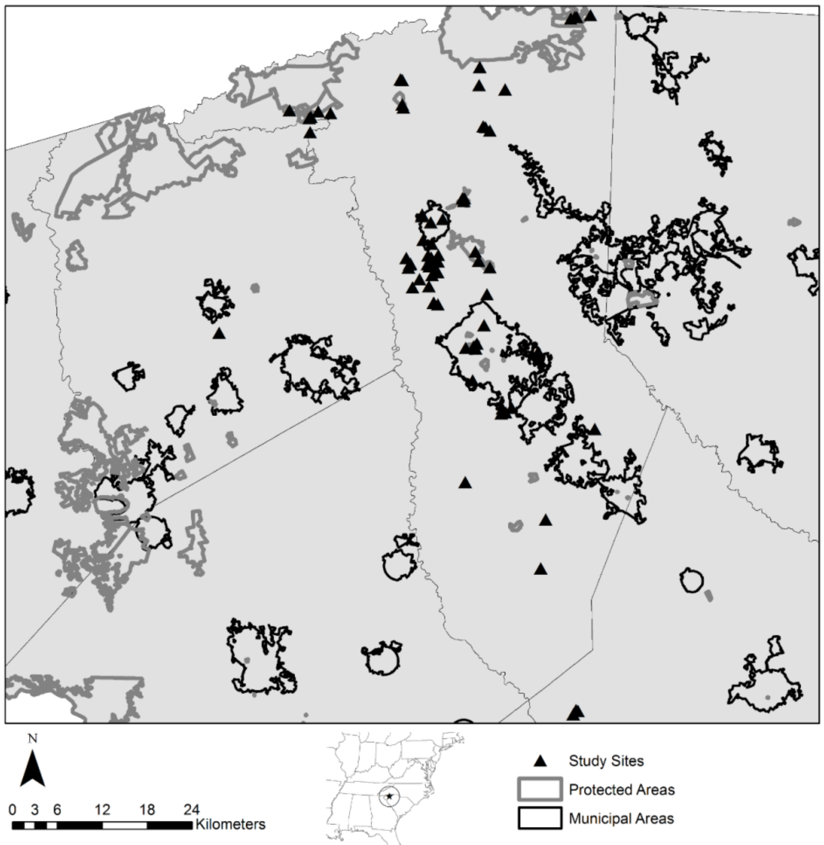

Figure 1. Location of patches sampled for vocalizations in the Upstate region of South Carolina, USA. Study sites are centered on the area north of the city of Greenville and are embedded within designated municipal areas (black polygons), protected areas (gray polygons), and low-density residential areas between.

Data collection

We gathered acoustic data with omnidirectional Song MeterSM2+ automated recording units (ARU; Wildlife Acoustics Inc., Concord, MA, USA) from May through July of 2013. Each unit was programmed to record for 10 minutes at the start of each hour, from 6:00 A.M. to 10:00 A.M daily. Each unit was left at the study site for a minimum of four days to maximize chances of recording the species of interest despite anticipated low detection probability (Quinn et al., 2011). Recorders were kept on consistent settings throughout the study, with a sampling rate of 16000 Hz, 0.0 dB gain (left and right), and compression set to off.

Acoustic Analysis

We used Raven Pro V1.4 software (Cornell Lab of Ornithology, Ithaca, NY, U.S.A.) to detect Brown-headed Nuthatch and Eastern Towhee vocalizations from the collected recordings. For each study site, we reviewed recordings, listening and visually scanning each in chronological order of being collected. We identified relevant vocalizations from the target species and annotated the file location. To reduce the likelihood of measuring the vocalization of the same bird more than once during the study, we

chose to systematically use only the first quality vocalization at each study site for subsequent analysis. We excluded vocalizations made during rain in order to eliminate possible confounding effects. Of our 41 study sites, we were able to isolate Brown-headed Nuthatch vocalizations from 23 locations, and Eastern Towhee vocalizations from 29 locations.

We measured the squeaky, two-syllable rubber duck vocalization of the Brown-headed Nuthatch (Figure 2a,b). This vocalization is a wheezy *tyah-dah* or *chee-da*. The literature suggests the frequency of this vocalization falls below 6 kHz (Slater et al. 2013). At this time, a distinction between songs and calls in the Brown-headed Nuthatch is unclear (Slater et al. 2013). This vocalization is made year round by both sexes and may serve many functions; importantly for this study as contact calls over longer distances (Slater et al. 2013). We measured each phrase individually of the *drink-your-tea* song of the Eastern Towhee (Figure 2c). We were particularly interested in the "*tea*" portion as it is suggested to contain more information than other parts of the call (Richards, 1981) and that it may be necessary for species recognition (Ewert 1978). Though frequencies can range as high as 9 kHz, most reported frequencies of this song fall between 2 and 7 kHz (Greenlaw, 2015).

We used Raven Pro V1.4 software, keeping contrast and color settings constant, to measure as response variables the minimum frequency (Hz), maximum frequency (Hz), and frequency range for the selected vocalization of each species. To limit process and observation error that can occur when defining minimum and maximum frequencies (Zollinger et al. 2012, Cardoso & Atwell, 2012), while benefiting from the use of ARUs, we kept settings in Raven consistent and used audio to verify the absence of the vocalization at a given frequency. For our explanatory variable, the intensity of traffic noise, we measured from the same recordings the average power in decibels (dB) of road noise recorded with the ARU. Average power is the summed value of the spectrogram's power spectral density in each pixel averaged over the selected time period and frequency divided by the number of time-frequency bins in the selection. We measured average power between 0-4 Hz, corresponding to the frequency of traffic noise (Parris & Schneider 2008), over the same time period of each individual vocalization used in the analyses. We used Program R (2013) for regression analysis, with an alpha value of 0.05.

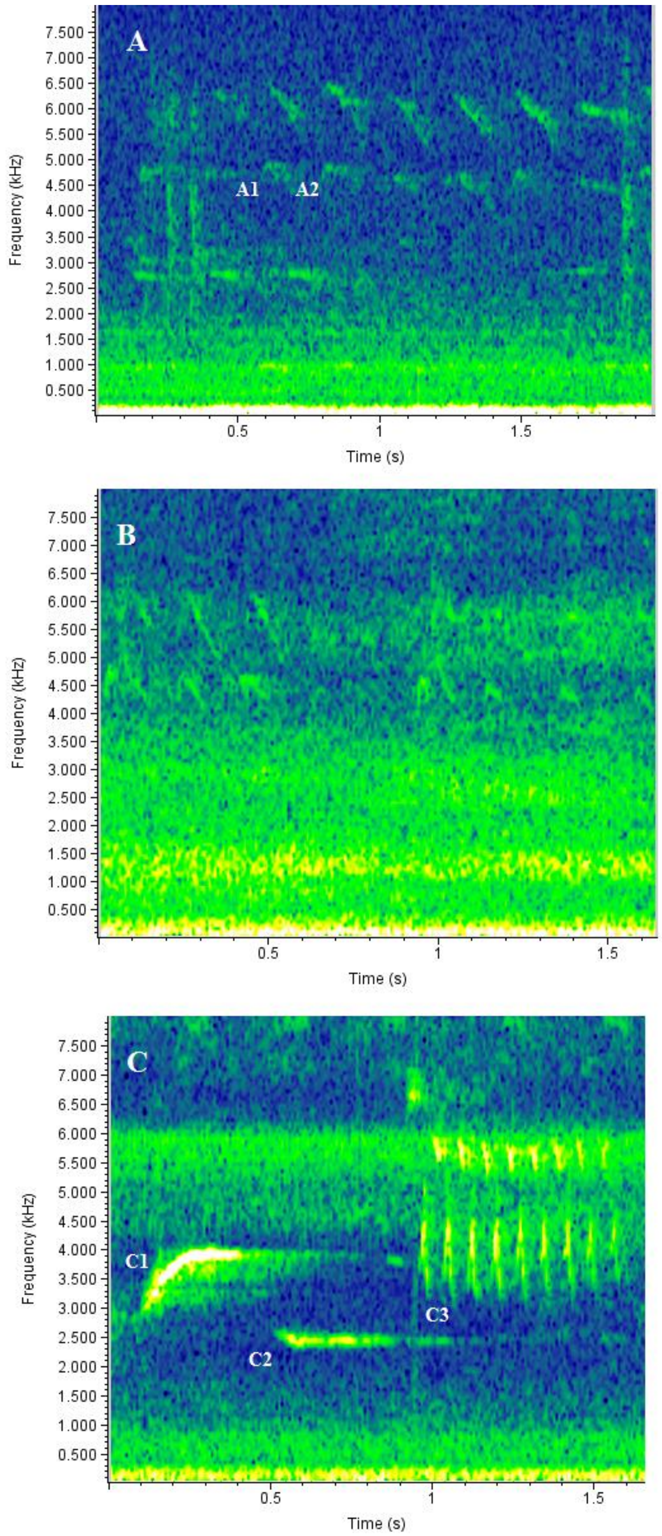

Figure 2. A) Brown-headed Nuthatch "rubber duck" *tyah-dah* vocalization (A1:*tyah, A2:dah*) in low noise soundscape, B) Brown-headed Nuthatch vocalization in high noise soundscape, C) Eastern Towhee song (C1:*drink*, C2:*your*, C3:*tea*). Audio sampled in Greenville Co., SC, USA, May, 2013 with Song MeterSM2+ ARU

RESULTS

We detected one of the two species at 36 of 41 sites and had 22 sites were only one of the two species was detected. We detected Brown-headed Nuthatches at 23 of 41 study sites and Eastern Towhees at 29 of 41 study sites. The mean nuthatch and towhee minimum vocalization frequencies fell within the acoustic space of traffic noise (1-4 kHz) as did the maximum frequency of the "your" phrase from the towhee (Table 1). The means of the remaining maximum frequency for both species fell outside this range (Table 1). The average power (dB) at the sites with nuthatch vocalizations was 70.99 (sd = 6.15). At the sites where towhees were detected, the average power was 64.56 (sd = 7.63).

	n	Mean	SD	Minimum	Maximum
Brown-headed Nuthatch					
Minimum Frequency	23	3358.3	661.7	2254.8	4524.4
Maximum Frequency	23	5923.6	732.6	4169.9	6723.3
Eastern Towhee					
Minimum Frequency (drink)	29	2816.6	528.3	1708.7	3724.7
Maximum Frequency (drink)	29	4257.4	890.5	2951.5	7189.9
Minimum Frequency (your)	29	2514.2	731.1	1461.0	4625.0
Maximum Frequency (your)	29	3656.9	1108.6	2471.0	6736.8
Minimum Frequency (tea)	29	2883.8	501.5	1626.0	4157.5
Maximum Frequency (tea)	29	5974.2	1142.7	4048.3	8000.0

Table 1. Measured mean, standard deviation, and range of vocalization frequencies of Brown-headed Nuthatch and Eastern Towhee. Vocalizations collected in Greenville County, SC between May-July, 2013 with Song MeterSM2+ automated recording units.

The Brown-headed Nuthatch minimum frequency was measured at higher frequencies at sites with greater traffic noise ($F_{1,21}$=12.370, P=0.002, Figure 3). No relationship was found between road noise and vocalization maximum frequency ($F_{1,21}$=1.524, P=0.231) or frequency range ($F_{1,21}$=1.982, P=0.174). For the Eastern Towhee, the minimum frequency ($F_{1,27}$=0.839, P=0.368), maximum frequency ($F_{1,27}$=0.518, P=0.478) and frequency range ($F_{1,27}$=0.037, P=0.848), of the "drink" portion song did not vary as a function of traffic noise. The minimum frequency ($F_{1,27}$=2.865, P=0.102), maximum frequency ($F_{1,27}$=2.012, P=0.168), and frequency range ($F_{1,27}$=0.212, P=0.649), of the "your" did not vary as a function of traffic noise. Lastly, the minimum frequency ($F_{1,27}$=0.351, P=0.559), maximum frequency ($F_{1,27}$=0.502, P=0.485), or frequency range ($F_{1,27}$=0.647, P=0.428) of the "tea" portion did not vary as a function of noise.

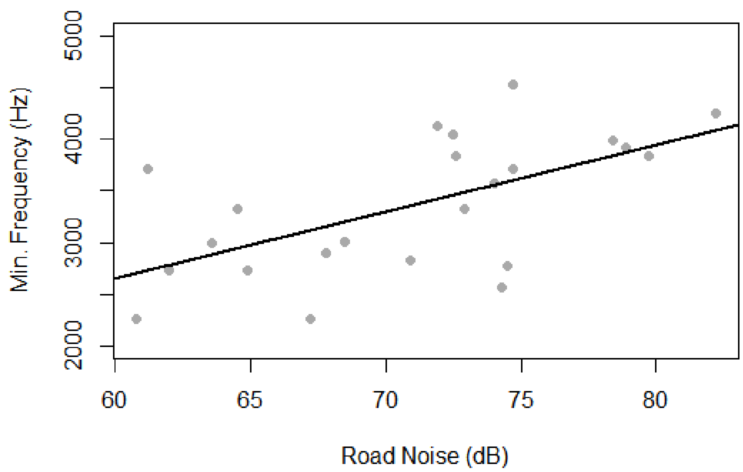

Figure 3. A scatterplot showing that the minimum frequency of the Brown-headed Nuthatch vocalization was higher with greater road noise (measured as average power). Vocalizations and traffic noise collected concurrently in Greenville County, SC between May-July, 2013 with Song MeterSM2+ automated recording units.

DISCUSSION

Despite greater ambient noise levels (LaZerte et al. 2015), biological diversity and associated biological sounds continue in urban spaces (Liu et al. 2013). However, our data suggest that as a consequence of their persistence in urbanized areas, the Brown-headed Nuthatch may adjust its vocalizations in response to a gradient of increased anthropogenic noise. Specifically, the minimum frequency of the Brown-headed Nuthatch vocalization was higher at sites with greater intensity of traffic noise. This aligns well with past work suggesting that individuals attempt to avoid acoustic masking by changing vocalizations that overlap with anthropogenic noise (Mockford & Marshall 2009, Slabbekoorn and den Boer-Visser 2006). Slater et al., (2013) suggest the rubber duck vocalization allows for long-distance communication between conspecifics. Given that low frequency vocalizations travel greater distances, an upward shift may reduce intra-species communication between fragmented forest patches, particularly if the loss of information the active space of the nuthatch vocalization is lower when shifting frequency than when masked by traffic noise (Parris & McCarthy 2013). The potential impacts of this change may be greater as fragmentation of pine patches becomes magnified due to expected land use change within this species range (Terando et al. 2014).

In contrast no part of the Eastern Towhee song changed in response to traffic noise, despite overlapping with traffic noise. This was unexpected, particularly for the *tea* component of the song given that the message of the Eastern Towhee in this section of song (Richards, 1981). Therefore, any message in this part of the song may be subject to loss by acoustic masking in noisy city environments. Given that this song is used for recognition, it may be a greater benefit the species to retain the normal song frequency. This may reflect a trade-off between being heard and maintaining the integrity of the song so as to be recognized by conspecifics.

Indeed, the different response of the two species highlights the evaluation of the tradeoff between being heard and communicating the correct message. Given the variation between species here and in the broader literature (Brumm & Zollinger 2013), future research that evaluated predicative natural history traits of species (e.g., a solitary vs cooperatively breeding, core vs satellite species in mixed flocks) and variation within families would be valuable. For example, in the Emberizidae family, of which the Eastern Towhee is a member, two of five reported species increase minimum frequencies, two show no responses, and a fifth species (Song Sparrow, *Melospiza melodia*) has conflicting reported responses (Brumm & Zollinger 2013). Additionally further work is needed to test if response to noise affects communication and ultimately fitness.

While it is valuable to consider the shift in bird vocalizations in cities, of additional value added here is the evidence that avian vocalizations may serve as a sensitive and accurate indicator in light of changing urban environments and associated green spaces. These data suggest that the nuthatch is sensitive to the presence and intensity of traffic noise. Indeed, the shift in minimum frequency of the nuthatch vocalization, seen at moderate levels of traffic noise frequency, suggests a high sensitivity of the Brown-headed Nuthatch to noise in urban, peri-urban, and ex-urban human systems. Thus, the Brown-headed Nuthatch and other species with similar vocalization structures may be valuable indicators of potentially harmful traffic and road noise.

Implications for urban conservation, planning, and management

Given the expected increase in urbanization and associated noise in the region (Terando et al. 2014) and the expected increased density of roads globally (Laurance et al. 2014) the need to align currently isolated management and planning goals in human and natural systems is evident (Martin et al. 2014). While increasing confirmation of the effect of traffic noise on birds warrants a response, we suggest that consideration of these data alongside the evidence of the impacts of traffic noise on human communities (European Commission 2003; Goines & Hagler 2007; Benfield et al. 2010; Shepherd et al. 2013) will improve dialog between disciplines and practitioners.

Our data should encourage conservation practitioners and planners working in cities to consider multiple indicators of disturbance caused by increased noise when designing human systems. For example, King et al. (2012) showed that noise levels were significantly greater in mixed use residential and commercial areas than within the strict residential areas. Yet, both areas exceeded World Health Organization guidelines, suggesting a need for further monitoring across system types, perhaps via bird vocalizations. Most valuably, integrating multiple measures would increasing the number of stakeholders working to reduce the impacts of increased noise. This improved attention to noise in urban conservation and planning could result in more positive health outcomes for humans and wildlife alike (Katti & Warren 2004).

When it is clear that noise levels are above safe thresholds, practitioners can draw on past research identifying land use types and behaviors that minimize negative impacts. Noise reduction strategies can supplement land use types and allow for mitigation of preexisting urban noise. Physical noise mitigation strategies include the use of soil berms, road overhangs, depressed roads, or noise barriers (Forman 2000; McClure et al. 2013; Slabbekoorn & Ripmeester 2008; Mize et al. 2008). Behavioral changes include lowering speed limits and reducing traffic density. Importantly, many of the above changes benefit both local bird conservation and public health.

These data likely include both process and observation error. Automated recording units (ARU) allow for a larger sampling effort, which has the capacity to increase sample size, particularly for species with low detection probability. Yet their use does result in a varied distances between birds and recorders, potentially confounding subsequent measurements. In addition, observation errors were made when measuring minimum and maximum frequencies by hand may bias the data (Zollinger et al. 2012). It is unlikely, but possible, that all measurements at louder sites were a consequence of bird being further from the ARU. To address these concerns we kept settings consistent and used audio to verify the absence of the vocalization. The two authors both measured each vocalization to add some level of inter-operator validity. Future work should seek to take advantage of the increased data collecting capacity of ARU while seeking to reduce observer error at both times of collection and vocalization measurement. This may require calibration and inclusion of sound level meter at each recording site. Lastly, it remains unclear if the measured shifts in bird vocalizations are consequence of birds adjusting their pitch or if the observed change in frequency is a consequence of increased vocalization amplitude (Zollinger et al. 2012, Nemeth et al. 2013). However, while it is likely that the birds were singing louder in noisy sites (Zollinger et al. 2012), it has been shown that frequency and amplitude can be controlled separately, and that both these strategies might be employed in noisy environments to communicate effectively through traffic noise (Cardoso & Atwell 2011, Cardoso & Atwell 2012, Potvin & Mulder 2013). It may be that future application of ARUs could provide the capacity to measure a broader suite of species within and between soundscapes to address variation observed across taxa.

CONCLUSION

The impacts of human activities on ecosystem and human health are increasingly clear and it is obvious that monitoring and mitigation strategies are needed to improve sustainability in human populated areas (Wu 2014). Our study focused on anthropogenic noise and its subsequent impacts on environmental health and by extension human health. We found that Brown-headed Nuthatch vocalizations were sensitive to increased levels of anthropogenic noise. Clearly noise is an important consideration in city planning that should not be ignored.

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