How traits affect bird responses to anthropogenic noise - a meta-analysis

Natalie Madden

A thesis submitted in partial fulfillment of the requirements of the degree of
Master of Science in Natural Resources and the Environment

School for Environment and Sustainability

University of Michigan

August 18, 2020

Thesis Committee:

Karen Alofs, PhD - Co-chair

Neil Carter, PhD - Co-chair

Abstract

Anthropogenic noise is a consequence of the expansion of humans across the globe. It has been labeled as a pollutant and threatens the health of not only humans, but wildlife as well. Birds are at an increased risk of being negatively affected by anthropogenic noise because of their reliance on acoustic information. Research has shown that noise can impact different aspects of bird behavior (e.g., foraging) and have negative consequences on their fitness (e.g., reproduction). Exploring how ecological and life-history traits make a species more, or less, vulnerable to anthropogenic noise is important to mitigating the negative impacts of this pollutant. We performed a meta-analysis to explore how birds varied in their responses to anthropogenic noise. We then explored how traits contribute to a variety of responses most directly related to fitness (physiology, reproduction, and growth). We found that species traits mediated the affects of noise on birds. Anthropogenic noise more negatively affected the physiology (e.g., stress hormones) and growth (e.g., body mass) of bird species with larger body sizes and that vocalized at a lower frequency. Several other traits including nesting height, nest type, foraging height, and song range were also predictive of growth responses to anthropogenic noise. Birds with open nests and with nests closer to the ground were found to have their growth more negatively affected. In addition, birds that fed mainly between 2m above the ground to canopy level and that had a wider song frequency range were found to have their growth more negatively affected. We did not find any traits to be related to reproductive responses but did see differences in responses among noise types. Industrial noises (e.g., resource extraction) had the most negative affect on reproductive responses. Our research indicates that the impacts of noise vary among responses and species. Birds are at risk of experiencing decreases in fitness due to anthropogenic noise, but more research is needed to determine how anthropogenic noise affects communities and populations.

Acknowledgments

Table of Contents

Introduction

Anthropogenic noise is an unintended consequence of the expansion of humans across the globe (Halfwerk and Slabbekoorn 2015). It has been recognized as a global pollutant (González 2014) and expands beyond crowded urban areas. Sound propagated through transportation networks, both on the ground and in the sky, industrial resource extraction, and military facilities can negatively impact cardiovascular health, cognitive function, and sleep patterns in humans (World Health Organization 2011). Moreover, studies are increasingly documenting detrimental effects of anthropogenic noise on a range of animal behaviors with lasting consequences on fitness. Researchers are questioning not only what the potential negative effects of increased noise are, but also how we can identify those effects and mitigate them to create a healthier environment.

Increasingly, wildlife ecologists are concerned about the impacts of anthropogenic noise because of its ability to infiltrate even remote locations. Mennitt et al. (2013) estimated that 88% of the contiguous United States is experiencing elevated sound levels due to humans. A recent meta-analysis found that a majority of species across taxonomic groups are affected by anthropogenic noise (Kunc and Schmidt 2019). This research included studies that affected communication, distribution, foraging, and homeostasis of different organisms (Kunc and Schmidt 2019).

Avian species are particularly vulnerable to anthropogenic noise because of their dependence on acoustic communications (Hu and Cardoso 2010; Nemeth and Brumm 2009; Slabbekoorn and Ripmeester 2008) and diverse habitats (Slabbekoorn et al. 2018). Dutta (2017) identified noise pollution as one of the top four environmental problems facing birds. Birds use vocalizations to communicate with their young, for alarm calls, and to attract mates (Parris and Schneider 2009). One of the leading ways noise impacts wildlife is through masking, the effect of noise inhibiting the perception of sound (Barber, Crooks, and Fristrup 2010; Dominoni et al. 2020). Birds have adapted to communicate among naturally occurring biotic and abiotic sounds including streams, insect noises, crashing waves and wind over many generations, and have adapted a number of strategies to avoid masking by these noises (Book 2108, Dutta 2017, Brumm and Slabbekoorn 2005). Evolutionarily, anthropogenic noise creates novel environments that have consequences for both individual birds and populations (Francis 2015). Just like naturally occurring sounds, not all anthropogenic noise is created equal, adding to the novelty of noise polluted environments. For example, noise produced in urban settings generally follows a consistent diurnal cycle (Bautista et al. 2004; Warren et al. 2006) whereas aircrafts often cause much louder and more spaced out bursts of noise (Dominoni et al. 2016; Klett-Mingo, Pavón, and Gil 2016). The differences in exposure to this pollutant due to variation in predictability of noises and amplitude, leads us to expect differing responses from birds. Noise pollution is a substantial threat largely because of its potential to impact not only communication, but also a number of other responses (Barber, Crooks, and Fristrup 2010; Dutta 2017).

A myriad of studies reporting varying impacts of noise on birds can make protecting birds challenging. The impact of anthropogenic noise on birds can vary depending on the species being examined, type of noise, and type of response being measured. Williams *et. al* (2018)

found that gas compressors had a negative impact on the hatching success of tree swallows (*Tachycineta bicolor*), whereas Meillere *et al.*(2015) found no impact of urban noise on the hatching success of house sparrows (*Passer domesticus*). Peris *et al.* (2004) found that while gas compressors had a negative effect on the density of woodlarks (*Lullula arborea*), they had no impact on density of blackbirds (*Turdus merula*). Similarly, one study measured an increase in stress hormones in song sparrows (*Melospiza melodia*) due to urban noise (Grunst, Rotenberry, and Grunst 2014), while another measured no impact of urban noise on mountain white-crowned sparrow (*Zonotrichia leucophrys*) chick mass (Crino et al. 2013). From this set of examples, it is easy to see that a comprehensive guide is necessary for practitioners to interpret these varying results.

Many of the previously mentioned responses including growth, reproduction, and physiology, as well as others, can be directly related to the fitness of individuals and could scale up to have lasting impacts on populations (Francis 2015). Other responses commonly examined, such as species densities and changes in communication, are behavioral responses. Behavioral responses to anthropogenic noise may lead to impacts on physiological or reproductive responses, but it is more difficult to interpret their effects on fitness. Both fitness and behavioral responses are important for recognizing the impacts of anthropogenic noise on the health of birds.

Ecological and life-history traits have proven to be useful tools in discerning the varying responses of birds to anthropogenic noise (Francis 2015; Paton et al. 2019) and may help us understand why it seems that certain species appear to be better adapted to living in noise polluted areas. By understanding the trait-based mechanisms through which species are affected by sensory pollutants, conservation practitioners can better target mitigation methods that address the problem. Researchers have suggested that due to the low-frequency of anthropogenic noise, species with high-frequency vocalizations may have an easier time communicating in these human dominated habitats (Colino-Rabanal et al. 2016; Francis 2015). Body mass is highly correlated with vocal frequencies and should also be included in such trait analysis (Hu and Cardoso 2010). Data pertaining to diet and dietary breadth can also be an indication of a species' ability to adapt to or be affected by anthropogenic noise. Birds with omnivorous or animal-based diets may be more negatively impacted by noise because of direct interference with capturing prey or indirectly through increased vigilance (Klett-Mingo, Pavón, and Gil 2016; Swaddle et al. 2015). Dietary generalists are predicted to more easily cope with an ecologically altered environment over specialists because they are adapted to heterogeneous environments and are better able to utilize alternative food sources (Murgatroyd et al. 2016).

Previous research on the impacts of anthropogenic noise on birds often has a narrow focus, the target being a single species or community and focusing on the influence of a single noise source. Single species research, although important for base knowledge, lacks a holistic assessment necessary for practitioners to integrate scientific findings into their conservation plans. A majority of wildlife management plans in North America already lack scientific evidence in decision making (Artelle et al. 2018). In order to make meaningful comparisons across species and scenarios, a synthesis of single species data is necessary. It is also important to

2

recognize how effects of anthropogenic noise vary across responses and the role of traits in mediating these effects. Creating a comprehensive assessment through meta-analysis may aid in bridging the gap between science and implementation.

Here we develop a meta-analysis of the impacts of anthropogenic noise on birds by aiming to answer the following questions: 1) How do birds respond to anthropogenic noise? 2) how do different contexts (including source sound type and amplitude, and study design) affect the impact of anthropogenic noise on birds? Finally, 3) are there traits that make a species more vulnerable to anthropogenic noise? Through answering these questions, we will highlight remaining knowledge gaps that necessitate future research. We will also better clarify the mechanisms underlying bird response to anthropogenic noise and thus inform more effective actions for maintaining healthy populations of avian species.

Methods

Search protocol

Following the search protocol of Shannon et al. (2016), we conducted a detailed literature search using Thompson's ISI Web of Science within the following subject areas 'Acoustics', 'Zoology', 'Ecology', 'Environmental Sciences', 'Ornithology', 'Biodiversity Conservation', 'Evolutionary Biology', and 'Marine Freshwater Biology' from 1990 to 2017. The specific search terms were ([WILDLIFE or ANIMAL or BIRD] and [NOISE or SONAR]). Results from this search were filtered to only include empirical studies specifically documenting the effects of anthropogenic noise on birds. Reviews, syntheses, method papers, and studies dealing solely with natural acoustic sources were excluded.

After selecting the literature from the search, we performed a forward and backward search on each article to ensure the inclusion of as much data as possible. Backward searching consisted of selecting papers cited within already included articles. Forward searching consisted of using Google Scholar to identify studies that cited each article. After forward and backward searching, our dataset included literature from 1990-2020.

Data selection

Data were included in meta-analysis if authors explicitly tested for the effects of anthropogenic noise on bird responses. Authors needed to demonstrate that they tested for a difference in sound levels between "quiet" or "control" treatments and noise treatments. Control treatments could be achieved either through observational or experimental designs. "Before" treatments were also treated as control given that they met the same criteria and were compared with "during" treatments as the noise treatment.

We also required anthropogenic noise to be measured directly. While many studies explored urban vs. rural settings, if noise level was not measured, it was not included in our analysis. If subjects within a study were exposed to multiple amplitudes of noise, only the results from the loudest were recorded. In the case that the subjects were exposed to multiple sources of noise

(e.g., traffic vs. aircraft), each was treated as separate experiments and yielded separate effects. Multiple responses were often collected from a single publication. We recorded multiple responses if multiple species were evaluated separately, if there were multiple sound types, and/or if multiple responses were measured. Each study was given a numeric identifier.

We collected data on several experimental moderators from each study. We recorded species identities, study type (experimental vs. observational), and amplitude of source noise. Response and source sound type were also categorized for analysis. Response types included behavioral responses – aggressive behavior, communication, foraging behavior, habitat use, reproduction, and behaviors related to risk – as well as fitness responses – growth, reproduction, and physiology. Sound types included aircrafts, military, industrial, urban, and other.

Aggressive behaviors included behaviors such as number of attacks (against other birds or researchers) and number of pecks. Any response related to song or call structure including song length, frequency range, song rate, as well as any response related to timing of calls was categorized as communication. Foraging behavior correlated with behaviors such as time spent foraging or latency to feeding. Any measure of physical growth such as fledgling mass or wing length was categorized as growth. Habitat use responses were those related to abundance or nest density. Physiological responses were those related to hormones. Reproductive responses included anything from mating success to fledgling success. Lastly, risk responses were those having to do with responses to perceived risk, vigilance, or predator detection.

As for sound type categories, aircraft noises included both commercial, military, and personal aircrafts. Industrial noises consisted mostly of noises related to resource extraction such as well compressors. Military noises were recorded directly outside or within military training facilities. Urban noises were those recorded within urban settings or relating to transportation networks. Finally, other noises were those created or manipulated by researchers such as white noise.

To calculate effect size, we collected or derived mean response, error measurements, and treatment sample sizes. DataThief software was used to extract data from figures that contained the appropriate parameters (DataThief v1.7).

Noise effects on bird behaviors and habitat-use

In order to compare results between studies, effect sizes were calculated using Hedges' g (Eq.1-3). For studies that reported results using *t* or *F* values we used alternate methods to calculate Hedges g' (Eq.4 & 5; Borenstein et al. 2009).

$$g = \frac{(\bar{X}_T - \bar{X}_c)}{s} J \tag{eq.1}$$

$$J = 1 - \frac{3}{4(n_T + n_c) - 9} \tag{eq.2}$$

$$s = \sqrt{\frac{(n_T - 1)SD_T^2 + (n_c - 1)SD_C^2}{n_T + n_C - 2}} \tag{eq.3}$$

There were a number of studies exploring differences in song structure and communication. The impacts of changes in song structure and communication on individual fitness, and whether they may have negative or positive effects was unclear (Hu and Cardoso 2010; Parris and Schneider 2009). Similarly, the impact of aggressive behaviors, risk aversion behaviors, foraging behaviors, and habitat use on individual fitness was difficult to determine. For these behavioral responses, we used absolute values to ensure all effects reflect the size of their impact (Kunc and Schmidt 2019).

$$g = t\sqrt{\frac{n_T + n_C}{n_T n_C}} \qquad\qquad \text{(eq.4)}$$

$$|g| = \sqrt{\frac{F(n_T + n_C)}{n_T n_C}} \qquad\qquad \text{(eq.5)}$$

Most studies yielded multiple effect sizes (Table S1). To control for this dependency, the weighted mean effect size (wES) for responses was analyzed using robust variance estimation (RVE; Hedges, Tipton, and Johnson 2010). Robust variance estimation accounts for dependency by incorporating an estimate of within-study covariance and does not require the user to know the covariance structure among effect sizes within each study (Polanin, Hennessy, and Tanner-Smith 2017). Heterogeneity was estimated with τ^2 and I^2. The τ^2 is the between study heterogeneity measured in absolute value and I^2 is the proportion of the between study heterogeneity that is not due to sampling errors (Borenstein et al. 2009; Polanin, Hennessy, and Tanner-Smith 2017). In other words, I^2 is the proportion of heterogeneity that could be explained by moderators (Borenstein et al. 2009). All calculations were done in R using the packages *robumeta* and *metafor* (version 3.5.1; R Development Core Team 2018).

Trait data collection

For each species included in the study, we collected trait data related to song structure, life history, and physical attributes. For song structure, we focus on peak frequency, the frequency at which an individual vocalizes at the highest amplitude (Antze and Koper 2020), frequency range, and song length. Vocalizations were collected from audio archives (xeno-canto.org) and analyzed using Raven Lite 2.0 (Cornell Laboratory of Ornithology, Ithaca, NY,USA). We analyzed three songs for each species and used the average for statistical analysis. We also collected data on diet and dietary breadth. Diet and foraging height data were collected from Elton traits (Wilman et al. 2014).Other traits included in analysis were body mass, nest type, nest height, whether a species is migratory or not, habitat type, and taxonomic family. Data for these traits were collected from Birds of the World from the Cornell Lab of Ornithology (Cornell Laboratory of Ornithology, Ithaca, NY,USA). Further description of all trait data can be found in Table 1.

Table 1: description of each trait including the format of the data.

Trait	Description	Type
Diet	The dominant diet type: invertebrate, omnivore, plant/seed, fruit/nectar, vertebrate/fish/scavenger.	Categorical
Dietary breadth	The number of diet categories a species falls in	Continuous
Foraging height	Dominant height at which species feed	Categorical
Nest type	Cavity vs. open nest	Categorical
Nesting height	Average height within at the canopy at which a species builds its nest	Continuous
Peak frequency	Average frequency of the highest decibel of song	Continuous
Song length	Average song length	Continuous
Song range	Average frequency range of song	Continuous
Migratory	Migratory vs. non-migratory. If species was partially migratory, was categorized as a migratory species	Categorical
Habitat type	Dominant habitat type	Categorical
Family	Taxonomic family	Categorical

Trait mediated effects of noise on bird fitness

Hedges' g was calculated in the same manner for fitness responses as for behavioral responses. Unlike behavioral responses, for physiological, reproductive, and growth responses, the directionality of impacts on fitness were clear. With a variety of responses evaluated, raw positive and negative effect sizes did not necessarily correlate with positive or negative effects on fitness . For example, based on our equations, an increase in cortisol in experimental treatments would lead to a positive effect size when an increase in cortisol levels is known to indicate increased stress and therefore a negative effect on fitness (Ray et al. 2018). We corrected for this by changing the sign of each effect size to match the effect on fitness.

Subgroup analyses were performed on each fitness response category (i.e., growth, physiology, reproduction) separately, allowing us to examine differences in effects and consider their impacts on fitness. We calculated wES for each group using RVE. The effects of experimental moderators (source sound type, study type, and amplitude of source noise) were explored through a meta-regression.

We examined the relationship between species traits and responses to anthropogenic noise for response groups directly related to fitness. We did not explore relationships between traits and responses indirectly related to fitness because of the inability to interpret the directionality of impacts. Before beginning analysis, we log transformed song length and body size to represent a linear relationship. We examined correlations between traits and log transformed body size and peak frequency were most highly correlated ($R^2 = 0.54$). All other relationships showed low correlation.

We fitted single-trait linear mixed effect models (LMM; Anderegg et al. 2016) to determine which trait predictors were most strongly related to the effects of anthropogenic noise by response type (e.g., growth). In each model, study identification was treated as a random effect. Three species (zebra finch (*Taeniopygia guttata*), rainbow lorikeet (*Trichoglossus moluccanus*), and

northern spotted owl (*Strix occidentalis caurina*)) were removed from trait analysis due to an inability to retrieve recordings of their vocalizations. All models were fitted in R using the package lme4.

Results

Noise effects on bird behaviors and habitat-use

We collected 369 effect sizes related to behavioral responses from 68 studies and our data included 98 unique species (Table S1). Robust variance estimation revealed two of the five response groups, risk (11.2; p = 0.003; CI95%: 4.44 -18.00) and communication (3.59; p <0.001; CI95%: 2.20 - 4.99) were found to have significant wES (Fig.1). The total between study variance (τ^2) of risk responses was 25.37 while the heterogeneity (I^2) potentially explained by moderators was 98.84. Responses related to communication had little between study variance (τ^2= 3.40), but considerable heterogeneity not due to sampling errors ($I^2 = 96.76$).

Trait mediated effects of noise on bird fitness

We collected 147 effect sizes for fitness responses. Our data included 29 studies and 21 species.

Reproductive responses had a wES of -4.61 (p = 0.061; CI95%: -9.47 - 0.24; Fig. 2) indicating an overall negative effect on reproductive responses. The total between study variance (τ^2) was 61.85. A high portion of heterogeneity could be explained by moderators ($I^2 = 99.09$). Moderator analysis showed that sound type had a significant effect on outcomes. Industrial noises (-11.92; p = 0.002) and military noises (10.21; p = 0.02) had significant effects on reproductive responses. Urban noises (-9.75; p = 0.07), other noises (-5.25; p = 0.054) had negative, but non-significant effects. Effect size also varied by study type, observational studies had strong negative effects (-10.36; p= 0.06), but they were also not significant at alpha = 0.05.

Physiological responses had a wES of -0.221 (p = 0.934; CI95%: -5.91 - 5.46). Our LMM revealed that physiological responses were predicted by body size (-11.720; p < 0.001; Fig. 3) and peak frequency (11.504; p < 0.001; Fig.4); with larger birds and those singing at a lower frequency more negatively affected.

Growth responses had wES of -0.348 (p = 0.79; CI95%: -3.26 - 2.56). Several traits were significantly related to growth responses to anthropogenic noise. Similar to physiological responses, growth responses were predicted by body size (-49.21; p = 0.002; Fig.5) and peak frequency (44.48; p = 0.006; Fig.6). Bird growth was negatively related to the song frequency range; that is, birds that exhibited a greater range of song frequencies were likely to have their growth hampered by anthropogenic noise (-48.24; p = 0.003; Fig. 7). We saw that species foraging at mid-heights (2m above the ground to below the canopy; Wilman et al. 2014) had negative responses to growth (-0.66; p = 0.02; Fig. 8). Nesting characteristics were also related

to growth responses with open nests having a negative relationship (-92.54; p = 0.006; Fig. 9) and nesting height having a positive relationship (42.96; p = 0.009; Fig.10). It is important to note that growth models were strongly influenced by the results of a single study (Ray et al. 2018) examining the impacts of an electric bell on domestic chickens (*Gallus gallus domesticus*).

Discussion

Although a growing body of studies indicate negative effects of anthropogenic noise on bird species, we lack a clear understanding of the mechanisms underlying bird responses to this pollutant. We used a meta-analytic approach, informed by bird traits, to better elucidate these mechanisms. We found clear evidence that anthropogenic noise affects bird behaviors, habitat uses, and fitness. In addition, specific bird traits related to their life-history and habitat preferences mediated the strength of the effects of noise on bird growth and physiology.

Body size and peak frequency strongly influenced how bird physiology responds to anthropogenic noise. The inverse relationship between body size and physiological responses from our study indicates that larger birds are more negatively affected by anthropogenic noise. This finding supports previous research that also reported a negative relationship between body size and environmentally induced stress (Hau et al. 2010). The relationship we see between peak frequency and physiological responses in our study is more than likely due to the correlation between body size and peak frequency, rather than the frequency alone. We were not able to find evidence in the literature of a direct relationship between peak frequency of birdsong and physiological stress. Across studies birds did not demonstrate an overall significant physiological response to noise, however, responses varied by species body size and peak frequency. Injaian (2020) similarly found no general relationship between urbanization and corticosterone levels in birds.

The trends we saw in growth responses to noise mimicked those of physiological responses. We found that many traits had strong relationships with growth responses. Body size and peak frequency displayed the same relationship with growth as with physiological responses with larger birds singing at a lower frequency being the most negatively affected by noise. Birds foraging between 2m above the ground and below canopy level were found to have a slightly negative relationship with growth outcomes. It also happens that each of the species in our dataset foraging at this height are relatively small, which may explain this relationship. In addition to body size and peak frequency, nesting characteristics showed strong relationships with growth responses. Noise had stronger negative effects for species with open nests and those species which nest closer to the ground. Both cavity nests and nests located in the canopy have the protection of dense vegetation to attenuate sound (Nemeth and Brumm 2009). The reason that we see similar traits involved in physiological and growth responses is likely due to the relationship between stress hormones and growth. Developmental stress, such as that brought on by anthropogenic noise, is known to depress growth, inhibit immune function, and even suppress the expression of sexually selected traits (Buchanan et al. 2003; Crino and Breuner 2015).

The negative effect of anthropogenic noise on reproduction is concerning for avian species because reproduction directly contributes to individual fitness. It is also concerning that none of the traits explored in this analysis strongly predicted reproductive effects, indicating widespread negative effects on reproduction. Our results suggest that the mechanism by which noise affects bird reproduction likely transcends differences in traits and suggests a generalized effect that warrants urgent action. We do see that certain experimental and environmental factors may be the cause of this negative outcome. Industrial noises, mainly those related to resource extraction, were negatively related to reproductive responses. This may be the results of the loud, chronic noise created by some forms of energy extraction including compressors (Bayne, Habib, and Boutin 2008). Interestingly, our results indicated positive responses near military bases although this data is difficult to interpret due to the small sample size (n=3) and inclusion of only one species (red-cockaded woodpecker (*Picoides borealis*)).

The negative impact of noise on reproduction could be related to the impacts on communication. It is possible that because of masking effects and the need to alter communication, anthropogenic noise could be interfering with mating selection (Ríos-Chelén 2009). We also know that communication between parents and their offspring is essential to offspring survival (Lucass, Eens, and Müller 2016). For example, nesting passerine birds display begging, a combination of postures and calls, to communicate that they are in need of food (Wright & Leonard, 2002). Individuals with longer and louder calls generally receive more frequent food visits (Wright & Leonard 2002, Kilner & Hinde 2008). Masking has the potential to disrupt this acquisition of food if the message is not received by the parents. Through masking, anthropogenic noise could be inhibiting communication necessary for survival and therefore impacting reproductive success. Future research identifying the role of communication in reproduction and reproductive success is important for a deeper understanding of the downstream effects of anthropogenic noise.

Interestingly, we also saw a strong effect of anthropogenic noise on risk related responses. Risk is a compelling group of behaviors because of its potential to cause harm through downstream effects. Numerous studies have shown that there is a balance between foraging and vigilance (Beauchamp, 2015; Lima, 1998). More time spent vigilant means less time foraging, and when perceptions of threat are inhibited by noise, species often increase vigilant behavior (Klett-Mingo, Pavón, and Gil 2016). A decrease in foraging could lead to decreased growth and overall health. We were unable to determine the downstream effects of these responses on fitness, given the information present in the studies included in our meta-analysis. We suggest future work examining how the novel sensory pollutant of anthropogenic noise alters the causal linkages between risk perception, foraging, and fitness.

We also call for the need to study a more diverse set of species. Unfortunately, empirical studies of the impacts of anthropogenic noise have focused on only a small subset of bird diversity. Nearly half of all effect sizes (255/533) were collected from just five families (Paridae (n=81), Turdidae (n=47), Phasianidae (n=43), Troglodytidae (n=42), and Hirundidae (n=42); Fig.11). Because noise pollution is so pervasive, examining only a subset of families does not

9

allow us to fully understand the effects of anthropogenic noise. Exploring a more diverse set of families with differing traits will allow for a more robust analysis in determining how traits contribute to responses to anthropogenic noise.

Our data confirms the sentiment that more data exploring the impacts of anthropogenic noise on communities is needed (Francis et al. 2012). Here we examined only individual responses to noise, focusing mainly on impacts related to fitness. While not examined here, our literature review revealed only five studies that focused on responses of avian communities, rather than individual species.

Conservation applications

When designing conservation strategies, it is imperative that practitioners recognize the intersectionality between traits and context; both contribute to the effects anthropogenic noise has on avian species. Noise from industrial resource extraction has one of the largest negative effects on reproduction of avian species. Patricelli, Blickley, and Hooper (2013) put forth a few management suggestions to protect sage-grouse (*Centrocercus urophasianus*) from the effects of gas development noise. These include allowing for no more than 10dB above ambient noise levels and to focus protection on areas of mating, foraging, brooding, and nesting (Patricelli, Blickley, and Hooper 2013). Our research reinforces the idea of protecting areas of mating, brooding, and nesting as we saw sweeping effects on reproduction across species. Similar recommendations could be applied to the protection of other species facing similar threats. Our research also recognizes that larger birds and those that communicate at lower frequencies are more vulnerable to anthropogenic noise. These birds should be given appropriate attention when creating management plans.

It is also important to make noise management a priority when designing management plans. In the United States, noise management has not been the focus in the creation, legislation, or management of protected areas (Buxton et al. 2017). Similarly, most management plans surrounding airports around the world are focused on decreasing physical strikes by aircrafts, with little focus on noise pollution (Bradbeer et al. 2013). Monitoring noise pollution is key to putting noise management at the forefront of protection. Sethi et al. (2020) has put forth an innovative framework for monitoring eco-acoustic data. Eco-acoustic data was embedded into a classification convolutional neural net (CNN; a network used to identify and classify sounds) which allows them to not only discern anomalous sounds within an ecosystem, it also has the ability to assess ecosystem health through soundscapes (Sethi et al. 2020). Using a CNN also allows for less labor-intensive monitoring through machine-learning and automated analysis of soundscapes (Sethi et al. 2020). New technologies, along with understanding the ecology of species, are crucial for successful management.
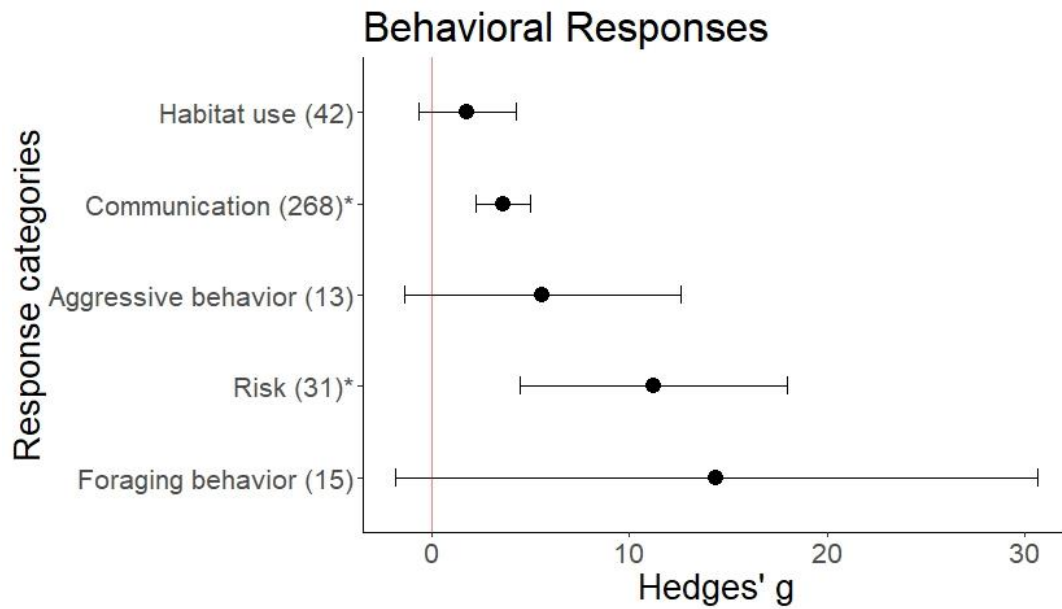
Fig. 1: forest plot showing the wES of each behavioral response group with 95% confidence intervals. Asterisks indicate significant (α = 0.05) results.
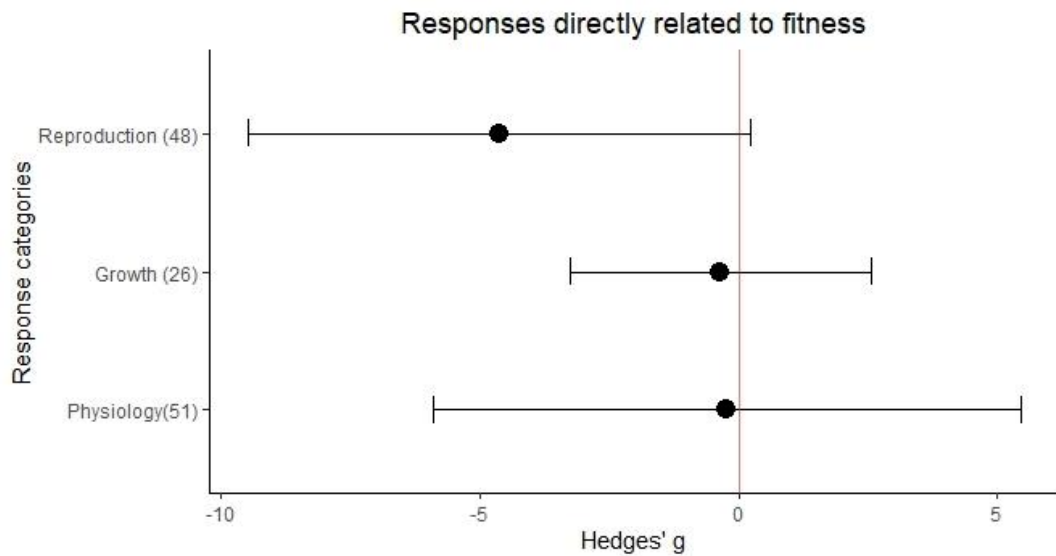

Fig. 2: forest plot showing wES of each fitness group with 95% confidence intervals.

Fig. 3: relationship between effect sizes for physiological responses and body size with 95% confidence intervals.
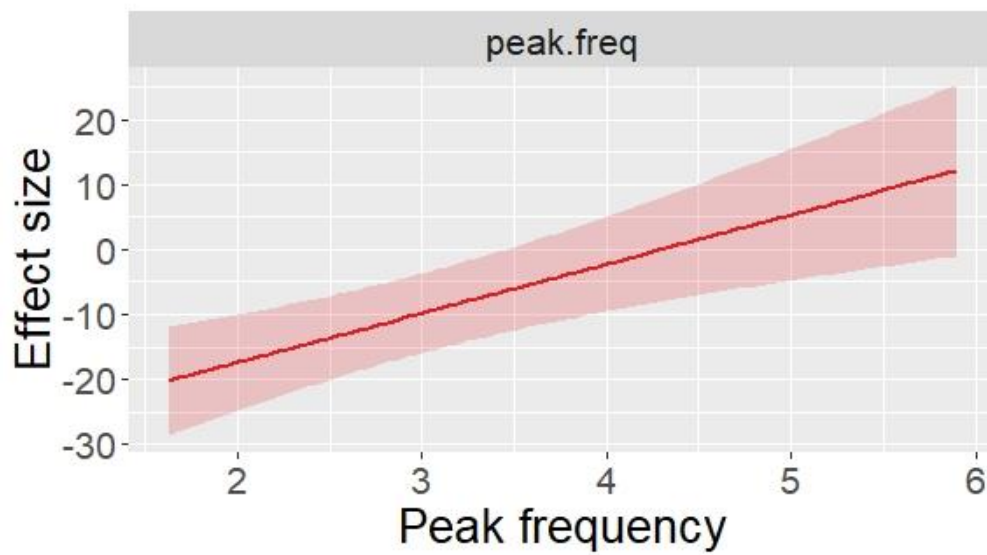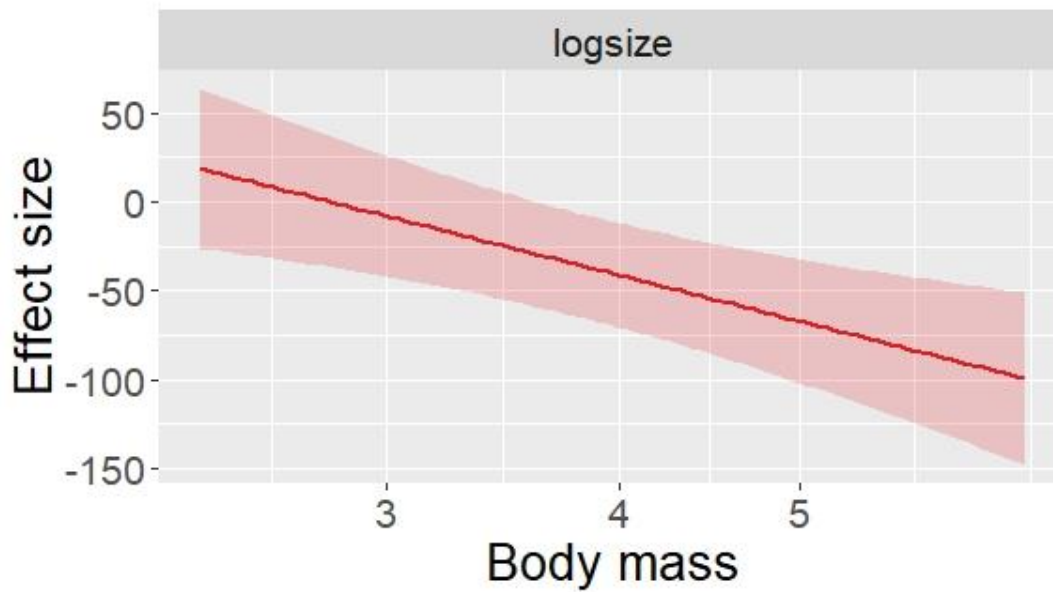

Fig. 4: relationship between effect sizes for physiological responses and peak frequency with 95% confidence intervals.

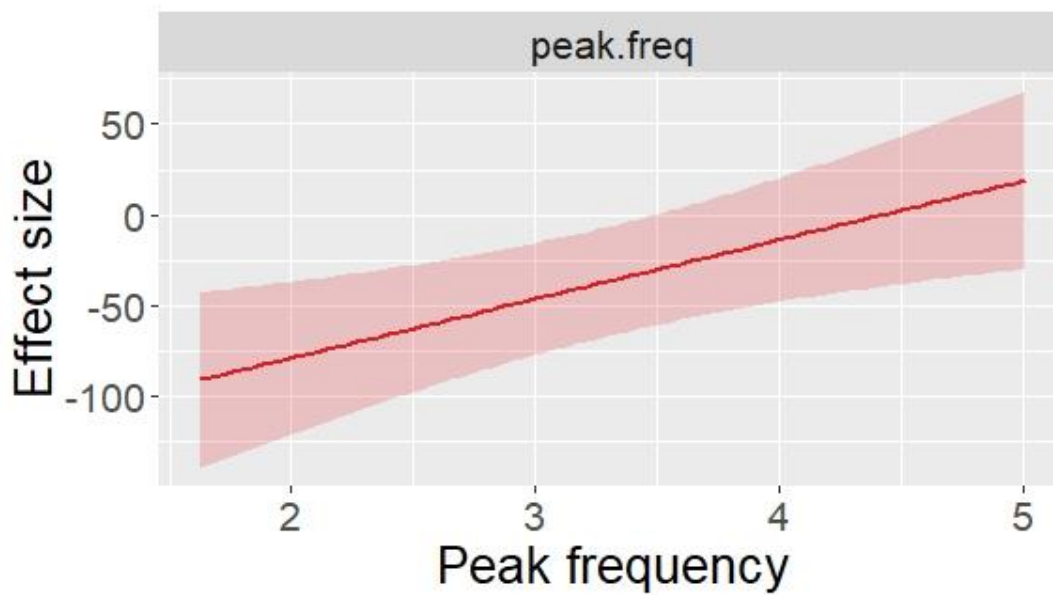Fig. 5: relationship between effect sizes of growth responses and body size with 95% confidence interval

Fig 6: relationship between effect sizes of growth responses and peak frequency with 95% confidence intervals.
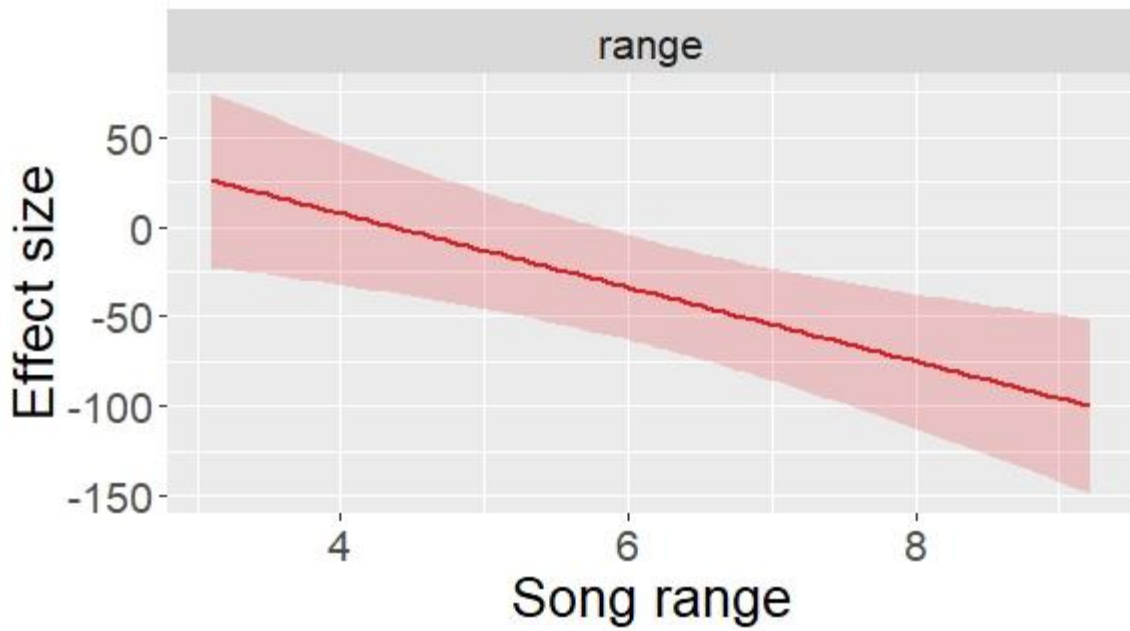
Fig. 7: relationship between effect sizes of growth responses and song range with 95% confidence interval
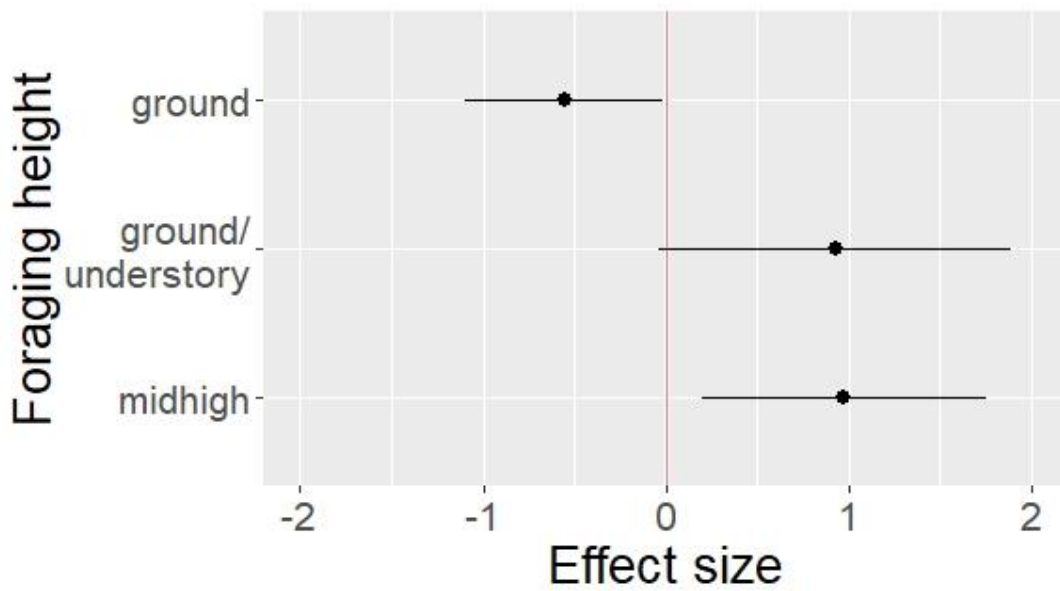

Fig. 8: Forest plot of average effect size (with 95% confidence interval) of growth responses varying by various foraging heights.
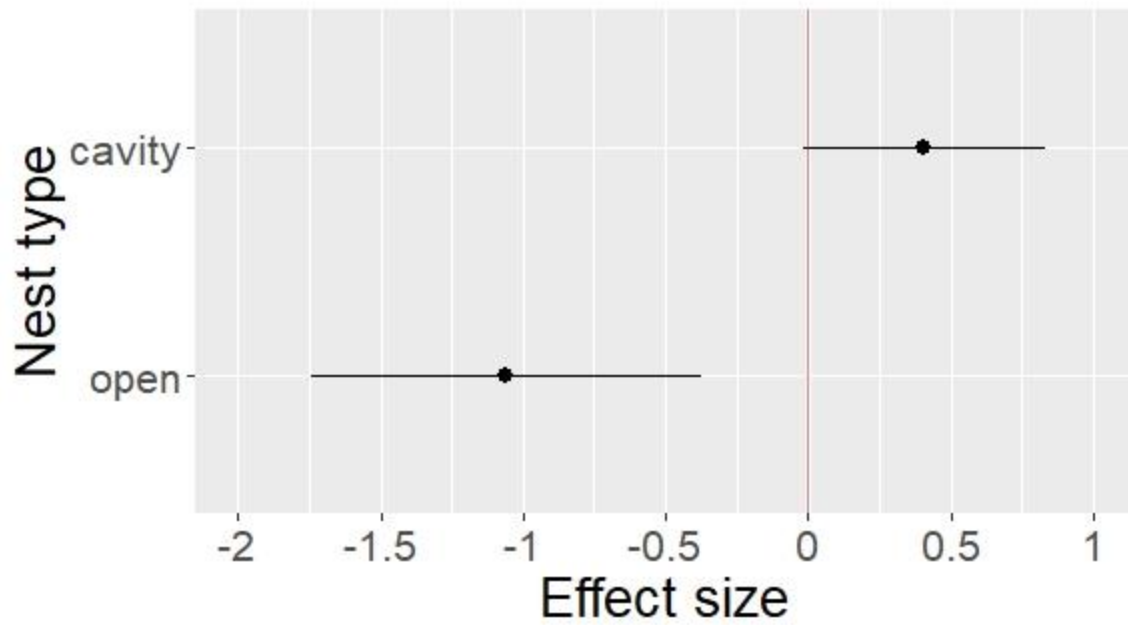
Fig. 9: Forest plot showing average effect size (with 95% confidence interval) of growth responses for open vs. cavity nests.
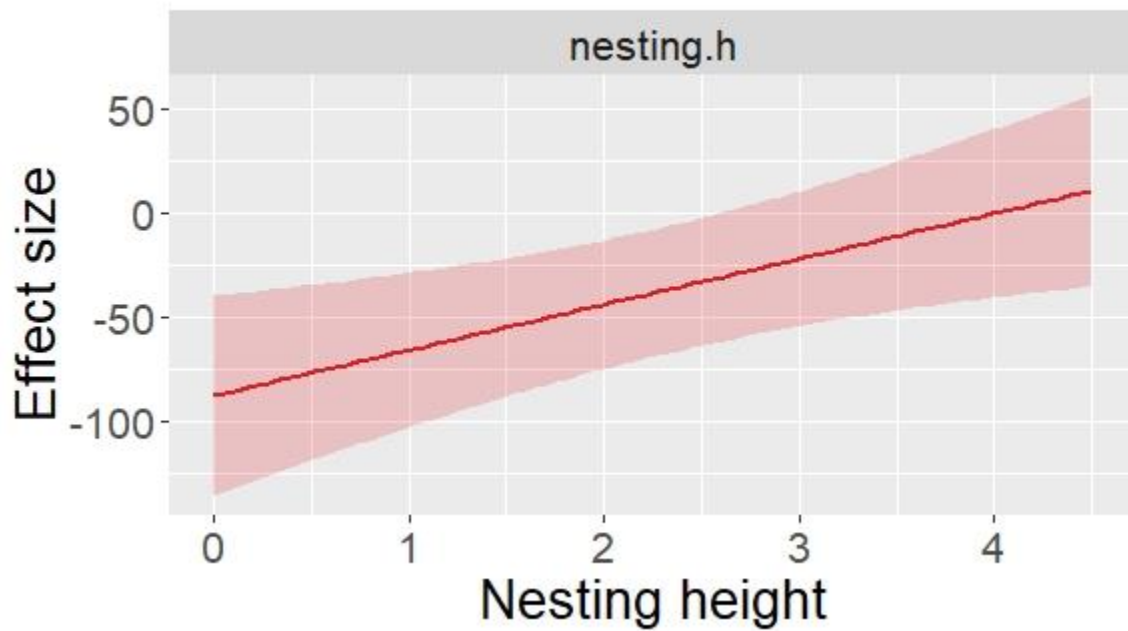

Fig. 10: relationship between effect size of growth responses and nesting height with 95% confidence interval.
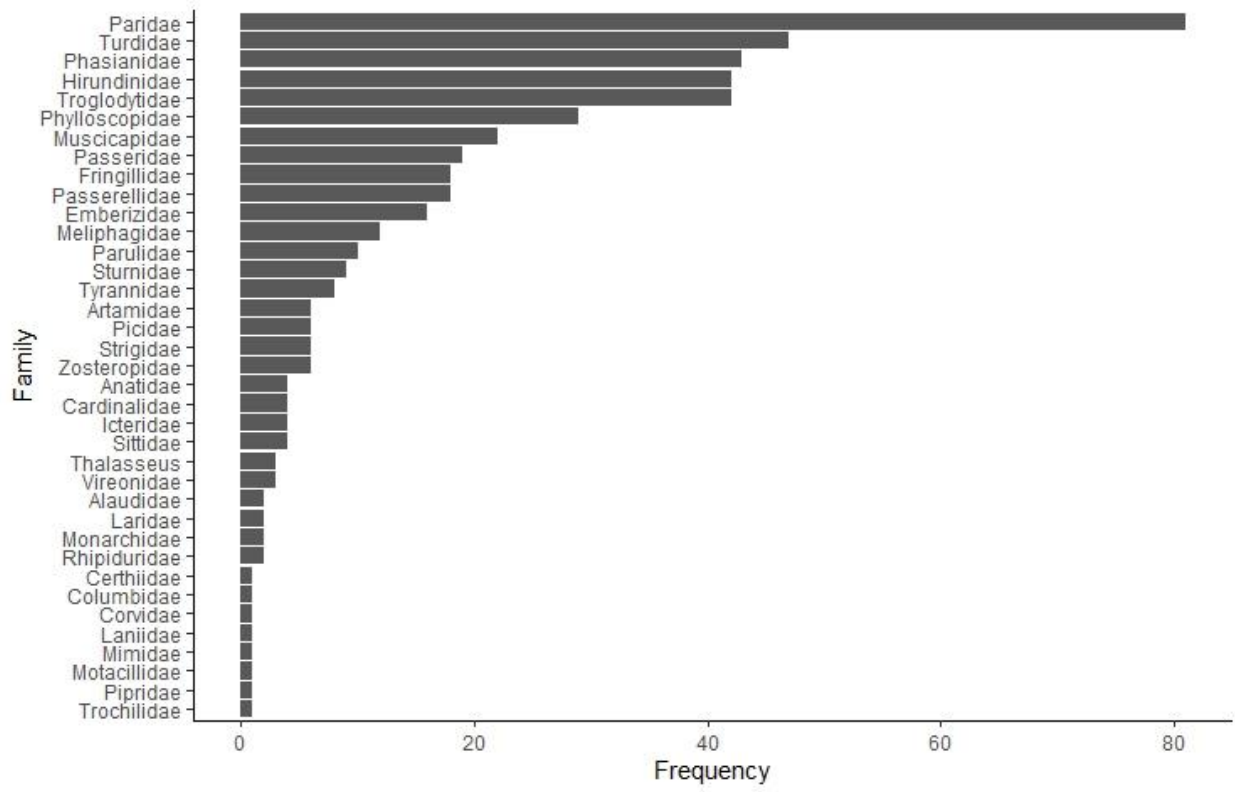
Fig. 11: Taxonomic families included in study in descending order of number effect sizes associated with them.

Supplemental material

Table S1: data of each effect size included in study.

References

Anderegg, William R.L. et al. 2016. "Meta-Analysis Reveals That Hydraulic Traits Explain Cross-Species Patterns of Drought-Induced Tree Mortality across the Globe." *Proceedings of the National Academy of Sciences of the United States of America* 113(18): 5024–29.

Antze, Bridget, and Nicola Koper. 2020. "Savannah Sparrows (Passerculus Sandwichensis) Nesting Close to Energy Infrastructure Alarm Call at a Lower Frequency." *Bioacoustics* 29(2): 168–81. https://doi.org/10.1080/09524622.2018.1563869.

Artelle, Kyle A. et al. 2018. "Hallmarks of Science Missing from North American Wildlife Management." *Science Advances* 4(3): 1–7.

Barber, Jesse R., Kevin R. Crooks, and Kurt M. Fristrup. 2010. "The Costs of Chronic Noise Exposure for Terrestrial Organisms." *Trends in Ecology and Evolution* 25(3): 180–89. http://dx.doi.org/10.1016/j.tree.2009.08.002.

Bautista, Luis M. et al. 2004. "Effect of Weekend Road Traffic on the Use of Space by Raptors." *Conservation Biology* 18(3): 726–32.

Bayne, Erin M., Lucas Habib, and Stan Boutin. 2008. "Impacts of Chronic Anthropogenic Noise from Energy-Sector Activity on Abundance of Songbirds in the Boreal Forest." *Conservation Biology* 22(5): 1186–93.

Borenstein, Michael, Larry V. Hedges, Julian P. T. Higgins, and Hannah R. Rothstein. 2009. *Introduction to Meta-Analysis*. John Wiley and Sons, Ltd.

Bradbeer, David et al. 2013. "WILDLIFE HAZARD MANAGEMENT Second Edition 2013." *Airports Council International*.

Buchanan, K. L., K. A. Spencer, A. R. Goldsmith, and C. K. Catchpole. 2003. "Song as an Honest Signal of Past Developmental Stress in the European Starling (Sturnus Vulgaris)." *Proceedings of the Royal Society B: Biological Sciences* 270(1520): 1149–56.

Buxton, Rachel T. et al. 2017. "Protected Areas." *Regional Cooperation in Amazonia* 533(May): 437–90.

Colino-Rabanal, Víctor J., Solange Mendes, Salvador J. Peris, and Moisés Pescador. 2016. " Does the Song of the Wren Troglodytes Troglodytes Change with Different Environmental Sounds? ." *Acta Ornithologica* 51(1): 13–22.

Crino, Ondi L. et al. 2013. "Effects of Experimentally Elevated Traffic Noise on Nestling White-Crowned Sparrow Stress Physiology, Immune Function and Life History." *Journal of Experimental Biology* 216(11): 2055–62.

Crino, Ondi L., and Creagh W. Breuner. 2015. "Developmental Stress: Evidence for Positive Phenotypic and Fitness Effects in Birds." *Journal of Ornithology* 156: 389–98.

Dominoni, Davide M. et al. 2020. "Why Conservation Biology Can Benefit from Sensory Ecology." *Nature Ecology and Evolution* 4(4): 502–11. http://dx.doi.org/10.1038/s41559-020-1135-4.

Dominoni, Davide M., Stefan Greif, Erwin Nemeth, and Henrik Brumm. 2016. "Airport Noise Predicts Song Timing of European Birds." *Ecology and Evolution* 6(17): 6151–59.

Dutta, Himangshu. 2017. "Insights into the Impacts of Four Current Environmental Problems on Flying Birds." *Energy, Ecology and Environment* 2(5): 329–49.

Francis, Clinton D. 2015. "Vocal Traits and Diet Explain Avian Sensitivities to Anthropogenic Noise." *Global Change Biology* 21(5): 1809–20.

Francis, Clinton D., Nathan J. Kleist, Catherine P. Ortega, and Alexander Cruz. 2012. "Noise Pollution Alters Ecological Services: Enhanced Pollination and Disrupted Seed Dispersal." *Proceedings of the Royal Society B: Biological Sciences* 279(1739): 2727–35.

González, Alice Elizabeth. 2014. "What Does 'Noise Pollution' Mean?" *Journal of Environmental Protection* 05(04): 340–50.

Grunst, Melissa L., John T. Rotenberry, and Andrea S. Grunst. 2014. "Variation in

Adrenocortical Stress Physiology and Condition Metrics within a Heterogeneous Urban Environment in the Song Sparrow Melospiza Melodia." *Journal of Avian Biology* 45(6): 574–83.

Halfwerk, Wouter, and Hans Slabbekoorn. 2015. "Pollution Going Multimodal: The Complex Impact of the Human-Altered Sensory Environment on Animal Perception and Performance." *Biology Letters* 11(4).

Hau, Michaela et al. 2010. "Corticosterone, Testosterone and Life-History Strategies of Birds." *Proceedings of the Royal Society B: Biological Sciences* 277(1697): 3203–12.

Hedges, Larry V., Elizabeth Tipton, and Matthew C. Johnson. 2010. "Robust Variance Estimation in Meta-Regression with Dependent Effect Size Estimates." *Research Synthesis Methods* 1(1): 39–65.

Hu, Yang, and Gonçalo C. Cardoso. 2010. "Which Birds Adjust the Frequency of Vocalizations in Urban Noise?" *Animal Behaviour* 79(4): 863–67.

Injaian, Allison S. et al. 2020. "Baseline and Stress-Induced Corticosterone Levels across Birds and Reptiles Do Not Reflect Urbanization Levels." *Conservation Physiology* 8(1): 1–18.

Klett-Mingo, J. Ignacio, Ignacio Pavón, and Diego Gil. 2016. "Great Tits, Parus Major, Increase Vigilance Time and Reduce Feeding Effort during Peaks of Aircraft Noise." *Animal Behaviour* 115: 29–34.

Kunc, Hansjoerg P., and Rouven Schmidt. 2019. "The Effects of Anthropogenic Noise on Animals: A Meta-Analysis." *Biology Letters* 15(11).

Lucass, Carsten, Marcel Eens, and Wendt Müller. 2016. "When Ambient Noise Impairs Parent-Offspring Communication." *Environmental Pollution* 212: 592–97. http://dx.doi.org/10.1016/j.envpol.2016.03.015.

Meillère, Alizée, François Brischoux, and Frédéric Angelier. 2015. "Impact of Chronic Noise Exposure on Antipredator Behavior: An Experiment in Breeding House Sparrows." *Behavioral Ecology* 26(2): 569–77.

Murgatroyd, M., G. Avery, L. G. Underhill, and A. Amar. 2016. "Adaptability of a Specialist Predator: The Effects of Land Use on Diet Diversification and Breeding Performance of Verreaux's Eagles." *Journal of Avian Biology* 47(6): 834–45.

Nemeth, Erwin, and Henrik Brumm. 2009. "Blackbirds Sing Higher-Pitched Songs in Cities: Adaptation to Habitat Acoustics or Side-Effect of Urbanization?" *Animal Behaviour* 78(3): 637–41. http://dx.doi.org/10.1016/j.anbehav.2009.06.016.

Organization, World Health. 2011. "Burden of Disease from Environmental Noise." : 128.

Parris, Kirsten M., and Angela Schneider. 2009. "Impacts of Traffic Noise and Traffic Volume on Birds of Roadside Habitats." *Ecology and Society* 14(1).

Paton, Grant D., Alexandra V. Shoffner, Andrew M. Wilson, and Sara A. Gagné. 2019. "The Traits That Predict the Magnitude and Spatial Scale of Forest Bird Responses to Urbanization Intensity." *PLoS ONE* 14(7): 1–20.

Patricelli, Gail L., Jessica L. Blickley, and Stacie L. Hooper. 2013. "Recommended Management Strategies to Limit Anthropogenic Noise Impacts on Greater Sage-Grouse in Wyoming." *Human-Wildlife Interactions* 7(2): 230–49.

Peris, S. J., and M. Pescador. 2004. "Effects of Traffic Noise on Paserine Populations in Mediterranean Wooded Pastures." *Applied Acoustics* 65(4): 357–66.

Polanin, Joshua R., Emily A. Hennessy, and Emily E. Tanner-Smith. 2017. "A Review of Meta-Analysis Packages in R." *Journal of Educational and Behavioral Statistics* 42(2): 206–42.

Ray, Prajna Paramita et al. 2018. "Noise Induces Hypothyroidism and Gonadal Dysfunction Via Stimulation of Pineal–Adrenal Axis in Chicks." *Proceedings of the Zoological Society* 71(1): 30–47.

Ríos-Chelén, Alejandro Ariel. 2009. "Bird Song: The Interplay Between Urban Noise and Sexual Selection." *Oecologia Australis* 13(01): 153–64.

Sethi, Sarab S. et al. 2020. "Characterizing Soundscapes across Diverse Ecosystems Using a

Universal Acoustic Feature Set." *Proceedings of the National Academy of Sciences* 117(29): 17049–55.

Shannon, Graeme et al. 2016. "A Synthesis of Two Decades of Research Documenting the Effects of Noise on Wildlife." *Biological Reviews* 91(4): 982–1005.

Slabbekoorn, Hans, Robert J Dooling, Arthur N Popper, and Fay R Richard. 2018. *Efects of Anthropogenic Noise on Animals*.

Slabbekoorn, Hans, and Erwin A.P. Ripmeester. 2008. "Birdsong and Anthropogenic Noise: Implications and Applications for Conservation." *Molecular Ecology* 17(1): 72–83.

Swaddle, John P. et al. 2015. "A Framework to Assess Evolutionary Responses to Anthropogenic Light and Sound." *Trends in Ecology and Evolution* 30(9): 550–60. http://dx.doi.org/10.1016/j.tree.2015.06.009.

Tummers, Bas. 2006. "DataThief III Manual v. 1.1." *Manual*: 1–52. www.datathief.org.

Warren, Paige S., Madhusudan Katti, Michael Ermann, and Anthony Brazel. 2006. "Urban Bioacoustics: It's Not Just Noise." *Animal Behaviour* 71(3): 491–502.

Williams, David et al. 2018. "Evaluating Outcomes of Community-Based Conservation on Kenyan Group Ranches with Remote Sensing." *Environmental Conservation* 45(2): 173–82.

Wilman, H. et al. 2014. "EltonTraits 1 . 0 : Species-Level Foraging Attributes of the World ' s Birds and Mammals." *Ecology* 95(October 2013): 2027.