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Author for correspondence:
Natalie L. Madden
e-mail: nmadden@defenders.org

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Trait-mediated effects of anthropogenic noise on bird behaviour and fitness

Natalie L. Madden[1,3], Kirby L. Mills[1,2], Karen M. Alofs[1], Clinton D. Francis[4] and Neil H. Carter[1]

[1]School for Environment and Sustainability, and [2]Institute for Global Change Biology, University of Michigan, Ann Arbor, MI, USA
[3]Center of Conservation Innovation, Defenders of Wildlife, Washington, DC, USA
[4]Department of Biological Sciences, California Polytechnic State University, San Luis Obispo, CA, USA

NLM, 0009-0003-0965-0413; KLM, 0000-0001-7693-9629; CDF, 0000-0003-2018-4954

Birds are considered especially vulnerable to anthropogenic noise because of their reliance on acoustic information. Single-species research shows that noise can impact different aspects of bird behaviour and consequently reduce their fitness. However, we have a limited understanding of how ecological and life-history traits mediate responses to anthropogenic noise across species. We performed a meta-analysis to quantify noise impacts on bird behaviours (communication, cognition, aggression, risk, foraging and habitat use) and fitness-related responses (growth, physiology and reproduction), and how bird traits, such as nesting and habitat type, mediated those responses. Using 944 effect sizes from 160 bird species across six continents, we found that anthropogenic noise significantly affected various behaviours as well as physiology and had strong negative effects on reproductive responses. We also found that anthropogenic noise had stronger negative effects on bird reproduction for species that nest nearer to the ground, while growth and physiological responses were stronger for species that nested in open rather than cavity nests and those living in deciduous forests, respectively. Our results highlight the characteristics of those birds most vulnerable to noise pollution and inform how conservation actions can best reduce the impacts of human-made noise in those species' habitats.

1. Introduction

Anthropogenic noise is an underappreciated consequence of the expansion of humans across the globe [1]. In contrast to understanding consequences of human expansion such as habitat destruction, invasive species and chemical pollution, the consequences of exposure to noise pollution for the behaviour, physiology and overall fitness of animals have only recently captured the attention of researchers [2]. Birds have been considered particularly vulnerable to anthropogenic noise because of their conspicuous dependence on acoustic communications [3–5]. Noise pollution can interfere with important vocalizations used for attracting mates, communicating with young or signalling danger to conspecifics [6]. Beyond disrupting communication, noise pollution can interfere with acoustic surveillance for threats [7] and hence strongly contribute to perceptions of risk that can alter behaviour [8,9]. Noise pollution also has the potential to interfere with or elicit a number of other responses [10,11], including changes in hormone levels, time spent feeding and growth rates [12]. 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 [13,14].

Existing evidence suggests that the impact of anthropogenic noise on birds can vary depending on the species, type of noise and type of response being

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measured. For example, Williams [15] found that noise from gas compressors had a negative impact on the hatching success of tree swallows (*Tachycineta bicolor*), whereas Meillere *et al*. [16] found no impact of urban noise on the hatching success of house sparrows (*Passer domesticus*). Peris & Pescador [17] found that while proximity to traffic noise had a negative effect on the density of woodlarks (*Lullula arborea*), it had no impact on the density of blackbirds (*Turdus merula*) in a given area. Similarly, one study measured an increase in stress hormones in song sparrows (*Melospiza melodia*) due to urban noise [18], while another measured no impact of traffic noise on mountain white-crowned sparrow (*Zonotrichia leucophrys*) chick mass [19]. Clearly, a lot of variation exists in responses to noise that appear to be context and species dependent [20,21]. What is unclear, however, is whether there are generalizable patterns in these responses that could lead to predictive insight into the vulnerability of birds to noise pollution across gradients of exposure.

Ecological and life-history traits have proven to be useful tools in discerning the varying responses of birds to anthropogenic noise [22,23] and may help us understand why certain species appear to be better adapted than others 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. For example, 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 [22,24]. Diet composition and 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 [25,26]. Dietary generalists are predicted to more easily cope with an ecologically altered environment than specialists because they are adapted to heterogeneous environments and are better able to utilize alternative food sources [27]. Diet, vocalization and other traits may hold the key to understanding how best to mitigate the effects of noise for the most vulnerable species.

Here, we conducted a phylogenetically controlled meta-analysis on bird responses to anthropogenic noise in order to provide generalizable insight on how this sensory pollutant in various forms—aircraft, industrial, military and urban—affects a range of responses. Notably, we include behavioural responses related to communication, cognition, aggression, risk, foraging and habitat use, as well as impacts to responses closely related to fitness, including growth, physiology and reproduction. Moreover, we evaluate how traits—song structure, life history and physical attributes—mediate bird response (table 1). By synthesizing responses across bird species and contexts, we further investigate the mechanisms underlying bird responses to anthropogenic noise that can inform more effective actions for maintaining healthy bird populations amid human pressures.

2. Methods

(a) Search protocol

Data collection consisted of two primary literature searches. The first was performed in 2017 following the search protocol by Shannon *et al.* [35] that was published in 2016 and had just completed a comprehensive search spanning 1990–2013. We limited our earliest search date to 1990 based on prior searches that resulted in no studies that explicitly studied the impacts of noise on birds prior to 1990 [36]. We conducted a detailed literature search using Thompson's ISI Web of Science All Databases 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 to 2020. At this point, we were able to extract data from 89 studies identified in our literature searches.

Due to complications and to the loss of personnel, plus the COVID-19 pandemic, we were unable to advance this project for several years. For this reason, in 2025, we conducted a second, more targeted literature search to update the previous repository. We conducted a search in Web of Science All Databases with the keywords 'birds' and 'anthropogenic noise'. We limited our search from 2018 to 2025 so as not to duplicate results from the previous literature search. This yielded 400 potential studies. We then narrowed the list by title and abstract, leaving us with 162 studies. We also conducted a search using Elicit, an AI search tool. To conduct a search in this programme, we asked the question, 'How does anthropogenic noise impact bird reproductive success, communication, habitat, selection, growth, physiology, foraging, and other behaviours across different bird species?' We again limited this search to the years 2018–2025. The initial search using Elicit yielded 495 results. After further screening, we were left with 109 potential studies. Seventy-five studies were matched between the two searches after initial screening. We therefore assessed the full text of 162 studies from our Web of Science search and 34 from the Elicit search. Ultimately, we were able to extract data from an additional 71 studies from these more recent literature searches and a total of 160 studies overall. See electronic supplementary material, figure S1, for more details.

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Table 1. Description of each trait type. Predicted effects describe how each trait is predicted to mediate the impacts of noise on birds.

trait	description	type	predicted effects	rationale
body size	average body mass of adult individuals (g)	continuous	species with a lower body mass expected to be impacted less	the negative correlation between body size and song frequency [28,29]
clutch size	average clutch size	continuous	species with large clutch sizes expected to be less impacted	species with large clutch sizes have been shown to tolerate urban environments [30]
diet	a species' dominant diet type: invertebrate, omnivore, plant/seed, fruit/nectar, vertebrate/fish/scavenger	categorical	omnivorous species expected to be impacted the least	omnivores occupy a broader niche and therefore have the potential to better adapt to novel environments
dietary breadth	the number of diet categories a species falls in	continuous	species with larger breadth expected to be impacted less	species with a larger dietary breadth may be less affected by the impacts of noise interference in foraging strategies
foraging height	dominant height at which species feed	categorical	species foraging at higher heights expected to be impacted less	canopy from trees helps attenuate noise and potentially lessen its impacts [4]
frequency range	average frequency range of song	continuous	species with a wider frequency range expected to be impacted less	more complex songs propagate through noisy environments better [31]
habitat type	dominant habitat type of species	categorical	generalist species and those in densely vegetated habitats expected to be impacted the least	generalist species, or those with a wider niche, are better able to adapt to novel environments. Forests and tallgrass prairies have been shown to attenuate noise [32]
migratory	migratory versus non-migratory. If species were partially migratory, they were categorized as migratory	categorical	non-migratory species expected to be impacted less	noise has been shown to degrade migratory stopover sites by affecting the ability of species to gain body conditions necessary for migration [33]
nesting height	average nesting height within canopy	continuous	species nesting at higher heights expected to be less impacted	canopy from trees attenuates noise and potentially lessens impacts [4]
nest type	cavity versus open nest	categorical	species nesting in cavity nests expected to be impacted less	cavity nests have been shown to attenuate noise and potentially lessen the impacts [34]
peak frequency	average frequency of the highest decibel of song	continuous	species with a higher peak frequency expected to be impacted less	anthropogenic noise tends to be at a lower frequency [22]. Birds with a higher peak frequency may be able to avoid masking of their songs
song length	average song length	continuous	species with a longer song expected to be impacted less	longer songs are more detectable in noisy environments as they give listeners more opportunities to hear them [31]

(b) Data selection

Data were included in the 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 through either observational or experimental designs. 'Before' or 'after' 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 versus rural settings, if the 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 versus aircraft), each was treated as a separate experiment and yielded separate effects. Multiple responses were often collected from a single publication. We recorded multiple responses if multiple species or sound types were evaluated separately and/or if multiple responses were measured. Each study was given a study ID.

We collected data on several experimental moderators from each study. We recorded the identity of species, study type (experimental versus observational) and amplitude of source noise. Response and source sound type were also categorized for analysis. Response types included behavioural responses—aggressive behaviour, cognition, communication, foraging behaviour, habitat use, reproduction and behaviours related to risk—as well as responses more directly linked to fitness—growth, reproduction and physiology. Aggressive behaviours included behaviours such as the number of attacks (against other birds or researchers) and the number of pecks. Any response related to song or call structure including song length, frequency bandwidth, song rate, as well as any response related to the timing of calls was categorized as communication. Cognitive

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behaviour is related to learning. Our analysis included studies in which researchers tested the ability of birds to learn certain behaviours in experimental settings under noisy conditions. Foraging behaviour includes behaviours 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 changes in hormones or blood composition. Reproductive responses included anything from mating success to fledging success. This included changes in mating behaviour, changes in clutch size or latency to egg laying, as well as parental care and fledging success. Lastly, risk responses were those having to do with responses to perceived risk, vigilance or predator detection. If communicative responses were measured as a specific response type and not simply the structure or timing of the vocalization, they were placed in the respective category. For example, if researchers measured the number of begging calls, this was measured as reproduction as it is related to parental care, and not as communication. Similarly, in some instances, response calls to predators were measured. In these cases, responses were categorized as risk.

How we categorized sound type was guided by the research from which we extracted data and based on the description from the original authors. Aircraft noises included both commercial, military and personal aircraft. Many studies explored responses directly related to aircraft flight presence. Industrial noises were those caused by large industrial machinery. This mainly consisted of noises related to resource extraction such as gas or oil well compressors, but also included renewable energy sources such as wind turbines. Military noises were recorded directly outside or within military training facilities. As previously mentioned, if the noise being measured was specifically military aircraft, it was categorized as aircraft and not military. Urban noises were those recorded within urban settings, such as cities or other areas highly populated by humans, or relating to transportation networks. Urban noise also consisted of machinery commonly present in urban settings including lawn mowers. Recordings of these different sound types that were later used as playbacks were also categorized according to their respective sound type. Finally, other noises were those created or manipulated by researchers such as white, brown or pink noise.

To calculate effect size, we collected or derived mean responses, error measurements and treatment sample sizes. DataThief software was used to extract data from figures that contained the appropriate parameters (DataThief v. 1.7).

(c) Effect size calculation

To compare results between studies, effect sizes were calculated using Hedges' g [37]. For studies that reported results using *t* or *F* values, we used alternate equations to calculate Hedges' g [38].

Most behavioural and physiological responses to noise documented to date have not been explicitly linked to fitness [7] and cannot be assumed to negatively or positively affect fitness. Therefore, for communication, aggression, risk aversion, foraging, habitat use, cognition and physiological responses, we used absolute values to ensure all effects reflect the magnitude of their impact [39]. In contrast, the directionality of noise impacts on reproductive and growth responses was clear. For these response categories, we evaluated raw, positive and negative effect sizes.

(d) Bird traits

For each species included in the study, we collected trait data related to song structure, life history and physical attributes (table 1). For song structure, we focus on peak frequency, the frequency at which an individual vocalizes at the highest amplitude [40], song bandwidth and song length. Vocalizations were collected from audio archives from Xeno-Canto and analysed using Raven Lite 2.0 (Cornell Laboratory of Ornithology, Ithaca, NY, USA). We analysed three songs from three different recordings for each species and used the average for statistical analysis. Although the availability of recordings is growing in repositories such as Xeno-Canto and Cornell's Macaulay Library, because our analysis included research from around the globe, we were unable to obtain songs from the exact location of each study included in the dataset. Moreover, we often had multiple study locations per species. For this reason, we prioritized using the highest quality archived recordings we could find and used the same song structure trait data for each instance of the corresponding species regardless of location. We also collected data on diet and dietary breadth. Diet and foraging height data were collected from Elton traits [41]. Data cataloguing habitat type, adult body mass, and whether a species was migratory or not were collected from BirdLife [42]. Other traits included in the analysis were nest type and average nest height, which we collected from Birds of the World (Cornell Laboratory of Ornithology, Ithaca, NY, USA). Lastly, we used the taxonomy from Jetz *et al*. [43] for our phylogenetic hypotheses and taxonomy. We log-transformed song length and body size to account for higher representation of smaller values.

(e) Meta-analysis: noise effects on bird responses and trait-mediated effects

We used univariate meta-analytic linear models to assess the overall effects of anthropogenic noise on each of the bird response types (i.e. habitat use, risk responses, foraging behaviour, aggression, cognition, physiology, growth and reproduction). Most studies yielded multiple effect sizes resulting in non-independence among effect sizes calculated within a given study. Additionally, shared phylogenetic history among bird species could contribute to dependencies among study outcomes. To control for intra-study and phylogenetic dependencies, we conducted meta-analytic multilevel mixed-effects models that account for the non-independence of study outcomes via random intercepts for effect ID nested within study ID as well as a phylogenetic correlation matrix. Phylogenetic correlations among species were calculated using a consensus phylogeny based on trees available at birdtree.org [43].

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We weighted the studies using the inverse of their calculated sampling variance and used the maximum-likelihood estimation of residual heterogeneity. The intercept terms and 95% confidence intervals (CIs) of the models were interpreted as the average weighted effect size (wES) of anthropogenic noise on each study response type. For physiology and all behavioural responses, which were calculated as the absolute values of Hedge's g, we log-transformed the wES response variable in the models to account for the fact that the absolute values of Hedges' g were skewed towards 0, and then exponentiated the model intercept and 95% CIs to represent wES for interpretation. In these cases, the back-transformed 95% CIs were bounded at 0. For all models, we based the significance of the average effect size on the 95% CI of the final wES value being different from ±0.2 and thus a moderate strength effect [38]. Because the models included complex random-effects structures and those using log-transformed absolute values have inherently asymmetrical response values, we were unable to explicitly test for publication bias using common approaches. We thus evaluated potential sensitivity to publication bias by re-fitting each model while excluding smaller, less precise studies at varying levels of specificity (i.e. including effect sizes with variances less than the 0.50, 0.75 and 0.90 percentiles; electronic supplementary material, table S1). If publication bias were present, we would expect wES estimates from the reduced datasets to decrease towards zero as imprecise studies are excluded.

We used Cochran's Q-test to test whether the true effects in the meta-analytic model are heterogeneous. We also estimated the proportions of the heterogeneity among effect sizes that are attributable to similarities within studies or the phylogenetic relationships among species by calculating multi-level I^2 metrics proposed by Nakagawa & Santos [44]. We thus calculated the study-level heterogeneity (I^2_{study}) and species-level heterogeneity (I^2_{species}) by dividing the estimated variance components of the models for the nested study/ID and phylogenetic random effects by the total heterogeneity in the true effects (the sum of the model variance components). All models were built and assessed using the 'metafor' package in R [45].

To assess whether study-specific components influenced the strength of bird responses to anthropogenic noise, we also added study characteristics (i.e. experiment type (experimental/observational), sound type (urban/industrial/military/other) and sound amplitude) as moderators to the mixed-effects models, producing a separate model for each study characteristic. We assessed the univariate models for significant effects of study components based on 95% CIs of the fixed model coefficients.

To evaluate how species traits mediated the directional effects of anthropogenic noise on each response that is closely related to fitness (i.e. growth, physiology, reproduction) and habitat use, we added fixed effects of traits (electronic supplementary material, table S2) to the meta-analytic models used to calculate wES, maintaining the previously described random effects structure. We created a mixed-effects model with a univariate fixed effect for each species trait, and we assessed how traits mediated noise impacts on bird responses by assessing fixed-effect coefficients and 95% CIs. For physiology and habitat use responses that were calculated as the absolute values of Hedges' g, we again log-transformed the response variable to account for the fact that the absolute values of Hedges' g were skewed towards 0. 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.

Additionally, we performed an intercept-only model to give insight into the distribution of heterogeneity among effect sizes. Because of the numerous response types and varying interpretations of the response values in those categories, this model should not be used to interpret the impacts of noise on birds, but only the variance structure of these data.

3. Results

(a) Noise effects on bird behaviors and habitat use

We collected 944 total effect sizes from 160 studies that quantified the behavioural and fitness consequences of anthropogenic noise on 161 species of birds. While a majority of studies took place in the global north, our meta-analysis spans studies from six continents (figure 1). The intercept-only model revealed that a majority of the heterogeneity in our dataset stemmed from among-study variation (electronic supplementary material, table S3).

Univariate meta-analytic models for behavioural responses revealed that anthropogenic noise led to significant changes in bird communication (wES = 0.99, 95% CI: 0.51–1.91), risk behaviours (wES = 3.49, 95% CI: 1.2–10.131), foraging behaviours (wES = 2.80, 95% CI: 1.72–4.57), aggressive behaviour (wES = 2.19, 95% CI: 0.58–8.24) and physiology (wES = 0.95, 95% CI: 0.55–1.65) (figure 2). Anthropogenic noise also appeared to negatively affect bird reproduction (wES = −2.06, 95% CI: −4.43 to 0.31) and had a strong association with habitat use (wES = 0.58, 95% CI: 0.18–1.88). Models for all response types showed significant heterogeneity among true effects (Q-test, $p < 0.001$ for all models). Within-study heterogeneity accounted for a large portion of the overall effect size heterogeneity in the models for communication, habitat use, risk, foraging, aggression and growth responses, and we detected only a moderate signal of influence on bird physiology in response to noise (figure 2). Overall, we found very little evidence of publication bias in our dataset. Effect size estimates from the reduced datasets excluding less precise studies were highly similar to those from the full analysis, except for a loss of significance of foraging responses when only the most precise 50% of foraging effects were included (electronic supplementary material, table S1).

We found only a few instances of study characteristics influencing the strength of bird responses to noise (electronic supplementary material, table S4). Compared to experimental studies, observational studies produced stronger effects of anthropogenic noise on bird aggression ($\beta_{\text{ref:experiment}}$ = 2.04, 95% CI: 0.45–3.63), foraging ($\beta_{\text{ref:experiment}}$ = 1.55, 95% CI: 0.02–3.09) and growth ($\beta_{\text{ref:experiment}}$ = 4.87, 95% CI: 0.65–9.09). Other sound types had significant impacts on foraging ($\beta_{\text{ref:experiment}}$ = −1.65, 95% CI: −3.25 to −0.04) and reproduction ($\beta_{\text{ref:experiment}}$ = −6.52, 95% CI: −12.03 to 1). Amplitude consistently had very small effects on bird responses to noise across response types (electronic supplementary material, table S4).

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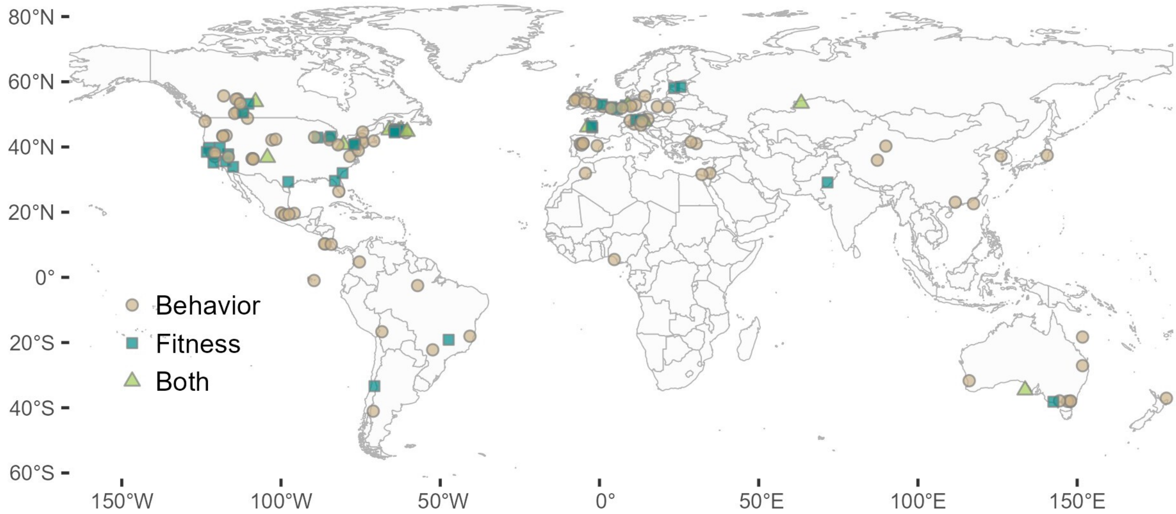

Figure 1. A global map displaying the location of each study included in our analysis. The various shapes represent whether the research explored responses related to behaviour ($n = 110$), fitness ($n = 39$) or both ($n = 13$). Study locations are not exact because we included a jitter to increase visibility of overlapping points.

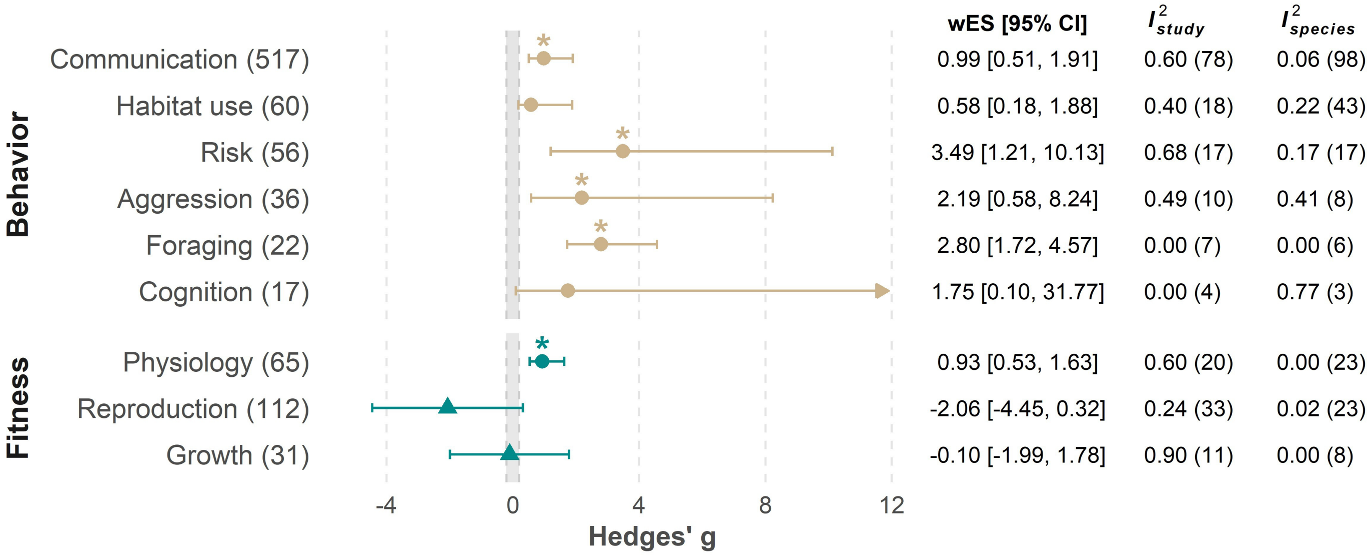

Figure 2. Weighted mean effect sizes (wES) of bird responses to noise across behavioural and fitness response types. For behavioural and physiological responses that were log-transformed absolute values of effect sizes (circles), we back-transformed estimates of Hedges' g for interpretation by exponentiating the model outputs, while wES values for reproduction and growth models were calculated using true (not log-transformed) effect sizes (triangles). Stars denote significance based on ±0.2 Hedges' g threshold (shaded region). The numbers in parentheses next to model categories indicate the number of effect sizes included, and numbers in parentheses after I^2 values denote the number of studies and species included in the model.

(b) Trait-mediated effects of noise on bird fitness

We found that in some cases the impacts of anthropogenic noise on bird fitness were mediated by species' traits. Noise significantly increased the growth of bird species that nested in the open rather than in cavities ($\beta_{ref:cavity}$= 5.59, 95% CI: 1.05–10.14) (figure 3). Similarly, we see that impacts to habitat use are mediated by birds nesting in open cups ($\beta_{ref:cavity}$= 1.37, 95% CI: 0.34–2.40) (figure 3). We also found that the effects of noise on physiological responses were significantly smaller for species living in deciduous forests compared to those in generalist habitats ($\beta_{ref:generalist}$ = −2.25, 95% CI: −3.90 to −0.60), as well as those living in grassland habitats ($\beta_{ref:generalist}$ = −1.4, 95% CI: −2.75 to −0.05) (figure 3).

Additionally, we found a number of strong associations between traits and the effects of noise that had strong, but variable associations between traits and the effects of noise, which were not statistically significant (figure 4). Song length was positively associated with effects on growth responses (β = 2.22, 95% CI: 0.07–4.51). Diet and foraging habits also seemed to mediate the impacts of noise with an omnivorous diet having a positive relationship with the effects of noise on growth responses (β = 5.00, 95% CI: −0.21 to 10.20). Though not significant, average nesting height mediated the impacts of noise on habitat use (β = −0.12, 95% CI: −0.25 to 0.001). Similar to significant patterns we saw with effects of noise on physiological responses, species living in mixed forests had notably smaller responses compared to generalist species ($\beta_{ref:generalist}$ = −1.45, 95% CI: −3.16 to 0.26). Physiological responses to noise were also smaller for species that forage at mid-high levels in comparison to those that forage on the ground ($\beta_{ref:ground}$ = −1.17, 95% CI: −2.42 to 0.08).

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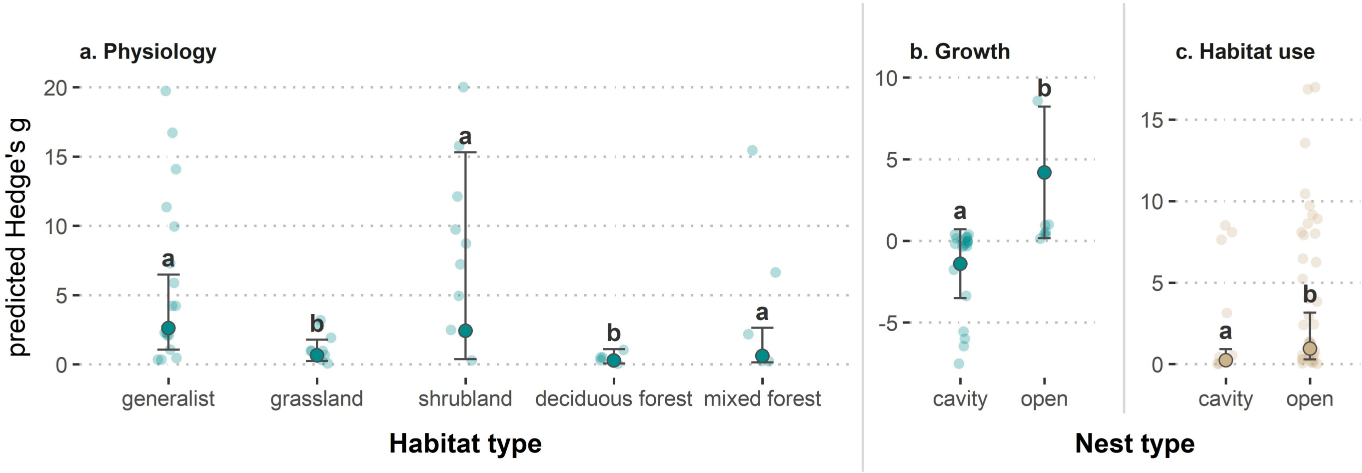

Figure 3. Predictions of effect size strength as mediated by traits according to the univariate models. Letters above CIs denote significant differences in the strength of responses between groups according to 95% CIs of beta coefficients. Predicted physiological and habitat use responses were exponentiated from log-transformed effect sizes to reflect the same scale as other plots.

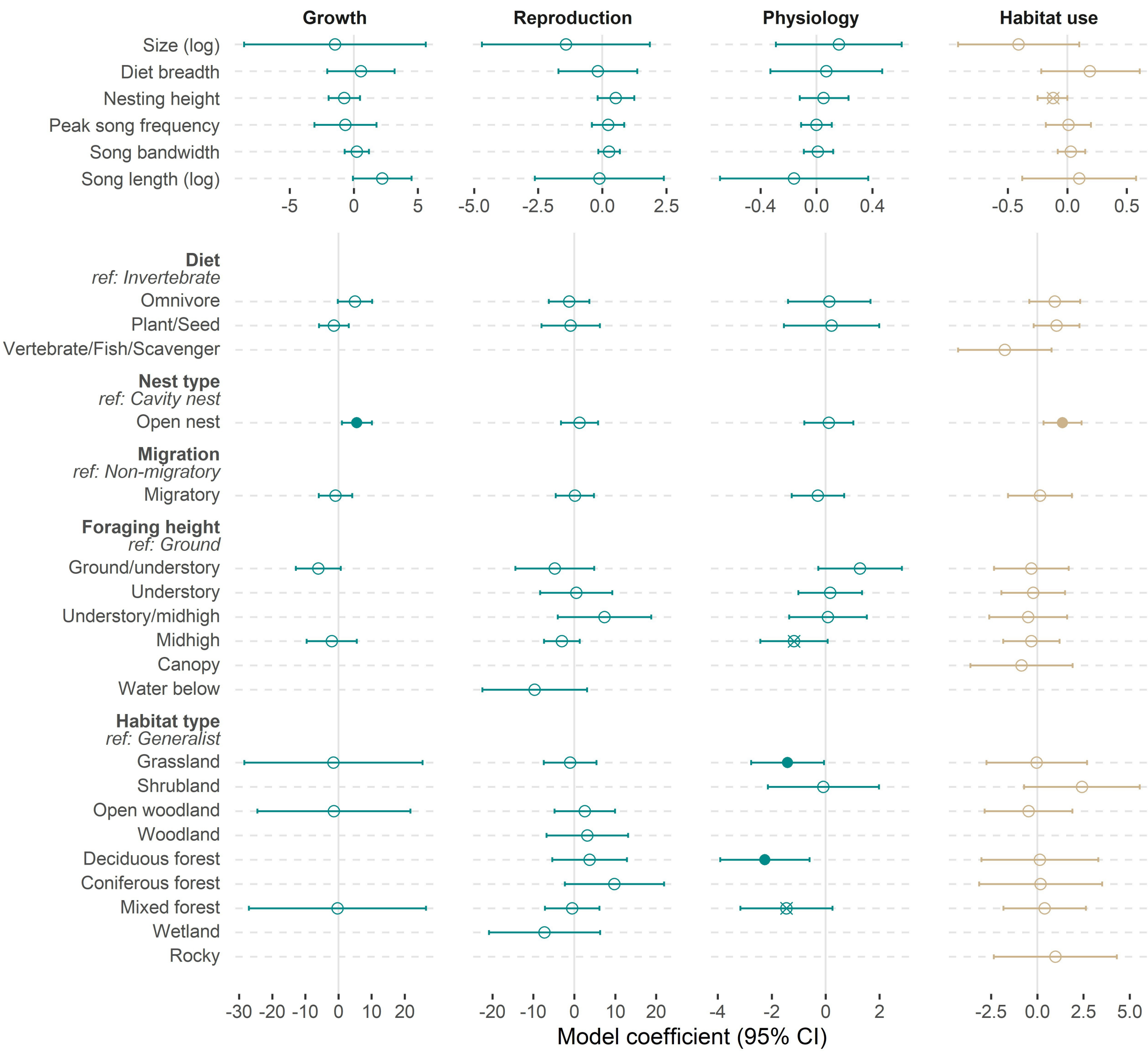

Figure 4. Fixed-effect coefficients and 95% CIs demonstrating how each trait moderates the impacts of noise on growth, reproductive, physiological and habitat use responses. Filled circles represent significant effects of traits based on 95% CIs. Circles with × fill represent significance based on 90% CIs. Open circles show insignificant effects.

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4. Discussion

We found clear evidence that anthropogenic noise affects bird behaviours, habitat use and responses closely linked to fitness. In addition, traits related to species' life history and habitat preferences mediated the strength of the effects of noise on bird growth, physiology and habitat use. Our findings thus reinforce the notion that anthropogenic noise has serious implications for nearly all aspects of avian life, but that those impacts are contingent on traits and the characteristics of the environments that species occupy.

Notably, bird reproduction is negatively associated with anthropogenic noise, which in our analysis spans the entire breeding cycle, spanning pairing success to egg survival to fledging success. While we did not find any traits strongly associated with the impacts on reproduction, interestingly, some study characteristics were strongly linked with these responses. The 'other' sound type was negatively associated with reproductive responses, while amplitude was positively associated, suggesting that noise characteristics, rather than bird traits, are influencing impacts to reproduction. A recent systematic review similarly found evidence of nearly every categorization of anthropogenic noise (e.g. drilling/construction noise, military activity, human noise, urban noise, traffic noise) having negative impacts on reproductive or breeding success [46].

Much of our data reflecting physiological responses to noise measured changes in hormone concentrations following noise exposure, and our results indicate a clear change in hormone concentrations. Studies have shown that both increases and decreases in hormone concentrations, such as corticosterone, can have negative impacts on overall health and could potentially further affect metabolism, reproduction, immune function, development and maintenance of homeostasis [47]. Interestingly, habitat type was the best indicator of a strong impact of noise pollution on physiological responses. Based on the data we collected, species that primarily inhabit deciduous forests, mixed forests or grasslands were less vulnerable to noise-induced changes in physiology than species considered habitat generalists. This was a surprising finding given that typically, generalists, or those species with a larger niche, have been found to be urban-tolerant species [30]. One possibility is that the generalists that often inhabit urbanized areas experience much louder noise conditions than the species in our database associated with other habitat types. As such, it may be that this is the only group with exposure levels that result in physiological changes.

Although we did not detect a strong association between anthropogenic noise and growth, we did determine a few traits that mediated growth response to noise pollution. Species inhabiting cavity nests are more likely to experience negative impacts on their growth compared to those with open nests when exposed to noise. This was an unexpected finding as cavity nests have previously been shown to lessen the impacts from noise [34]. Our analysis, however, only included the growth response of two open nesting species and therefore may not be generalizable to the difference experienced by all cavity and open nesting species. Nevertheless, noise pollution can be especially detrimental for developing animals such as embryos and nestlings because they are unable to move away from the sound as freely as adults [48]. Such exposure to constant stress can be detrimental during development but may also have long-term and transgenerational effects on reproductive success and survival [19,48]. We also found that species with a longer song length and those with an omnivorous diet are less vulnerable to the effects of noise on growth. The generalist nature of omnivory allows for more flexibility in terms of food options as well as foraging strategies, leaving individuals less vulnerable to novel environments [49]. As for song length, there is some evidence that receivers may be able to better detect longer songs in noisy environments [31]. This concept was studied in the context of signals used to attract mates but could be an indication of how begging or other signals tied to growth may also disperse in noisy environments and have an impact on physical traits.

The significant effects of anthropogenic noise on bird behaviours help clarify some of the behavioural mechanisms underlying fitness-related effects. For example, communication is important for reproduction-related actions at each life stage [6] and is directly tied to the survival of individuals [50]. Noise pollution can interfere with songs that evolved for female mate selection either by interrupting these mating displays or causing males to change their songs to avoid masking [51]. Furthermore, noise pollution can also mask communication between parents and offspring, thus preventing parents from meeting their offspring's food demands—with implications on growth—when begging messages are not received by the parents. Additionally, more time spent vigilant—a risk-related behaviour—translates to less time foraging, and when perceptions of threat are inhibited by noise, species often increase vigilant behaviour [25].

Not only did we see a strong impact of noise on habitat use, but we also found that a couple of traits mediated the impacts of these changes. We found strong evidence that birds nesting higher off the ground experienced smaller responses to noise. It may be the case that higher, denser tree canopies attenuate noise [32] for those species nesting higher off the ground, whereas species nesting at lower heights, where vegetation can be sparser, do not get the same benefit [4]. We also found evidence that species nesting in open cups exhibited larger changes in habitat use when exposed to noise. This finding supports the notion that cavity nests attenuate noise, potentially shielding species from its impacts [34]. The changes in habitat use that we have documented are important to recognize as they can alter numerous aspects of species ecology including putting them in competition with new species and changing the threats and risks they face, all compounding the challenge of conservation [52].

Unfortunately, empirical studies of the impacts of anthropogenic noise thus far have focused on only a small subset of bird diversity. Just under half of all effect sizes (459/944) were collected from just six families (Paridae (n = 131), Emberizidae (n = 79), Turdidae (n = 73), Hirundidae (n = 72), Troglodytidae (n = 54) and Passerellidae (n = 50)). As noise pollution is so pervasive, examining only a subset of families does not allow us to fully understand the effects and therefore manage the impacts. 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. Likewise, our literature review revealed only about 15 studies that focused on responses of avian communities, rather than individual species. As changes to individual species can indirectly influence other community members and overall community structure, more research on the effects of noise pollution on bird communities is an important area of future work [53]. We were surprised to find that traits of bird songs did not mediate impacts from noise

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because of the close tie between bird communication and numerous other behavioural or fitness-related responses to noise [31]. However, recently, researchers have suggested that communication signals may not adequately reflect how noise interferes with hearing function more broadly, and increased knowledge of variation in hearing sensitivities in and outside of noise could help explain variation in responses to noise among species [7]. Future efforts should leverage more precise vocalization data from the population studied along with hearing data to determine whether signal features or hearing features better explain responses.

5. Conclusion

Our meta-analysis suggests that the effects of anthropogenic noise are pervasive and span proximate responses such as behaviour and physiology and responses closely linked to fitness. We found that noise significantly impacts communication risk behaviours, foraging, aggression and physiology and had a strong effect on habitat use and a negative impact on reproduction. We have also highlighted a number of traits, both ecological and life history, that mediate the responses to noise that may help us understand why we see varying responses as well as which species may be more vulnerable to the effects of noise. This analysis emphasizes the need for future studies exploring the long-term effects of anthropogenic noise on birds and the impacts that these changes in behaviour and fitness have on communities and populations. These findings should be integrated into various levels of management from local guidance to federal policy aimed at protecting these vulnerable species from the damaging effects of noise pollution.

Ethics. This work did not require ethical approval from a human subject or animal welfare committee.

Data accessibility. We are committed to ensuring data and code for this research are publicly accessible. This information can be found in the Dryad Digital Repository [54].

Supplementary material available online [55].

Declaration of AI use. Elicit AI was used to assist in the literature search done in 2025.

Authors' contributions. N.L.M.: conceptualization, data curation, formal analysis, methodology, project administration, writing—original draft, writing—review and editing; K.L.M.: formal analysis, visualization, writing—review and editing; K.M.A.: conceptualization, methodology, project administration, supervision, writing—review and editing; C.D.F.: conceptualization, data curation, funding acquisition, methodology, resources, supervision, writing—review and editing; N.H.C.: conceptualization, methodology, project administration, supervision, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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