Review

Trends and knowledge gaps in field research investigating effects of anthropogenic noise

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Abstract: Anthropogenic noise is a globally widespread sensory pollutant, recognized as having potentially adverse effects on function, demography, and physiology in wild animals. Human population growth and associated changes in urbanization, transportation, and resource extraction all contribute to anthropogenic noise and are predicted to increase in the coming decades. Wildlife exposure to anthropogenic noise is expected to rise correspondingly. Data collected through field research are uniquely important in advancing understanding of the real-world repercussions of human activity on wildlife. We, therefore, performed a systematic review of literature published from 2008 to 2018 that reported on field investigations of anthropogenic noise impacts. We evaluated publication metrics (e.g., publication rates and journal type), geographical distribution of studies, study subject, and methods used. Research activity increased markedly over the assessment period. However, there was a pronounced geographical bias in research, with most being conducted in North America or Europe, and a notable focus on terrestrial environments. Fewer than one-fifth of terrestrial studies were located in rural areas likely to experience urbanization by 2030, meaning data on ecosystems most likely to be affected by future changes are not being gathered. There was also bias in the taxonomic groups investigated. Most research was conducted on birds and aquatic mammals, whereas terrestrial mammals, reptiles, amphibians, fish, and invertebrates received limited attention. Almost all terrestrial studies examined diurnal species, despite evidence that nocturnality is the prevailing animal activity pattern. Nearly half the studies investigated effects of road or urban noise; the bulk of research was restricted to functional, rather than physiological or demographic consequences. Few experimental studies addressed repercussions of long-term exposure to anthropogenic noise or long-term postexposure effects, and multiple noise types or levels were rarely compared. Tackling these knowledge gaps will be vital for successful management of the effects of increasing wildlife exposure to anthropogenic noise.

Keywords: disturbance, noise pollution, sound pollution, urbanization, wildlife

Tendencias y Vacíos de Conocimiento en el Trabajo de Campo que Investiga los Efectos del Ruido Antropogénico

Resumen: El ruido antropogénico es un contaminante sensorial con amplia distribución global. Se le reconoce como un contaminante con efectos adversos potenciales sobre la función, demografía y fisiología de la fauna silvestre. El crecimiento de las poblaciones humanas y los cambios asociados a la urbanización, transporte y extracción de recursos contribuyen al ruido antropogénico y se pronostica que todos incrementarán en las siguientes décadas. Se espera que la exposición de la fauna al ruido antropogénico aumente en correspondencia. Los datos recolectados por medio del trabajo de campo tienen una importancia única en el avance del entendimiento de las repercusiones reales de la actividad humana en la fauna. Por lo tanto realizamos una revisión sistemática de la literatura publicada de 2008 a 2018 en la que se reportaron investigaciones en campo de los impactos del ruido antropogénico. Evaluamos las medidas de publicación (p. ej.: las tasas de publicación y el tipo de revista), la distribución geográfica de los estudios, el sujeto del estudio y los métodos que se utilizaron. La actividad de investigación aumentó de manera marcada a lo largo del periodo de evaluación. Sin embargo, hubo un sesgo
geográfico pronunciado en las investigaciones pues la mayoría se realizó en América del Norte o en Europa y hubo un enfoque notable sobre los ambientes terrestres. Menos de la quinta parte de los estudios terrestres estuvieron ubicados en áreas rurales con una probabilidad de sufrir urbanización para el 2030, lo que significa que no se están recopilando datos para los ecosistemas con mayor probabilidad de ser afectados en el futuro. También hubo un sesgo en los grupos taxonómicos investigados. La mayoría de las investigaciones se realizó en aves y en mamíferos acuáticos, mientras que los mamíferos terrestres, los reptiles, los anfibios, los peces y los invertebrados recibieron una atención limitada. Casi todos los estudios terrestres trabajaron con especies diurnas, a pesar de la evidencia existente de que los hábitos nocturnos son el patrón prevaleciente de actividad animal. Casi la mitad de los estudios investigaron los efectos del ruido urbano o de las carreteras; el grueso de las investigaciones estuvo restringido a las consecuencias funcionales y no tanto a las fisiológicas o demográficas. Pocos estudios experimentales trataron el tema de las repercusiones a largo plazo de la exposición al ruido antropogénico o el de los efectos post-exposición a largo plazo. Tampoco encontramos muchos estudios en los que se compararan los tipos o niveles de ruido. Será vital lidiar con estos vacíos de conocimiento para el manejo exitoso de los efectos de la creciente exposición de la fauna al ruido antropogénico.

**Palabras Clave:** contaminación por ruido, contaminación sonora, fauna, perturbación, urbanización

**Introduction**

Anthropogenic noise is a globally widespread sensory pollutant recognized as having potentially adverse effects on multiple aspects of function, demography, and physiology of wild animals (Slabbekoorn & Ripmeester 2008; Barber et al. 2010; Blickley & Patricelli 2010; Kight & Swadle 2011; Morley et al. 2013; Halfwerk & Slabbekoorn 2014; Williams et al. 2015; Gomez et al. 2016; Kunc et al. 2016; Shannon et al. 2016; Rosa & Koper 2018). Although there are numerous sources, anthropogenic noise is primarily associated with 4 main interrelated factors—human population growth, urbanization, transportation, and resource extraction—all of which are predicted to increase markedly in coming decades. The global human population is expected to rise by 1 billion by 2050 (UN Department of Economic and Social Affairs 2017). To accommodate population growth, urban land cover is forecast to double by 2040 in countries with emerging or developing economies and to expand by more than half in nations with advanced economies (Angel et al. 2011). On land, the number of cars is set to double by 2050, again with the largest gains (2.8–3.7 times) in the developing world (World Energy Council 2011). Air passenger numbers and container or bulk carrier shipping fleets are expected to increase by comparable margins over even shorter periods (Kaplan & Solomon 2016; International Air Transport Association 2017). Similarly, global extraction of biomass, fossil fuels, metals, and nonmetallic minerals is projected to grow from 79 to 167 GT by 2060 (Organisation for Economic Co-operation and Development 2019). Wildlife exposure to anthropogenic noise is expected to increase correspondingly.

Data collected through field research are uniquely important in advancing understanding of the repercussions of human activity on wildlife. Although laboratory studies contribute valuable information (Blickley & Patricelli 2010), captivity can induce chronic stress in wild-caught and captive-bred animals (Bolasina 2011; Terio et al. 2013), which may interact with or mask effects of noise. Moreover, selective pressures in captivity differ from those in the wild (Frankham 2008) and can potentially lead to phenotypic and genetic differences between
captive and wild populations (Johnsson et al. 2011; Fraser et al. 2019). Thus, field data are vital to determining real-world responses of wildlife to environmental change.

Given this situation, quantifying the characteristics of the field research would be of substantial value in identifying trends and knowledge gaps. We, therefore, performed a systematic review of literature published from 2008 to 2018 that reported results of field investigations into the impacts of anthropogenic noise. We evaluated article publication metrics, geographical distribution, study subject, and methods to provide an exhaustive overview of recent research efforts and to draw conclusions on approaches most likely to yield valuable advances.

Methods

Literature Search

To characterize the current research landscape in field studies investigating effects of anthropogenic noise on wildlife, we created a database through a systematic review of relevant literature published from 2008 to 2018. We used a Web of Science “all database” search (Clarivate Analytics 2019) to generate our list of candidate studies because of its broad interdisciplinary coverage and ease with which citing and cited articles can be determined. We performed a search with the following terms: (“anthropogenic noise” OR “noise pollution” OR “sound pollution”) AND (wild animal OR “free-living” animal OR wild mammal OR “free-living” mammal OR wild bird OR “free-living” bird OR wild reptile OR “free-living” reptile OR wild amphibian OR “free-living” amphibian OR wild fish OR “free-living” fish OR wild invertebrate OR “free-living” invertebrate), where an asterisk indicates truncation wildcard and quotation marks encapsulate search phrases. The terms wild and free-living were used to filter laboratory and theoretical studies from the search results. Preliminary investigations indicated that without this filter, it would have been necessary to screen an unfeasibly large number of articles (around 18,000), most of which would have been outside the scope of our review because they were not field studies. After the initial search, we identified papers cited by, or citing, articles listed in the search results and added these to the database (citing papers were identified using the Web of Science “times cited” function between 5 and 6 November 2018).

Study Screening

Inclusion criteria were first applied to titles and abstracts. Full texts were obtained for articles with titles and abstracts that appeared to meet the inclusion criteria or lacked the information required to make a judgment. The inclusion criteria were then reapplied to the full-texts to confirm eligibility.

We used a PICO framework (Frampton et al. 2017) to define our inclusion criteria. Articles within the database were included in our analyses if they were judged to report primary research addressing the question, What are the effects of anthropogenic noise on wild animals? We specified the PICO components for this question as follows: population, wild animals; intervention, anthropogenic noise; comparators, absence or differing types or levels of anthropogenic noise; and outcomes, functional, demographic, or physiological effects of anthropogenic noise. Hence, articles were considered eligible for inclusion only if the reported study met all of the following criteria: investigated populations of free-living animals in natural or urban environments; examined effects of anthropogenic noise; compared anthropogenic noise with no-noise controls or different types or levels of anthropogenic noise; and assessed functional, demographic, or physiological outcomes of anthropogenic noise exposure (see Data Extraction for definitions).

Data Extraction

Data relating to literature characteristics, geography, subject, and methodology were extracted from each included study.

To assess changes in the level of interest in this research area over time, we calculated annual publication rates. Also, for each included paper, we noted the journal title and publication-year impact factor (Clarivate Analytics 2019) as simple proxies for the type of interest in this research area (i.e., applied vs. fundamental), and the relative importance of the subject matter within the academic community (notwithstanding the debate about the relevance of impact factors as an indicator of individual study value [Seglen 1997]). Contributing journals were categorized as dealing primarily with applied research (as opposed to fundamental) if the words conservation, applied, management, planning, monitoring or their synonyms appeared in the journal title. Studies from journals not listed in Incites Journal Citation Reports were excluded from impact-factor analyses (n = 9 out of 267). Where journal impact factor was not available for the year of publication but was available for other years (n = 44 out of 258 included full-texts with impact factor available), the impact factor for the nearest year was used (mean [SD] difference between year of publication and impact factor year = 1.41 [0.81]).

The geographic distribution of included studies was evaluated by documenting the continent and country of the study. Additionally, country economic class (advanced or emerging or developing as defined in World Economic Outlook Database [International Monetary Fund 2018]) and 2 aspects of the studied habitat type...
Table 1. Category definitions and subcategories of effect types investigated in included studies examining effects of anthropogenic noise on wild animals.

| Effect category | Functional | Physiological | Demographic |
|-----------------|------------|---------------|-------------|
| Definition       | Affecting individual activity or processes | Affecting mechanisms underlying individual activity or processes | Affecting changes at a population level |
| Subcategories    |            |               |             |
| Acoustic       | Acoustic communication | Auditory damage | Biodiversity |
| communication  | nonacoustic communication development ecological services foraging movement behavior reproduction survival vigilance | energy reserves immune function metabolism oxidative stress respiration stress telomere dynamics | distribution population structure |

*a Includes echolocation.
*b Assessed based on body-condition indices.
*c Hypothalamus-pituitary-adrenal or sympathetic-adrenal-medullary axis activity.
*d Includes abundance, occupancy, and spatial and temporal distribution.

were recorded. We defined *habitat* for all studies as either terrestrial, marine, or freshwater. For simplicity, marine studies were related to the nearest country without formal reference to territorial water ownership. For terrestrial studies, *habitat* was further categorized as urban, rural, or both urban and rural. Individual study sites used in terrestrial studies were also compared with the probability of their location becoming urbanized by 2030 based on global 5-km resolution projections developed by Seto et al. (2012). Sites were classified as urban or rural, with rural sites being assigned an urbanization probability of 0.0–1.0, depending on the value of the 5-km grid square in which they were situated. Only sites described in sufficient detail to be located with ≤5-km accuracy were included in this analysis (n = 127). Multiple sites used in the same study that were <5 km apart were treated as a single site located at the central point between them.

Study subject was characterized by species taxonomic group (mammal, bird, reptile, amphibian, fish, or invertebrate) and diel activity pattern (diurnal, nocturnal, crepuscular, or cathemeral). Data on diel activity pattern for each subject species were compiled from peer-reviewed primary and secondary research papers, books, and online databases. Where data for a particular species were not available, activity pattern was assumed from the timing of data collection reported in the study’s methods and labeled as such (n = 30). Activity pattern was defined only for terrestrial species because insufficient data were available from the literature on aquatic species. Taxon-specific diel activity pattern distributions were compared between included studies and those reported in the literature for mammals (Bennie et al. 2014), birds, and amphibians (Anderson & Wiens 2017). Such comparisons were not possible for reptiles or invertebrates, owing to inadequate numbers of included studies and a lack of published activity-pattern distribution data, respectively.

The methods for all included studies were categorized as either observational or experimental. Also, the type of noise to which subjects were exposed and the effect of noise exposure assessed were recorded. Effects were classified according to the categories in Table 1. For experimental studies, we also noted noise exposure duration (short, seconds, minutes, or hours; medium, days or weeks; long, months or years); response assessment timing (during, after, or during and after); postexposure response assessment duration (short, medium, or long, as defined above); and number of experimental noise types and levels of noise to which subjects were exposed. A single noise exposure level represents one level of playback amplification, rather than actual noise amplitude, which may vary continuously with many of the experimental noise types used (e.g., road noise).

Where a study fulfilled more than one level of a category (e.g., it was conducted across multiple countries), each level of that category was counted as an independent data point in analyses. Therefore, sample size is reported separately for each analysis and is in some cases larger than the number of included studies. Where data appeared to be shared between studies (e.g., breeding-success metrics for the same species from the same year at the same location), one publication was selected at random from the group, and the others were excluded.

**Statistical Analyses**

We used R version 3.4.1 (R Core Team 2017) to conduct all our analyses. Relationships between the number of included papers published annually (response variable) and the year of publication were analyzed using
generalized linear models (glm command, R Base package), with a Poisson error distribution and log-link function. The relationship between journal impact factor (response variable) and year of publication was analyzed using a general linear model (lm command, R Base package). Model assumptions (linearity, normal distribution of residuals, homoscedasticity, and leverage) were checked visually and found to have been met. Effect size calculations followed Nakagawa and Cuthill (2007). Model predictions were plotted with visreg (visreg version 2.5-0 [Breheny & Burchett 2016]), and all other visualizations were generated with ggplot (ggplot2 version 2.2.1 [Wickham 2009]). Comparisons of activity-pattern distributions between studies and taxonomic groups and comparisons of overall methodological approach distributions with distributions within subsets of the data (e.g., urban, or bird studies) were made with multinomial goodness-of-fit tests. In these tests, we used chi-square as the test statistic to calculate p values (xmulti, XNomial version 1.0.4 [Engels 2015]). Effect sizes for the goodness-of-fit analyses were calculated as Craven’s V with cramerVFit (rcompanion version 2.3.7 [Mangiafico 2019]). Maps were created in QGIS version 3.4.9 (QGIS Development Team 2018).

Results

Systematic Review

We identified 1721 unique articles, of which 276 papers met the inclusion criteria (Supporting Information). Nine full-texts publications were removed from the included group because they shared data with other included papers, leaving 267 papers for inclusion in the analyses.

Literature

The number of included papers published annually increased between 2008 and 2018 ($Z_{19} = 6.17$, $p < 0.0001$, effect size $r = 0.89$ [95% CI 0.62, 2.22], Fig. 1a). In 2008, 7 papers meeting the inclusion criteria were published, but in 2017 this increased more than 6-fold to 43. Data presented for 2018 are incomplete because our database search was carried out in October of that year.

Journal impact factor of included papers did not vary with year of publication ($F_{1,256} = 0.001$, $p = 0.98$) (Fig. 1b). Mean (SE) impact factor over the entire period (2008–2018) was 3.0 (0.1); only 7 papers (2.6%) were published in journals with impact factors $\geq 6$.

Of 88 journals with papers included in this study, 12 titles published $>5$ papers each (Fig. 1c), together providing 43.8% (117/267) of the total. The remainder were split across 76 titles. The 6 titles providing the most papers were either specialist behavioral journals (Behavioral Ecology and Animal Behaviour) or journals with broad interest (Proceedings of the Royal Society B: Biological Sciences, Biology Letters, Scientific Reports, and PLoS ONE). Behavioral Ecology published 16 included papers, the most of all contributing journals. Journals dealing primarily with applied research contributed 11.6% (31/267) of included papers, and the proportion

Figure 1. (a) Annual number of papers published, (b) regression predictions of paper journal impact factor, and (c) journals publishing $>5$ papers included in the systematic review of studies investigating effects of antropogenic noise on wild animals.
of papers published in these journals did not change over time \((Z_{1.7} = 1.29, \ p < 0.19)\) (Fig. 2a).

### Geography

Studies were carried out on all continents except Antarctica. Most were based in North America and Europe \((47.6\% \ [128 \text{ of } 269] \ \text{and } 32.0\% \ [86 \text{ of } 269], \ \text{respectively})\), whereas Africa and Asia accounted for \(3.3\% \ (9 \text{ of } 269)\) of the total. Overall, research was conducted in 42 countries (or their adjacent waters) (Figs. 2a & 2b & Supporting Information). The United States was the most actively researched country \((29.7\%; \ 81 \text{ of } 273)\), with more than twice the number of studies as Canada, the next most actively researched country. Fewer than one-quarter of the studies were conducted in countries with emerging or developing economies.

More studies took place in terrestrial habitats \((70\%; \ 187 \text{ of } 267)\) than in aquatic environments \((30\%; \ 80 \text{ of } 267)\), with all but one aquatic study being conducted in the marine environment. Although most terrestrial studies were carried out in North America \((31.6\%; \ 59 \text{ of } 187)\) (Fig. 2a & Supporting Information), most marine studies \((43.9\%; \ 35 \text{ of } 80)\) were conducted in European waters (Fig. 2b & Supporting Information). None of the aquatic studies took place in or off Asia.

Terrestrial studies were predominantly conducted in entirely rural environments \((47.0\%; \ 88 \text{ of } 187)\). Of the remainder, there were similar numbers of urban-rural habitat comparisons \((27.8\%; \ 52 \text{ of } 187)\) and exclusively urban studies \((24.0\%; \ 45 \text{ of } 187)\). Within the terrestrial studies, 246 sites (from 127 studies) were described in sufficient detail to assess their probability of urbanization by 2030 (covered in Methods). Only \(19.5\% \ (48 \text{ of } 246)\) of these sites were in rural areas with some probability of urbanization \((<50\% \ \text{probability} = 7.3\%; \ 18 \text{ of } 247, >50\% \ \text{probability} = 12.1\%; \ 30 \text{ of } 247)\) (Fig. 2c). Approximately half the sites \((48.4\%; \ 119 \text{ of } 246)\) were in rural areas with 0% likelihood of becoming urbanized during this period.
The remaining one-third (32.1%; 79 of 246) were situated on land that was already urban.

**Subject**

Birds and mammals were the 2 most intensively studied taxonomic groups, together being the subject of almost 90% of all included studies (birds = 57.2%; 155 of 271, mammals = 31.4%; 85 of 271) (Fig. 3a). Within the mammal studies, 82.3% (70 of 85) investigated marine species. Fish and invertebrates were the subject of 7 studies each, and just 1 study considered a reptile species.

Almost all terrestrial studies (80.6%; 158 of 196) investigated diurnal species; nocturnal and cathemeral species were the subject of 10.7% (21 of 196) and 5.6% (11 of 196) studies, respectively (Fig. 3b). Crepuscular species were the least studied (subject of 6 papers). Distributions of diel activity patterns among bird and amphibian studies broadly matched expectations based on the literature for their taxonomic group (birds, \(p = 0.10\); amphibians, \(p = 0.13\)) (Fig. 3c). In contrast, most studied terrestrial mammals were diurnal, despite the taxonomic group being predominantly nocturnal (\(p = 0.0004\), effect size Cramer’s \(V = 0.90\), 95% CI 0.71, 1.16).

**Methodology**

Methodological approaches were relatively evenly split across all included studies (observational = 52%; 144 of 277, experimental = 48%; 133 of 277). Nonetheless, within urban environments, there were more observational studies than would be expected (\(p < 0.0001\), effect size Cramer’s \(V = 0.69\), 95% CI 0.51, 0.83). Similarly, a higher than expected proportion of studies of birds were observational (\(p < 0.0001\), effect size Cramer’s \(V = 0.53\), 95% CI 0.18, 0.48) (Fig. 3a), whereas the opposite was true for mammals (\(p < 0.0001\), effect size Cramer’s \(V = 0.45\), 95% CI 0.24, 0.63).

Road and urban noise were the most frequently examined types of anthropogenic noise, together accounting for 48.1% (140 of 291) of the total (Fig. 4). Studies examining effects of urban, oil or gas extraction, and wind turbine noise were mainly observational. None of the limited number of investigations evaluating effects of aircraft (\(n = 6\)) or rail noise (\(n = 1\)) employed an experimental approach.

Most studies addressed questions relating to organism function; physiological and demographic mechanisms were considered comparatively rarely (Fig. 4b). Within functional studies, most (76.1%; 216 of 284) investigated effects on acoustic communication (52.5%; 149 of 284) or movement (23.6%; 67 of 284) (Fig. 4c). Physiological research predominantly assessed effects on energy reserves and stress (Fig. 4d), whereas demographic studies were primarily concerned with effects on species distribution (Fig. 4e).

Figure 3. Numbers of included studies investigating effects of anthropogenic noise on wild animals relative to (a) taxonomic group and method (experimental or observational) across all studies, (b) animal diel activity pattern, study method, and source of activity pattern data for all species in terrestrial studies, and (c) comparison of distributions of diel activity patterns, grouped by taxon, among subjects of terrestrial studies, with those reported in the literature for each taxonomic group (see Methods for data sources).
Figure 4. (a) Noise type, (b) broad category of noise effect investigated and specific (c) functional, (d) physiological, and (e) demographic effects assessed in included studies examining effects of anthropogenic noise on wild animals.
Of the 132 experimental studies, approximately two-thirds examined consequences of short-term (≤24 h) noise exposure, whereas long-term (≥1 month) effects were rarely investigated (Fig. 5a). Just over half the studies assessed responses both during and after exposure; 43.2% (57 of 132) assessed responses only during exposure (Fig. 5b). Of the 75 studies assessing responses after exposure, this was usually for short periods (≤24 h); fewer than 10% examined responses more than a month after exposure (Fig. 5c). Almost two-thirds of the experimental studies considered a single noise type, and only 6 studies compared more than 4 types (Fig. 5d). Similarly,
most experimental studies (84.4%) used a single noise level (Fig. 5e).

Discussion

Our systematic review identified clear patterns in the publication metrics, geographical distribution, subject, and methodological characteristics of field research investigating the effects of anthropogenic noise. The number of included studies published annually increased markedly over the assessment period, whereas the impact factor of publishing journals and the proportion of studies published in specialist applied journals did not change. Most studies were carried out in North America or Europe and were conducted in terrestrial environments. Fewer than one-fifth of terrestrial studies were located in rural areas likely to experience urbanization by 2030, meaning data on ecosystems most likely to be affected by future changes are not being gathered. Birds and aquatic mammals were the most investigated taxonomic groups, with terrestrial mammals, reptiles, amphibians, fish, and invertebrates receiving only a relatively small fraction of total research attention. Almost all terrestrial studies examined diurnal species. This was not solely a function of the large number of bird studies, because terrestrial mammals studied were also largely diurnal, despite the group being predominantly nocturnal or crepuscular. Nearly half the studies investigated effects of road or urban noise, with the bulk of research effort across all studies being directed toward assessment of functional (rather than physiological or demographic) consequences. Among experimental studies, few addressed repercussions of longer term exposure to anthropogenic noise or longer term postexposure effects, and multiple noise types or levels were rarely compared. Consequently, considerable knowledge gaps remain that will need to be tackled to ensure successful management of the effects of increasing wildlife exposure to anthropogenic noise.

Literature

Comparing the 6-fold increase in anthropogenic noise articles published from 2008 through 2017 with the doubling over the same period for the whole field of biological sciences (Kelly 2018) confirms growing research effort toward effects on wildlife. Nonetheless, relatively few articles (2.6%) appear in higher ranking (impact factor ≥6) journals, suggesting that editorial interest remains comparatively restricted and perhaps indicating a need to better communicate the broad potential threat posed. Consistently low proportions of included studies appearing in specialist applied journals throughout the assessment period are notable, given the growth in knowledge concerning anthropogenic noise impacts since the 1990s (Morley et al. 2013; Williams et al. 2015; Shannon et al. 2016). However, most new information collected on the impacts of noise is behavioral (as demonstrated by the prominence of Behavioral Ecology and Animal Behaviour among contributing journals) and tends to be published in behavior–rather than conservation–journals. Hence, a strong research focus on identifying mitigation strategies appears yet to develop, although useful attempts have been made for the marine environment (McGregor et al. 2013; Perrow 2019).

Geography

The geographical distribution of study locations was similar to that reported by Shannon et al. (2016), indicating minimal change since 2015 (the end of that study’s assessment period). That most studies were conducted in North America and Europe (79.6%) highlights continued lack of research attention toward nations with emerging or developing economies. This situation is further emphasized by the lack of terrestrial studies in areas likely to undergo urbanization, which predominantly occur in such countries (Angel et al. 2011; Seto et al. 2012, Fig. 2c). These states (particularly those in the tropics) are home to the majority of global biodiversity (Myers et al. 2000), which having experienced less historical exposure to anthropogenic noise is likely to be less tolerant of this disturbance than biodiversity in nations with advanced economies (Blickley & Patricelli 2010; Shannon et al. 2016). Consequently, there is a need to boost research effort in these areas to levels proportionate with their greater relative risk.

Relative to marine habitats, freshwater habitats were underrepresented by an order of magnitude, when compared with their relative biodiversity. Freshwater species are exposed to an exceptional range of anthropogenic noise because aquatic (e.g., boating or shipping, construction, and energy generation) and terrestrial (e.g., road traffic) noise penetrate freshwater environments (Holt & Johnston 2015; Mickle & Higgs 2018). Therefore, this omission represents a substantial missed opportunity—despite covering only approximately 0.8% of Earth’s surface, freshwater environments hold 9.5% of all recognized species (Balian et al. 2008) and one-third of all vertebrate species (Strayer & Dudgeon 2010).

Subject

Although our results are consistent with previous reports that birds and marine mammals are generally overrepresented as research subjects (Slabbekoorn et al. 2010; Morley et al. 2013; Hawkins et al. 2015; Williams et al. 2015; Shannon et al. 2016), the corresponding underrepresentation of terrestrial mammals in noise research has received little comment. Almost all (97.5%) mammal species live on land (Cole et al. 1994), but only 17.6% of
included mammal studies examined terrestrial species. Because most terrestrial mammals are nocturnal (Bennie et al. 2014) and the majority tend to be comparatively elusive irrespective of diel activity pattern (Couzens et al. 2017), this disparity may be a consequence of the difficulties presented by their study. Indeed, the added impracticalities of conducting research at night (Gaston 2019) almost certainly contributed to the low proportion of included mammal studies investigating nocturnal subjects. Nevertheless, such difficulties need to be overcome if a comprehensive account of the impacts of anthropogenic noise on wildlife is to be achieved. Not least because nocturnality may be the prevailing animal diel activity pattern (30% of vertebrates and 60% of invertebrates [Hölker et al. 2010]) and nocturnal noise exposure will increase as humans shift toward a 24-h society (Rosekind 2005).

More broadly, if taxon-group biomass is a reasonable proxy for potential exposure levels, then research effort must be substantially redirected to more accurately mirror this. Estimates suggest that fish and invertebrates make up approximately 90% of the total biomass attributed to the taxonomic groups examined in this review (Bar-On et al. 2018). Yet, birds and marine mammals were the subject of 83% of studies included here (Supporting Information). Of the less well-studied groups, reptiles were the least studied. This may result from the historic preoccupation of anthropogenic noise research with effects on vocal communication (Rabin & McCowan 2000; Patricelli & Blickley 2006; McGregor et al. 2013; Shannon et al. 2016), which is comparatively rare in reptiles (Young et al. 2013). Regardless, most reptiles are capable of hearing to some extent (Dooling et al. 2000) and so could potentially be affected by anthropogenic noise (Simmons & Narins 2018). Also, noise effects on prey are likely to affect this group because most reptiles are active predators (Hutchins 2003).

Methodology

Although the overall proportions of experimental and observational research suggest an appropriately synthetic combination of methodological approaches (Tilman 1989), departures from this pattern within certain groups of included studies most likely relate to 2 factors. First, the preponderance of experimental mammal studies appears to be an artifact of bias toward marine mammals as subjects (82.4% of included mammal studies). The dominant interests of marine-mammal researchers were effects of seismic surveys, pile driving, sonar, and deterrent pingers (61% of included marine mammal studies). All these noise sources are intermittent and so facilitate experimental study, regardless of whether researchers have control over the noise source. Second, the high prevalence of observational studies among those carried out in urban environments and those with birds as subjects may all be linked to the difficulties of reproducing (and so manipulating) urban and traffic noise. Birds were the subject of most terrestrial studies, and most bird studies investigated urban or traffic noise. Hence, these groups effectively comprise the same studies. Neither birds nor terrestrial environments limit the capacity for experimental study. However, replicating the spectral composition and sound pressure-level attenuation of loud, low-frequency, anthropogenic noise via playback of recordings is fairly involved (Rosa et al. 2015) and especially challenging at large scales and over long periods (Blickley et al. 2012). Therefore, researchers may have used actual urban and traffic noise to avoid methodological complications and ensure stimulus validity, at the expense of being able to demonstrate causation. Studies investigating the effects of other, predominantly low-frequency noise types (e.g., aircraft, rail, oil and gas extraction, and wind turbine) were also mainly, or entirely, observational. In this sense, the development of user-friendly protocols for high-fidelity playback of such noise types would undoubtedly help facilitate experimental studies.

Noise types investigated in included studies largely matched expectations that the most extensive sources (i.e., those relating to transport networks [Barber et al. 2010; Blickley & Patricelli 2010]) should be the most widely examined. Even so, effects of aircraft (6 studies) and to a lesser extent, rail noise (one study) were both assessed surprisingly little. Aircraft noise is particularly omnipresent, being audible, for example, across virtually the entire continental United States, including protected natural areas (Barber et al. 2011) and underwater (Erbe et al. 2018). Also, rail noise is set to increase substantially across Europe, given European Commission commitments to triple the length of the existing high-speed rail network by 2030 (European Commission 2011).

One of the most conspicuous (and perhaps critical) knowledge gaps we identified is the lack of studies on physiological and demographic responses to anthropogenic noise. Effects of anthropogenic noise are likely to occur at all levels within biological systems, from cellular processes to population dynamics (Kight & Swaddle 2011). Accordingly, accurate predictions of how noise will affect wildlife (and therefore the prescription of effective management decisions) will depend on information from across this range. High costs frequently associated with mark-recapture schemes and large population studies (Skalski et al. 2005) probably limit demographic research on effects of anthropogenic noise, whereas the deficit of physiological research is more likely a consequence of practical difficulties inherent in acquiring such data in the field. Most commonly used methods require subjects to be trapped and handled, for blood or tissue sampling (Dantzer et al. 2014) or attachment of measurement devices (Whitford & Klimley 2019). This restricts research to species and individuals that can be
caught, making physiological field research impractical in many scenarios. But, while our results underline the need to overcome these problems, they should not be interpreted as demonstrating an overall lack of knowledge regarding physiological effects of anthropogenic noise. A sizeable body of data has been collected using captive animals (e.g., 38 of 49 physiological anthropogenic noise studies identified in Shannon et al. [2016] took place in the laboratory) and provides much useful information, despite limitations imposed by artificial environments.

A need to address biases in functional research effort is also evident from the high proportion of included papers investigating acoustic communication and movement behavior. Such focus is understandable, given the likelihood of interference when acoustic communication and anthropogenic noise share frequency ranges and the relative ease with which GPS tags allow tracking of marine mammal movements (81.5% [53 of 65] of movement behavior studies investigated marine mammals). Nonetheless, only by paying greater attention to the full range of potentially affected functions, such as reproduction and development, foraging and antipredatory behaviors, and general cognition (Kight & Swaddle 2011; Jafari et al. 2019), will it be possible to provide the comprehensive, integrated understanding necessary to generate effective mitigation strategies.

The shortage of long-term experimental studies, both in terms of exposure duration and post-exposure response assessment duration, is also striking and limiting, as is the lack of studies comparing noise types and levels. Long-term studies are often crucial in quantifying ecological impacts of environmental change (Lindenmayer et al. 2012), not least because short-term responses may be misleading and can even suggest the exact opposite of eventual outcomes (Tilman 1989). Additionally, characterizing developmental effects of early-life anthropogenic noise exposure (Swaddle et al. 2015) will necessitate multiyear studies in many species. Securing long-term research funding is undoubtedly difficult, but addressing comparisons between effects of different noise types and levels of exposure is comparatively quick, straightforward, and immediately beneficial. Contrasting responses between different noise types establishes whether reactions are specific or relate only to general noise disturbance. And, comparing responses between multiple levels of exposure permits dose–response curves to be generated (Goudie & Jones 2004; Houser et al. 2013; Dunlop et al. 2018), allowing mitigation measures to be precisely optimized (Von Benda-Beckmann et al. 2014). In discussing noise types and levels, it is also worth noting that standards of reporting regarding noise playback are frequently insufficient to permit precise replication. Our original intention was to include basic descriptive data concerning experimental noise frequency range and peak amplitude in our analyses. Yet, of 132 included experimental studies, only 34 contained enough information to extract even these rudimentary details. More detailed reporting, including comparison of recording and playback frequency or power spectra, comprehensive playback-equipment specifications, and sharing of sound files, would be advantageous in this regard.

Limitations

The validity of our conclusions depends on the reliability of our initial literature search. By employing a range of synonyms in our search terms, screening papers cited by, or citing, articles listed in the initial search results and using the 46-language default search, we aimed to provide the most exhaustive search possible. This strategy returned 1721 results, which were considered to constitute a representative proportion of the body of literature as a whole. Nevertheless, as with all systematic reviews, our choice of search terms means some relevant studies will not have been identified. In most cases, systematic bias is unlikely to result from the exclusion of such studies. However, we acknowledge the terms wild and free-living are less likely to be used in field studies published in applied journals when compared with fundamental journals. In addition, only 3 non-English language studies were included (2 Spanish and one Polish), representing just 1% of the total number. A recent survey of biodiversity conservation literature found over one-third of scientific documents were not published in English (Amano et al. 2016). Although the authors used Google Scholar, which includes non-peer-reviewed gray literature and government and institutional reports not covered by Web of Science (Haddaway et al. 2015), these proportions suggest that our search may have failed to identify some relevant non-English papers. Such omissions would likely have the greatest influence on our geographical results, particularly in underestimating the number of studies conducted in countries with emerging or developing economies, where use of English may be restricted. But, even in the unlikely event that one-third of papers were omitted and all were from countries with emerging and developing economies, they would still constitute less than half the full total, so such nations would continue to be underrepresented when considering their higher probability of future exposure.

Recommendations

Given the vital roles of field research in understanding and mitigating effects of anthropogenic noise on wildlife, it is imperative that research efforts are commensurate to the potential threat and appropriately directed. In conducting this systematic review, we identified a range of key areas where increased attention would advance
progress toward this goal. Based on these findings, our recommendations for future field research investigating effects of anthropogenic noise are as follows.

First, place increased emphasis on collecting data in locations likely to experience the greatest future exposure to anthropogenic noise (particularly areas predicted to become urbanized).

Second, pay greater regard to critically underrepresented habitats, taxonomic groups, and circadian habits—especially freshwater environments, invertebrates, fish, amphibians and reptiles, terrestrial mammals, and nocturnal species from all groups.

Third, make more effort to explore effects of important nonroad transport noise sources, such as aircraft and trains.

Fourth, increase vitally important focus on physiological and demographic responses, paying particular attention to overcoming practical limitations on physiological data collection in the natural environments.

Fifth, fully explore potential functional effects beyond acoustic communication and movement behavior.

Sixth, aim to gather evidence over longer time scales, assessing both long-term exposure and long-term consequences. And, seventh, make comparison of responses between multiple noise types and levels standard practice in experimental studies, alongside sufficiently detailed reporting of playback techniques to permit precise replication.

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Supporting Information

A flow chart of the systematic review process (Appendix S1), numbers of included terrestrial (Appendix S2) and marine (Appendix S3) studies, a graphical comparison of subject taxonomic distributions among included studies with biomass estimations by taxonomic group (Appendix S4), and the complete dataset of screened/included studies are available online. The authors are solely responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

Literature Cited

Amano T, González-Varo JP, Sutherland WJ. 2016. Languages are still a major barrier to global science. PLoS Biology 14:e2000933.
Frankham R. 2008. Genetic adaptation to captivity in species conservation programs. Molecular Ecology 17:325–333.

Fraser DJ, Walker L, Yates MC, Marin K, Wood JLA, Bernos TA, Zastavniouk C. 2019. Population correlates of rapid captive-induced maladaptation in a wild fish. Evolutionary Applications 12:1305–1317.

Gaston KJ. 2019. Nighttime ecology: the “nocturnal problem” revisited. The American Naturalist 193:481–502.

Gomez C, Lawson JW, Wright AJ, Buren AD, Tollit D, Lesage V. 2016. A systematic review on the behavioural responses of wild marine mammals to noise: the disparity between science and policy. Canadian Journal of Zoology 94:801–819.

Goudie RJ, Jones IL. 2004. Dose–response relationships of harlequin duck behaviour to noise from low-level military jet over-flights in central Labrador. Environmental Conservation 31:289–298.

Haddaway NR, Collins AM, Coughlin D, Kirk S. 2015. The role of Google scholar in evidence reviews and its applicability to grey literature searching. PLoS ONE 10(1):1–17.

Halfwerk W, Slabbeekorn H. 2014. The impact of anthropogenic noise on avian communication and fitness. Pages 84–97. Gil, Diego & Brumm, Henrik, in Avian urban ecology: behavioural and physiological adaptations. Oxford University Press, Oxford.

Hawkins AD, Pembroke AE, Popper AN. 2015. Information gaps in understanding the effects of noise on fishes and invertebrates. Views in Fish Biology and Fisheries 25:39–64.

Hölker F, Wolter C, Perkin EK, Tockner K. 2010. Light pollution and its impact on avian communication and fitness. Pages 84–97. Gil, Diego & Brumm, Henrik, in Avian urban ecology: behavioural and physiological adaptations. Oxford University Press, Oxford.

Hutchins M, editor. 2003. Grzimek’s animal life encyclopedia, volume 7: reptiles. 2nd edition. Gale Group, Farmington Hills, Michigan.

International Air Transport Association (IATA). 2017. 20 year passenger forecast. IATA, Montreal.

International Monetary Fund. 2018. World economic and financial surveys. World Economic Outlook Database — WEO groups and aggregates information. Available from https://www.imf.org/external/pubs/ft/weo/2018/02/wpoeodata/groups.htm (accessed February 2019).

Jafari Z, Kolb BE, Mohajerani MH. 2019. Noise exposure accelerates the risk of cognitive impairment and Alzheimer’s disease: adulthood, gestational, and prenatal mechanistic evidence from animal studies. Neuroscience and Biobehavioral Reviews https://doi.org/10.1016/j.neubiorev.2019.04.001.

Johnsson JL, Höjesjö J, Fleming IA. 2011. Behavioural and heart rate responses to predation risk in wild and domesticated Atlantic salmon. Canadian Journal of Fisheries and Aquatic Sciences 58:788–794.

Kaplan MB, Solomon S. 2016. A coming boom in commercial shipping? The potential for rapid growth of noise from commercial ships by 2030. Marine Policy 73:119–121.

Kelly S. 2018. The continuing evolution of publishing in the biological sciences. Biology Open 7:1–4.

Kight CR, Swaddle JP. 2011. How and why environmental noise impacts animals: an integrative, mechanistic review. Ecology Letters 14:1052–1061.

Kinc HP, McLaughlin KE, Schmidt R. 2016. Aquatic noise pollution: implications for individuals, populations, and ecosystems. Proceedings of the Royal Society B: Biological Sciences 283:20160859.

Lindemayer DB, et al. 2012. Value of long-term ecological studies. Austral Ecology 37:745–757.

Mangialfico S. 2019. rcompanion: functions to support extension education program evaluation. Available from https://cran.r-project.org/web/packages/rcompanion/index.html (accessed February 2019).

McGregor PK, Horn AG, Leonard ML, Thomsen F. 2013. Anthropogenic noise and conservation. Pages 409–444 in Brumm H, editor. Animal communication and noise. Springer-Verlag, Berlin.

Mickle MF, Higgs DM. 2018. Integrating techniques: a review of the effects of anthropogenic noise on freshwater fish. Canadian Journal of Fisheries and Aquatic Sciences 75:1534–1541.

Morley EL, Jones G, Radford AN. 2013. The importance of invertebrates when considering the impacts of anthropogenic noise. Proceedings of the Royal Society B: Biological Sciences 281:20152683.

Myers N, Mittermeier RA, Mittermeier CG, da Fonseca GAB, Kent J. 2000. Biodiversity hotspots for conservation priorities. Nature 403:853–858.

Nakagawa S, Cuthill I. 2007. Effect size, confidence interval and statistical significance: a practical guide for biologists. Biological Reviews of the Cambridge Philosophical Society 82:591–605.

Organisation for Economic Co-operation and Development (OECD). 2019. Global material resources outlook to 2060 — economic drivers and environmental consequences (highlights). OECD, Paris.

Patricelli GLPL, Blickley JL. 2006. Avian communication in urban noise: causes and consequences of vocal adjustment. The Auk 123:639–649.

Penrow M, editor. 2019. Wildlife and wind farms — conflicts and solutions. Volume 4. Pelagic Publishing, Exeter, United Kingdom.

QGIS Development Team. 2018. QGIS geographic information system v 3.4.9 Open Source Geospatial Foundation Project.

R Core Team. 2017. R: a language and environment for statistical computing.

Rabin L, McCowan A. 2003. Anthropogenic noise and its effect on animal communication: an interface between comparative psychology and conservation biology. International Journal of Comparative Psychology 16:172–192.

Rosa P, Koper N. 2018. Integrating multiple disciplines to understand effects of anthropogenic noise on animal communication. Ecosphere 9:e02127.

Rosa P, Swider CR, Leston L, Koper N. 2015. Disentangling effects of noise from presence of anthropogenic infrastructure: design and testing of system for large-scale playback experiments. Wildlife Society Bulletin 39:364–372.

Roeskind MR. 2005. Underestimating the societal costs of impaired alertness: safety, health and productivity risks. Sleep Medicine 6:25–29.

Seglen PO. 1997. Why the impact factor of journals should not be used for evaluating research. British Medical Journal 314:198–502.

Setsou KC, Generala B, Hutrya LR. 2012. Global forecasts of urban expansion to 2030 and direct impacts on biodiversity and carbon pools. Proceedings of the National Academy of Sciences of the United States of America 109:16083–16088.

Shannon G, et al. 2016. A synthesis of two decades of research documenting the effects of noise on wildlife. Biological Reviews 91:082–1005.

Simmons AM, Narins PM. 2018. Effects of anthropogenic noise on amphibians and reptiles. Pages 179–208 in Effects of anthropogenic noise on animals. Springer handbook of auditory research. Volume 66. Springer International Publishing, Cham.

Skalski J, Ryding K, Millsbaugh J. 2005. Wildlife demography — analysis of sex, age and count data. Academic Press, Cambridge, Massachusetts.

Slabbeekorn H, Bouton N, van Opzepeland I, Coers A, ten Cate C, Popper AN. 2010. A noisy spring: the impact of globally rising underwater sound levels on fish. Trends in Ecology & Evolution 25:419–427.

Slabbeekorn H, Ripmeester EAP. 2008. Birdsong and anthropogenic noise: implications and applications for conservation. Molecular Ecology 17:72–83.
Strayer DL, Dudgeon D. 2010. Freshwater biodiversity conservation: recent progress and future challenges. Journal of the North American Benthological Society 29:544–558.

Swaddle JP, et al. 2015. A framework to assess evolutionary responses to anthropogenic light and sound. Trends in Ecology and Evolution 30:550–560.

Terio KA, Marker L, Munson L. 2013. Evidence for chronic stress in captive but not free-ranging cheetahs (Acinonyx jubatus) based on adrenal morphology and function. Journal of Wildlife Diseases 40:259–266.

Tilman D. 1989. Ecological experimentation: strengths and conceptual problems. Pages 136–157 in Likens GE, editor. Long-term studies in ecology: approaches and alternatives. Springer-Verlag, New York.

United Nations Department of Economic and Social Affairs. 2017. World population prospects — key findings and advance tables. United Nations, New York.

Von Benda-Beckmann AM, Wensveen PJ, Kvadsheim PH, Lam FPA, Miller PJO, Tyack PL, Ainslie MA. 2014. Modeling effectiveness of gradual increases in source level to mitigate effects of sonar on marine mammals. Conservation Biology 28:119–128.

Whitford M, Klimley AP. 2019. An overview of behavioral, physiological, and environmental sensors used in animal biotelemetry and biologging studies. Animal Biotelemetry 7:1–24.

Wickham H. 2009. ggplot2: elegant graphics for data analysis.

Williams R, et al. 2015. Impacts of anthropogenic noise on marine life: publication patterns, new discoveries, and future directions in research and management. Ocean and Coastal Management 115:17–24.

World Energy Council. 2011. Global transport scenarios 2050. World Energy Council, London.

Young BA, Mathevon N, Tang Y. 2013. Reptile auditory neuroethology: what do reptiles do with their hearing? Pages 323–346 in Köppl C, Manley G, Popper A, and Fay R, editors. Insights from comparative hearing research. Springer-Verlag, New York.