BIOLOGICAL REVIEWS
Cambridge Philosophical Society

Biol. Rev. (2016), **91**, pp. 982–1005.
doi: 10.1111/brv.12207

A synthesis of two decades of research documenting the effects of noise on wildlife

Graeme Shannon[1,†*], Megan F. McKenna[2,†], Lisa M. Angeloni[3], Kevin R. Crooks[1], Kurt M. Fristrup[2], Emma Brown[2], Katy A. Warner[1], Misty D. Nelson[1], Cecilia White[1], Jessica Briggs[1], Scott McFarland[1] and George Wittemyer[1]

[1]*Department of Fish, Wildlife, and Conservation Biology, Colorado State University, Fort Collins, CO 80523, U.S.A.*
[2]*Natural Sounds and Night Skies Division, National Park Service, Fort Collins, CO 80525, U.S.A.*
[3]*Department of Biology, Colorado State University, Fort Collins, CO 80523, U.S.A.*

ABSTRACT

Global increases in environmental noise levels – arising from expansion of human populations, transportation networks, and resource extraction – have catalysed a recent surge of research into the effects of noise on wildlife. Synthesising a coherent understanding of the biological consequences of noise from this literature is challenging. Taxonomic groups vary in auditory capabilities. A wide range of noise sources and exposure levels occur, and many kinds of biological responses have been observed, ranging from individual behaviours to changes in ecological communities. Also, noise is one of several environmental effects generated by human activities, so researchers must contend with potentially confounding explanations for biological responses. Nonetheless, it is clear that noise presents diverse threats to species and ecosystems and salient patterns are emerging to help inform future natural resource-management decisions. We conducted a systematic and standardised review of the scientific literature published from 1990 to 2013 on the effects of anthropogenic noise on wildlife, including both terrestrial and aquatic studies. Research to date has concentrated predominantly on European and North American species that rely on vocal communication, with approximately two-thirds of the data set focussing on songbirds and marine mammals. The majority of studies documented effects from noise, including altered vocal behaviour to mitigate masking, reduced abundance in noisy habitats, changes in vigilance and foraging behaviour, and impacts on individual fitness and the structure of ecological communities. This literature survey shows that terrestrial wildlife responses begin at noise levels of approximately 40 dBA, and 20% of papers documented impacts below 50 dBA. Our analysis highlights the utility of existing scientific information concerning the effects of anthropogenic noise on wildlife for predicting potential outcomes of noise exposure and implementing meaningful mitigation measures. Future research directions that would support more comprehensive predictions regarding the magnitude and severity of noise impacts include: broadening taxonomic and geographical scope, exploring interacting stressors, conducting larger-scale studies, testing mitigation approaches, standardising reporting of acoustic metrics, and assessing the biological response to noise-source removal or mitigation. The broad volume of existing information concerning the effects of anthropogenic noise on wildlife offers a valuable resource to assist scientists, industry, and natural-resource managers in predicting potential outcomes of noise exposure.

Key words: acoustics, noise pollution, human disturbance, vocal communication, acoustic metrics, masking, physiology, behaviour, mitigation, fitness, conservation.

CONTENTS

*Address for correspondence (Tel: +1970 4915020; E-mail: graeme.shannon@colostate.edu).

† Authors contributed equally to the study.

I. INTRODUCTION

Noise generated by human activities has increased dramatically over recent decades as a result of population growth, urbanisation, globalisation of transportation networks, and expansion of resource extraction. Road traffic in the USA, for example, has outstripped population growth over the past 40 years by a factor of ten, and the number of domestic passenger flights has more than tripled since the early 1980s (Barber, Crooks & Fristrup, 2010). In marine environments, the distribution and effects of human activity (e.g. offshore oil extraction, commercial ship traffic) are extensive (Halpern *et al.*, 2008), and shipping alone is estimated to have increased low-frequency background sound levels by 12 dB over the past few decades (Hildebrand, 2009). With the rapid escalation of noise pollution, there is growing concern regarding its impacts on human health and the functioning of natural systems (Chepesiuk, 2005; McGregor *et al.*, 2013).

Anthropogenic changes to the acoustic environment include increases in the number of high-intensity noise events and chronically elevated and homogenised background sound levels. The impact of these changes has been most thoroughly assessed in humans, with profound physiological and psychological consequences, including increased risk of cardiovascular disease (Babisch *et al.*, 2005; Hansell *et al.*, 2013), sleep deprivation (Fyhri & Aasvang, 2010), and cognitive impairment (Szalma & Hancock, 2011). These impacts are estimated to cost at least one million healthy life years per annum in Western Europe (Fritschi *et al.*, 2011). Protective legislation for human communities was implemented four decades ago in the USA (Noise Control Act of 1972, Quiet Communities Act of 1978) and more recently in the European Union (Environmental Noise Directive 2002/49/EC).

Quantifying the effects of anthropogenic noise on wildlife is challenging. Sensitivity to noise varies widely across taxa (Kaseloo & Tyson, 2004; Brumm & Slabbekoorn, 2005; Morley, Jones & Radford, 2013; Slabbekoorn, 2013), and may also vary depending upon context, sex, and life history (Ellison *et al.*, 2012; Francis & Barber, 2013). Noise can induce compound biological responses (e.g. shifts in vocalisation and movement; McLaughlin & Kunc, 2013), and is rarely isolated from other forms of environmental disturbance, such as habitat alteration and visual disturbance, confounding interpretation of biological responses to noisy environments (Summers, Cunnington & Fahrig, 2011). Furthermore, determining the scale and extent of disturbance involves carefully measuring characteristics of the sound source, such as duration (chronic, intermittent), frequency content, and intensity (Nowacek *et al.*, 2007; Southall *et al.*, 2007; Francis & Barber, 2013; Gill *et al.*, 2015).

Despite these challenges, a coherent research focus on noise impacts has recently emerged. Review papers have either focussed broadly on wildlife (Brumm & Slabbekoorn, 2005; Barber *et al.*, 2010; Kight & Swaddle, 2011), or targeted specific taxonomic groups such as birds (Patricelli & Blickley, 2006; Slabbekoorn & Ripmeester, 2008; Ortega, 2012; Slabbekoorn, 2013), fish (Slabbekoorn *et al.*, 2010; Radford, Kerridge & Simpson, 2014), and invertebrates (Morley *et al.*, 2013). The Marine Mammal Protection Act stimulated noise regulation for marine mammals, and there have been several reviews of the effects of noise on these species (Richardson *et al.*, 1995; Boyd *et al.*, 2008; Tyack, 2008; Southall *et al.*, 2009; Ellison *et al.*, 2012). Some reviews have focused on specific behaviours (Luther & Gentry, 2013) or responses to noise (Wright *et al.*, 2007; Hotchkin & Parks, 2013), while conceptual frameworks for evaluating noise impacts to wildlife have also recently been published (Moore *et al.*, 2012; Francis & Barber, 2013).

This review provides a systematic and standardised synthesis of the peer-reviewed literature published from 1990 to 2013 reporting responses of wildlife to anthropogenic noise in terrestrial and aquatic habitats. It documents prominent trends in research topics and methods, the kinds of noise sources that have been studied and the measurements used to characterise them, and gaps in research coverage that merit attention in future research. Ultimately, we highlight the utility of existing scientific information concerning the effects of anthropogenic noise on wildlife for predicting potential outcomes of noise exposure and implementing meaningful mitigation measures.

II. LITERATURE REVIEW METHODOLOGY

We conducted a detailed literature search using Thompson's *ISI Web of Science* within the following subject areas 'Acoustics', 'Zoology', 'Ecology', 'Environmental Sciences', 'Ornithology', 'Biodiversity Conservation', 'Evolutionary Biology', and 'Marine Freshwater Biology' from 1990 to 2013. The specific search terms were ([WILDLIFE or ANIMAL or MAMMAL or REPTILE or AMPHIBIAN or BIRD or FISH or INVERTEBRATE] and [NOISE or SONAR]), which returned a total of 2205 scientific peer-reviewed articles. These papers were filtered so only empirical studies focussed on documenting the effects of anthropogenic noise on wildlife were included in the final data set ($N = 242$). Reviews, syntheses, method papers ($N = 32$), and studies dealing solely with natural acoustic sources ($N = 22$) were excluded.

We reviewed the remaining publications to systematically characterise each study using 21 attributes, including details on the publication (journal, discipline, and year published), study design (playback or natural experiment, field or laboratory-based), and biological information (geographic region, general taxonomic grouping, and whether the study occurred in aquatic or terrestrial habitats). Journal titles were used to classify each of the papers using the following disciplinary categories: acoustics, behaviour, captive animals and welfare, conservation and management, ecology, environment, general biology, taxon-specific, physiology, and other. In addition, studies were classified based on the type of anthropogenic noise source, the acoustic metrics reported to describe the noise source and the biological responses measured in the study (see online Supporting Information, Appendix S1 for full details of extracted information).

Prior to commencing the full literature review process, we characterised ten randomly selected publications as a group to ensure accuracy and consistency of reporting across individual reviewers. Each of the authors then characterised a subset of the publications (five studies) across all 21 attributes to ensure that definitions of categories were clear and assignments were unambiguous. To improve the consistency of the data-collection process further, each paper was reviewed independently by at least two authors with G.S. and M.F.M. resolving any inconsistencies.

(1) Noise-source categories

We considered all anthropogenic sound sources as noise, regardless of whether the noise was intentionally produced, such as seismic exploration, sonars, acoustic deterrents, or an unintended by-product of human activity such as maritime shipping, traffic corridors, and construction. Furthermore, we categorised noise sources based on anthropogenic activity, not necessarily the characteristics of the noise stimulus, although we also recorded and present this information (see online Appendix S1). Six noise-source categories were used: environmental, transportation, industrial, military, recreation, and other.

Studies were assigned to the environmental noise category when the noise investigated was not attributed to a specific source, but rather included all the acoustic energy generated by human activity at a given location and time, also known as urban noise or background noise. In many cases, these acoustic environments include sources from the other defined noise categories that were not identified in the experimental design. Noise sources in the transportation category comprised both commercial and private vehicles, including road traffic (motorcycles, automobiles, buses), waterway traffic (boats, ferries, commercial ships), and non-military aerial traffic (commercial jets, helicopters). Studies that investigated specific recreational activities, such as whale-watching boats and air tour helicopters, were separated from the transportation studies. The industrial noise source category included studies that examined the effects of energy exploration (e.g. seismic surveys), construction (e.g. pile driving), and the operations associated with different energy sectors. Military sources included gunfire, explosions, aircraft, naval sonar, and in some cases, entire military training operations. We categorised the remainder of the studies as 'other', with most studies in this category using a simulated noise source, such as white noise, and not representing a specific human activity.

(2) Acoustic measurements

We evaluated if complete and accurate characterisation of acoustic environments, signals or stimuli, was provided. Information was collected on the acoustic metrics reported, where the reported level was measured (i.e. on site, on animal, not reported, estimated), and if background sound levels were measured. In addition, we recorded whether details on spectral characterisation (e.g. bandwidth and frequency weighting) and analysis (e.g. duration of measurement, sampling frequency, reference pressure) were reported. If details on the analysis of the acoustic data were not presented, we noted whether the study referenced an established standard or included details on the settings of a commercially available instrument.

(3) Biological responses

A categorical framework was developed to summarise the biological responses measured in each study. The biological responses were classified into nine distinct categories to help assess the distribution of studies across types of responses. These included: (*i*) physiology (stress, hearing loss/damage, immune function, gene expression); (*ii*) direct fitness metrics (survival, fecundity, clutch size); (*iii*) mating behaviour (attraction, mating success, territorial behaviour, pair bonding); (*iv*) foraging behaviour (foraging rate, predation rate, hunting/foraging success); (*v*) movement (spatial distribution, fleeing rate, avoidance, dive pattern); (*vi*) vigilance; (*vii*) vocal behaviour (call rate, intensity/amplitude, frequency shift, song length, call type, signal timing); (*viii*) population metrics (abundance, occupancy, settlement, density); and (*ix*) community-level metrics (species composition, predator–prey interactions). If studies measured multiple biological responses, a second category was noted.

III. STATE OF THE KNOWLEDGE

Research on the impacts of anthropogenic noise on wildlife has steadily risen over the past two decades (1990–2013), with a rapid increase in the volume of published, peer-reviewed articles since 2010 (Fig. 1). The 242 studies that we reviewed have been published in 97 scientific journals, covering a broad range of scientific disciplines from general biology to conservation to physiology (Table 1). Documented responses to a variety of anthropogenic noise sources (Table 2) have included shifts in physiology (e.g. impaired hearing, elevated stress hormone levels), alteration of key behaviours (e.g. foraging, vigilance, movement), and interference with ability to detect important natural sounds (e.g. vocalisations of conspecifics) (Table 3). In the following sections, we explore topics that emerged from our analysis of the existing literature and provide supporting examples.

(1) The taxonomic and geographical diversity of noise research

Many animals have specialised auditory organs and utilise sound for a variety of ecological functions from navigation and detection of resources to alerting conspecifics to the presence of predators. It is not surprising that noise impacts have been investigated in many taxonomic groups of animals, including vertebrates and invertebrates, and across a diverse range of terrestrial and aquatic habitats (Table 1). This broad taxonomic and geographic sampling is crucial to understanding how animals respond to noise across a range of auditory capabilities, behavioural contexts, levels of prior exposure, and noise sources. Further, investigating the effects of noise on a diversity of taxa within a study system enables detailed exploration of the complex and potentially differential responses to the same noise source. For example, in the woodlands of north-western New Mexico, USA, species richness of nesting birds was reduced as a function of anthropogenic noise, but birds that were able to tolerate noisier habitats had higher reproductive success due to reduced predation (Francis, Ortega & Cruz, 2009).

Although the published literature includes broad taxonomic sampling, birds and marine mammals are by far the most studied groups (Table 1; Fig. 1). Terrestrial research has focused mainly on effects on vocal communication, while aquatic research has also explored noise effects on movement, foraging, and physiology (Table 3). Underrepresented taxa in the published literature include reptiles, amphibians, and invertebrates (Table 1). Invertebrate studies, for instance, contributed only 4% of the total data set, yet this group contains 97% of the world's documented animal species, fulfilling varied and important ecological roles, such as prey species, pollinators, and serving as sensitive indicators of environmental change (de Soto *et al.*, 2013). Invertebrate species also provide excellent model species for studying the complex effects of noise given their size, rapid generation time, and the ease of maintaining laboratory populations (reviewed by Morley *et al.*, 2013).

Similar to its taxonomic focus, research on the effects of anthropogenic noise on terrestrial systems has been geographically biased, with 81% of the research conducted in either North America or Europe (this includes all laboratory and theoretical studies), while South America, Asia, and Africa remain underrepresented (Table 1). Yet developing nations are likely to experience the greatest level of population and economic growth over coming decades (Bloom, 2011). This situation provides important opportunities and motivation to study the effects of noise in less-disturbed habitats and to introduce known mitigation strategies to avoid negative consequences, particularly given that South America, Asia, and Africa are also home to some of the most biodiverse regions on the planet (Jenkins, Pimm & Joppa, 2013). Individual-, population-, and community-level reactions to a novel noise stimulus will likely differ between areas previously exposed to anthropogenic noise over extended periods of time and areas where anthropogenic noise exposure is lower and the source was recently introduced.

(2) Isolating the effects of noise

Anthropogenic noise is commonly associated with human activities that produce multiple types of disturbances (e.g. visual, habitat fragmentation). A number of experimental approaches have been developed to isolate noise from these other confounding variables, these include natural experiments contrasting noisy and quiet areas while holding other variables constant (e.g. natural gas compressor studies; Habib, Bayne & Boutin, 2006; Bayne, Habib & Boutin, 2008; Francis *et al.*, 2009), and controlled playback experiments where noise is introduced in isolation to the other forms of disturbance (e.g. for free-ranging populations of marine

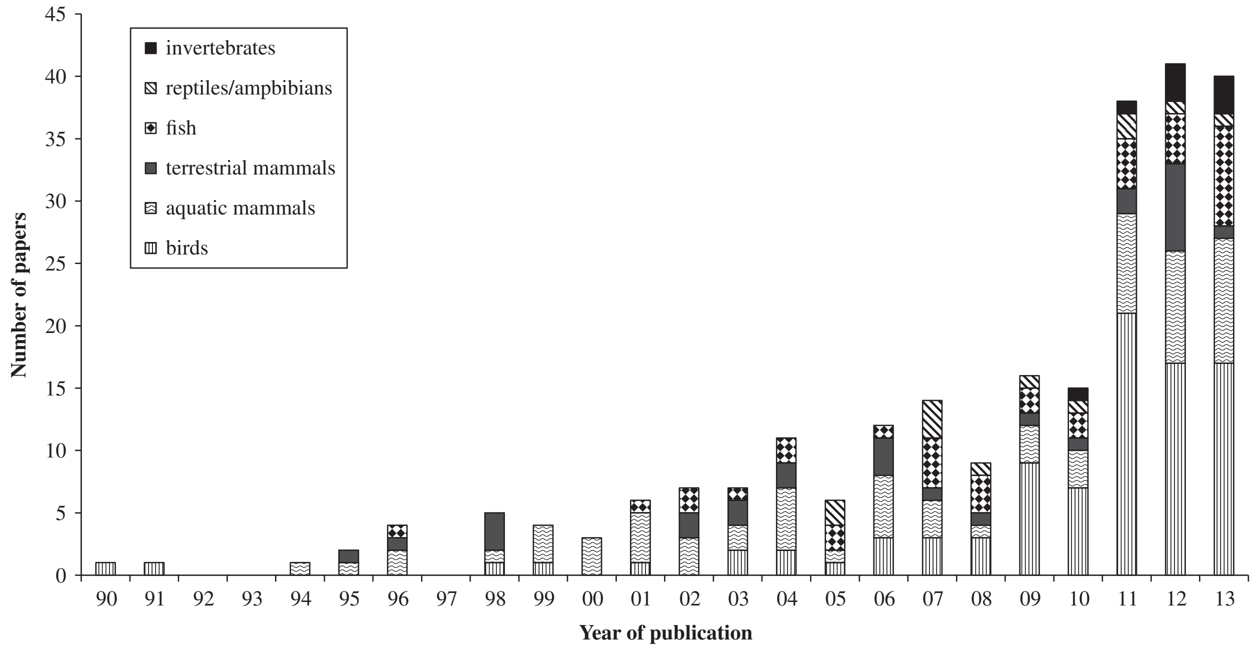

Fig. 1. Number of peer-reviewed publications reporting the effects of anthropogenic noise on wildlife from 1990 to 2013. Publications are divided into broad taxonomic categories: birds, aquatic mammals, terrestrial mammals, fish, reptiles/amphibians and invertebrates.

mammals and birds: Blickley, Blackwood & Patricelli, 2012*a*; Blickley *et al.*, 2012*b*; Goldbogen *et al.*, 2013; McClure *et al.*, 2013).

Studies that have isolated noise from potentially confounding variables have provided crucial evidence that noise alone can directly alter behaviour (Karp & Root, 2009; DeRuiter *et al.*, 2013*b*), reduce habitat quality (Blickley *et al.*, 2012*b*), and cause physiological impacts (Mooney, Nachtigall & Vlachos, 2009) across a range of species. For example, a recent playback study created a 0.5 km 'phantom acoustical road' to compare migratory bird habitat utilisation during 'on' and 'off' conditions (McClure *et al.*, 2013). The results from this sequence of trials, combined with concurrent observations of nearby control habitat (similar vegetation, no noise playback), provide decisive evidence that noise alone causes rapid changes in habitat use.

A combination of research approaches has proved important in identifying the consequences of noise disturbance. Natural experiments utilising existing acoustical gradients over time or space (48% of reviewed studies) have the potential to confound the effects of noise with other disturbances (see Summers *et al.*, 2011), but can be complimentary to controlled playback experiments conducted on free-ranging populations (15% of reviewed studies). Furthermore, biologically relevant responses at the individual, population, and community level can be identified in the field, whereas noise and the specific mechanisms driving changes in behaviour and physiology can be isolated with greater ease under laboratory conditions (Kight & Swaddle, 2011).

(3) Relationship between the perception of noise and response

Biological responses to noise are varied (Table 3), in part because responses depend upon the perception of noise (reviewed by Francis & Barber, 2013). Noise can be perceived as a threat, as observed when animals respond similarly to playbacks of anthropogenic noise and predator calls (e.g. Tyack *et al.*, 2011). In other cases, noise causes sensory degradation or the inability to detect acoustic cues from conspecifics, predators, prey or the environment, which can alter predator–prey interactions (Siemers & Schaub, 2011), reduce reproductive success (Halfwerk *et al.*, 2011*b*), and change settlement dynamics (Holles *et al.*, 2013). Additionally, noise can distract animals from attending to more crucial stimuli in the environment (Chan *et al.*, 2010), it can be a direct stressor causing pain or elevated stress hormone levels (Blickley *et al.*, 2012*b*; Rolland *et al.*, 2012), or in some instances, noise may provide a shelter from disturbance-sensitive predators (Francis *et al.*, 2009; Brown *et al.*, 2012).

The mechanisms by which animals respond to noise are not necessarily mutually exclusive. For example, animals that remain in a 'noisy' habitat because it provides a shelter from predators will likely have to contend with sensory degradation, either through changes in vocalisations (Mockford & Marshall, 2009; Mockford, Marshall & Dabelsteen, 2011) or vigilance patterns (Quinn *et al.*, 2006; Rabin, Coss & Owings, 2006). Noise can also induce the same response *via* compound mechanisms; for instance, reductions in foraging activity may be driven by a combination of increased perceived predatory threat,

Table 1. Summary of peer-reviewed literature reporting the effects of anthropogenic noise on wildlife published from 1990 to 2013 ($N = 242$)

Journal type									
General biology	Taxon-specific	Environment	Conservation and management	Behaviour	Acoustics	Ecology	Physiology	Captive animals & welfare	Other
22%	**13%**	**13%**	**12%**	**12%**	**11%**	**8%**	**3%**	**2%**	**2%**
Taxonomic diversity									
Birds	Aquatic mammals	Fish	Terrestrial mammals	Reptiles/ amphibians	Invertebrates	Multiple species			
37%	**28%**	**15%**	**11%**	**4%**	**4%**	**1%**			
Terrestrial geographic distribution (**$N = 128$, two studies that occurred in both aquatic and terrestrial habitats were excluded**)									
North America	Lab/theoretical	Europe	South America	Australia	Asia	Global	Africa	Antarctica	
36%	**24%**	**21%**	**7%**	**7%**	**4%**	**1%**	**0%**	**0%**	
Aquatic geographic distribution (**$N = 110$, two studies that occurred in both aquatic and terrestrial habitats were excluded**)									
Lab/theoretical	Atlantic Ocean	Pacific Ocean	Mediterranean Sea	North/ Norwegian Sea	Artic	Australia	Africa (estuary)	Antarctica	Indian Ocean
44%	**25%**	**12%**	**7%**	**5%**	**3%**	**2%**	**1%**	**1%**	**1%**
Noise sources									
	Transportation	Environmental	Industrial	Military	Other	Recreation			
Aquatic	**28%**	**5%**	**30%**	**22%**	**12%**	**3%**			
Terrestrial	**30%**	**35%**	**13%**	**8%**	**12%**	**2%**			
Biological responses									
	Vocalisation	Movement	Physiological	Population	Vigilance	Foraging	Mating	Direct fitness	Community
Aquatic	**21%**	**37%**	**32%**	**4%**	**0%**	**4%**	**1%**	**2%**	**0%**
Terrestrial	**44%**	**15%**	**10%**	**16%**	**6%**	**2%**	**4%**	**2%**	**2%**

Table 2. Proportion of studies in different noise-source categories

Noise-source category	Examples	Per cent of terrestrial studies	Per cent of aquatic studies
Environmental	General background noise (urban and developed areas, no specific source identified)	5	35
Transportation	Commercial (maritime shipping, commercial aircraft, train, bus) and private (general traffic, automobile, motorcycle, small boat) transport noise	30	13
Industrial	General construction, machinery, energy (wind, oil and gas) development and operation, pile driving, seismic survey (air-guns), echo sounder, and underwater communication network noise	23	8
Military	Gun fire, explosion, naval sonar, and aircraft noise	12	12
Recreation	Hunting, whale-watching, air tour, snowmobile, and race-track noise	3	2
Other	Simulated (white, pink, tones), human voice, alarm, aquarium, and chainsaw noise	27	31

distraction, stress-induced loss of appetite, and masking of prey cues (Bracciali *et al.*, 2012; Wale, Simpson & Radford, 2013).

Evidence suggests that the characteristics of the acoustic signal (e.g. frequency, duration, onset, intensity) and the biology of the species in question (e.g. hearing range, behavioural state, habitat, vocal behaviours) are important for predicting how noise is likely to affect a particular organism (reviewed by Francis & Barber, 2013; Parris & McCarthy, 2013). Chronic noise sources are likely to degrade auditory cues important for predator/prey detection (Siemers & Schaub, 2011), communication (Hatch *et al.*, 2012) and orientation (Ellison *et al.*, 2012), especially if the noise source is high intensity and overlaps in frequency with an organism's hearing capabilities or the sound of interest (e.g. footfalls, leaves rustling; see Goerlitz, Greif & Siemers, 2008). Shifts in vocal rate, call intensity, call type, call frequency (as reviewed by Slabbekoorn, 2013), the timing of singing (Fuller, Warren & Gaston, 2007), and duration of calling (Diaz, Parra & Gallardo, 2011) have been studied extensively among birds (and marine mammals) to explore how vocal communication is affected by anthropogenic noise (see Tables 1 and 3), and to examine possible behavioural adaptations that are employed to overcome masking. The link between vocal flexibility and persistence in noisy environments has been demonstrated in a number of species (Francis *et al.*, 2011*d*; Proppe, Sturdy & St Clair, 2013*b*) and vocal behaviour and ability to learn can influence a vocal response to noise (Hu & Cardoso, 2010; Ríos-Chelén *et al.*, 2012). Recent theoretical work predicted the reduction in active space of vocal signals for birds moving from rural to urban habitat and identified the communication benefits of raising vocal frequency in noisy environments, particularly for species with calls in the lower frequency range (reviewed by Parris & McCarthy, 2013). Nevertheless, a change in vocalisation may come with significant consequences, including altered energy budgets and loss of vital information (Read, Jones & Radford, 2014). Although explored to a lesser extent, responses to reduced cue detection, such as movement away from the noise (e.g. Miksis-Olds & Wagner, 2011; McLaughlin & Kunc, 2013) and a reduction in foraging efficiency (Schaub, Ostwald & Siemers, 2008; Siemers & Schaub, 2011), have also been demonstrated in the presence of chronic noise.

Noise sources that are novel, unpredictable, or are acoustically similar to biologically relevant sounds are predicted to elicit responses similar to those associated with predation risk (flee, hide, startle responses; reviewed by Francis & Barber, 2013). Although the sound must be detected, the noise does not need to overlap with peak hearing capabilities or be received at a high intensity to elicit antipredator behaviour. For example, beaked whales (*Ziphius cavirostris*) responded similarly to playbacks of military sonar and calls of killer whales (their main predator) (Tyack *et al.*, 2011). In this case sonar overlapped with the peak hearing range of the study species, but sonar also elicited antipredator responses in blue whales (*Balaenoptera musculus*) with hearing sensitivities in much lower frequencies (Goldbogen *et al.*, 2013), and failed to elicit responses in Atlantic herring (*Clupea harengus*), despite overlap with their most sensitive hearing range (Doksæter *et al.*, 2009). Thus, the frequency and intensity of noise are just a few of the factors driving responses, with temporal and spatial context of the disturbance, prior experience and similarity to relevant biological sounds also playing key roles (reviewed by Ellison *et al.*, 2012).

Current research is furthering our understanding of the specific mechanisms driving the observed biological responses to noise and the contextual factors that shape them. For example, the presence of young (Maier *et al.*, 1998), social status (Bruintjes & Radford, 2013), and spatial orientation relative to a noise source (Delaney *et al.*, 1999; Ellison *et al.*, 2012) can all drive differential responses. The duration and timing of noise stimuli are also important, as extended exposure to a chronic noise source may ultimately lead to tolerance or habituation, particularly if it provides an indirect benefit (e.g. a predator shelter; Francis *et al.*, 2009;

Table 3. Distribution of studies by biological response and noise source

		Noise source				
	Biological response	**Environmental**	**Transportation**	**Industrial**	**Military**	**Other**
All Studies (*N*=212)	*vocal behaviour*	20.3%	9.9%	1.4%	1.9%	2.8%
	movement	1.9%	4.2%	5.7%	6.1%	4.2%
	physiology	–	4.2%	5.2%	2.4%	7.5%
	population metrics	1.4%	4.2%	4.7%	0.5%	–
	vigilance	–	0.9%	0.5%	0.9%	0.5%
	mating behaviour	–	1.4%	0.9%	–	0.5%
	foraging behaviour	–	2.4%	–	0.5%	–
	direct fitness metrics	0.5%	0.5%	0.9%	–	–
	community-levelmetrics	0.5%	–	0.5%	–	–
Terrestrial Studies (*N*=120)	*vocal behaviour*	31.7%	11.7%	–	–	4.2%
	movement	2.5%	2.5%	–	3.3%	3.3%
	physiology	–	0.8%	2.5%	0.8%	5.8%
	population metrics	2.5%	5.8%	7.5%	0.8%	
	vigilance	–	1.7%	0.8%	1.7%	0.8%
	mating behaviour	–	1.7%	1.7%	–	0.8%
	foraging behaviour	–	1.7%	–	–	–
	direct fitness metrics	0.8%	-	0.8%	–	–
	community-levelmetrics	0.8%	-	0.8%	–	–
Aquatic Studies (*N*=92)	*vocal behaviour*	5.4%	7.6%	3.3%	4.3%	1.1%
	movement	1.1%	6.5%	13.0%	9.8%	5.4%
	physiology	–	8.7%	8.7%	4.3%	9.8%
	population metrics	–	2.2%	1.1%	–	–
	vigilance	–	–	–	–	–
	mating behaviour	–	1.1%	–	–	–
	foraging behaviour	–	3.3%	–	1.1%	–
	direct fitness metrics	–	1.1%	1.1%	–	–
	community-level metrics	–	–	–	–	–

Only studies that reported a statistically measured response were included. Colour shading indicates the relative number of studies in each category.

Brown *et al.*, 2012). Studies combining different metrics of response, such as spatial distribution and vocal activity, may offer further insight into the varied consequences and trade-offs for species and communities exposed to noise (McLaughlin & Kunc, 2013). Ultimately, predicting how noise characteristics, behavioural contexts, and animal biology interact will be central in identifying habitats that are of conservation concern and implementing effective mitigation strategies.

(4) Ecological consequences of noise

A diverse range of biological responses to noise, from altered hearing thresholds of captive fish to changes in movement and foraging behaviour of large marine mammals in the open ocean, have been measured. Of the 242 studies included in this review, 88% reported a statistically measured biological response to noise exposure (see Table 3 & online Appendix 1 for further details). A small number of these studies have begun examining the impacts of noise using metrics associated with population persistence (survival, reproductive fitness), community interactions (predator–prey interactions), and ecosystem services (pollination) to understand the biological costs of anthropogenic noise. For example, studies on the impacts of noise to population persistence measured declines in productivity of breeding (Kight, Saha & Swaddle, 2012), reduction in fitness (Schroeder *et al.*, 2012), and change in timing of settlement (Pine, Jeffs & Radford, 2012).

Investigating the effects of noise on multiple taxa within a study system enables detailed exploration of the complex and interactive nature of noise impacts. Noise was found to impact key ecological services, enhancing pollination *via* reduced predation in noisy areas for hummingbirds, while decreasing seed dispersal for dominant plants because key dispersers avoided noisy areas (Francis *et al.*, 2012). Investigating the effects of noise on lower trophic levels can also reveal community-level impacts of noise. For instance, exposure to continuous turbine noise interfered with natural settlement cues for two species of abundant estuarine crabs, likely disrupting food-web interactions (Pine *et al.*, 2012). Noise altered species interactions, including predator–prey interactions in terrestrial (Schaub *et al.*, 2008; Siemers & Schaub, 2011) and marine (Kuningas *et al.*, 2013; Wale *et al.*, 2013) communities, while social interactions of cichlid fish shifted in the presence of boat noise (Bruintjes & Radford, 2013). Although these studies did not directly test the consequences for community structure and function, changes in species interaction may ultimately translate into community-level effects.

The majority of noise research has used comparatively short-term natural or controlled experiments that commonly focus on behavioural change in single species and are spatially discrete. While this approach has proved pivotal in revealing the widespread impacts associated with noise, evidence for long-term effects on populations and communities is generally only suggestive. Long-term experiments conducted over broad spatial scales may offer a more complete understanding of the population-level and interacting effects of noise on wildlife.

(5) Application of research to develop and implement noise mitigation

The global increase in anthropogenic noise levels across both human-dominated and natural habitats presents a significant conservation challenge, especially when considered in conjunction with other threats to wildlife and ecosystem integrity. There is a real need for research on the impacts of noise on wildlife to translate into management actions or recommendations (Tabarelli & Gascon, 2005). While a variety of noise-mitigation methods exist, only 9% of the studies reviewed provided specific recommendations. Recommendations included the use of physical barriers to noise, geographical and temporal restrictions to human activity, and quiet technology (Table 4), yet few studies directly tested the effectiveness of these methods. The majority of studies with mitigation statements were published in conservation, ecology, and environmental journals and focussed primarily on terrestrial ecosystems.

Physical barriers are a commonly suggested mitigation tool that have been used along roadways to reduce noise levels for human populations (Murphy & King, 2011) and wildlife (Slabbekoorn & Ripmeester, 2008). However, the benefits of these barriers extend a relatively short distance. Barriers also can compound fragmentation effects by restricting animal movement, and their costs may well exceed other mitigation approaches (Summers *et al.*, 2011). Collectively, these considerations suggest that noise barriers are most suitable for roadside habitat of especially high conservation value, or to enhance the effectiveness of road-crossing structures or tunnels. Alternative options to reduce road noise include restrictions to traffic flows during sensitive life-history periods, speed reductions, improved road surface substrates, and new tyre technology. Controlled studies documenting changes in wildlife behaviour and habitat utilisation in response to reducing roadway noise would extend the findings of recent noise broadcast studies, and document the conservation value of quiet-road investment.

The noise-barrier approach can be effective for industrial activities such as resource extraction and construction, where machinery generates a point noise source that is spatially compact (Table 4). Specific methods have included the use of bubble curtains to reduce pile-driving noise in marine environments (Würsig, Greene & Jefferson, 2000) and the erection of sound barriers to minimise noise from terrestrial gas compressor stations (Francis *et al.*, 2011*d*). Implementing barrier mitigation measures may prove expensive (e.g. \$175–200 million to reduce oil and gas extraction noise by 4 dB; Bayne *et al.*, 2008), making it unlikely that industry will adopt these measures without specific regulations in place (Ortega, 2012).

(6) Characterising complex acoustic stimuli

Anthropogenic noise is a complex and challenging source of pollution to quantify, varying in duration, amplitude, and frequency content, while being modified by the medium through which it travels. The detailed reporting of acoustic measurements is necessary to repeat experiments, provide insight on the kinds of noise stimuli that induce a response, and synthesise results across studies. We were surprised that acoustic metrics and measurement methods were not always documented in these papers. Although the majority of studies used common acoustic metrics such as root-mean square sound pressure level (SPL), sound exposure level (SEL), or equivalent noise level (Leq) (see online Appendices S1 and S2 for descriptions of these metrics), 30% provided no details on the received sound levels of the noise stimulus and 10% simply reported a dB level without information on how the value was measured or calculated (Fig. 2). A notable proportion of studies (38%) lacked a record of the spectral analysis, such as duration of the measurement, frequency range, and weighting function (Fig. 2). Measurements of the background acoustic environment prior to exposure to a noise source (excluding the environmental noise category) were reported in only 53% of the literature (Fig. 2). Given the cross-disciplinary nature of terrestrial and aquatic bioacoustic research and the difference in reference pressure between air and water, it is surprising that the majority of studies (51%) did not report the reference pressure used when reporting a dB value (see Rossing, 2007 for further details). Ninety per cent of these studies were conducted in terrestrial environments, implying the use of the standard reference pressure in air, but this is a potential source of confusion (reviewed by Chapman & Ellis, 1998).

Table 4. Examples of reported mitigation methods for reducing the negative effects of noise on wildlife

	Environmental	Transportation	Industrial	Military
Birds	Urban planning (e.g. maintaining green spaces and reducing noise levels) to maintain biological communities [3]	Engineering solutions (e.g. road surfaces, tyres and vehicle engines) that reduce noise [13]	Use of sound barriers around compressors to reduce affected area by 70% and maintain occupancy and nest success rates [4]	
	Reduction of aircraft noise exposure to <80 dBA of river habitats used by harlequin ducks [5]	Closing key roads during breeding season; reducing traffic speed and volume [10]		
	Placement of new acoustically dominant features (roads, machinery) further from nesting areas; limits to production during sensitive periods of breeding; abatement of current noise by altering structures (e.g. sound walls, dense vegetation, removing highly reflective surfaces, rerouting traffic) [6]	Use of 105 m hemispherical protection to eliminate owl flush response to overflights; minimising flights 3 h following sunset and preceding dawn; separating overflights by at least 7 days [2]		
		Restricting traffic flow and heavy truck use [14]		
		Wise planning along transportation corridors and mitigation of noise along their paths to enhance habitat for the highest number of bird species [16]		
Terrestrial mammals		Setting criteria for height and density of road bordering vegetation, filling in gaps in tree lines and encouraging canopy growth [15]	Noise barriers; construction scheduling to avoid noise-sensitive experiments [12]	Limiting military training exercises during calving and post-calving season [8]
Aquatic fish/mammmals		Ship design and construction that includes methods to reduce underwater noise and limited navigation permitted within fish spawning grounds during the spawning season [17]	Air bubble curtains and 'Hydro Sound Dampers' [18]	Use of dose–function methods in predicting the harassment of marine mammals [20]
		Definition of noise-free areas or seasonal restriction of noise activities during sensitive biological periods [11]	Avoiding pile-driving during calving and when animals are in 500 m exclusion zone; soft start or alarm sound before operations; restricting operations to low tide; decoupling equipment from hull of piling vessel; use of bubble curtain within 25 m radius of the pile [1]	Consider the likely contexts of exposure and the foraging ecology of baleen whales in planning military sonar operations [19]

Table 4. Continued

	Environmental	Transportation	Industrial	Military
Reptiles & amphibians	Use of noise barriers on road network; construction of new roads at distances away from protected areas; technological advances; laws with standard noise emission for vehicles, speed and driver behaviour [7]	Dense vegetation along roadsides (as a less costly alternative to solid barriers) to attenuate traffic noise [9]		
Invertebrates			Applying the precautionary principle when planning high-intensity activities such as explosions, construction or seismic exploration, in spawning areas of marine invertebrates with high natural and economic value [21]	

[1] David (2006); [2] Delaney *et al.* (1999); [3] Fontana, Burger, & Magnusson (2011); [4] Francis *et al.* (2011*d*); [5] Goudie & Jones (2004); [6] Kight *et al.* (2012); [7] Lengagne (2008); [8] Maier *et al.* (1998); [9] Parris & Schneider (2009); [10] Parris *et al.* (2009); [11] Picciulin *et al.* (2010); [12] Rasmussen *et al.* (2009); [13] Summers *et al.* (2011); [14] Zhang *et al.* (2012); [15] Zurcher, Sparks, & Bennett (2010); [16] Proppe *et al.* (2013*b*); [17] Liu *et al.* (2013); [18] Dähne *et al.* (2013); [19] Goldbogen *et al.* (2013); [20] Houser, Martin & Finneran (2013*b*); [21] de Soto *et al.* (2013).

IV. IDENTIFYING NOISE LEVELS THAT ELICIT A BIOLOGICAL RESPONSE

Our compilation and synthesis of research on the effects of anthropogenic noise on wildlife offers an opportunity to identify the noise levels that elicit biological responses. To integrate information on wildlife responses to noise into a common framework, we identified a subset of studies (69 terrestrial and 62 aquatic) that documented a significant response to a noise stimulus and also reported an acoustic value and metric at which a response occurred. Our classification of a 'significant response' was based upon the study reporting a statistical change in the particular biological metric as a function of noise exposure. A variety of metrics with different frequency weighting and bandwidths were reported in this subset of studies (see online Appendix S2). It was not possible to adjust all values to a common acoustic metric to compare across studies. Instead, we reported the metrics used in each study and the specific sound level (see Fig. 3); this provided graphical indications of the different metrics to reveal potential artefacts or differences in interpretation (Madsen, 2005).

Extracted noise levels were sorted to produce a cumulative weight-of-evidence curve as a function of the noise level at which a biological response was documented, thereby summarising the number of studies reporting a response at or below a given noise level. We compiled the results for terrestrial and aquatic studies separately because they used different reference pressures to derive noise levels. These cumulative curves span a wide range of species and biological responses, in addition to different acoustic metrics. This framework was modelled after a dose–response relationship, but each increment in the weight-of-evidence function does not represent an increasing number of responsive species. Rather, these curves depict an increasing number of studies documenting a response at a given noise level. Therefore, the curves suggest accumulation of evidence, not accumulation of response.

The cumulative weight-of-evidence curves provide support for natural resource managers seeking to establish management objectives for anthropogenic impacts or developing policy on noise (Fig. 3). For example, a limit on allowable noise levels can be supported by citing the percentage or number of studies that have documented biological impacts at or below that level. Lower noise thresholds are more protective, but they are supported by a smaller number of studies. Note that responses have been documented in terrestrial environments at noise exposure levels as low as 40 dB SPL, and 14 studies documented responses below 50 dB (Fig. 3A). Predictions of natural sound levels for the coterminous USA range from 24 to 40 dB (LAeq, 1 s, median summer daytime level; Mennitt, Fristrup & Nelson, 2013). The terrestrial weight-of-evidence curve includes all noise-source categories and species groups, although representation is unbalanced (Table 5). Multiple bird studies documented changes in song characteristics,

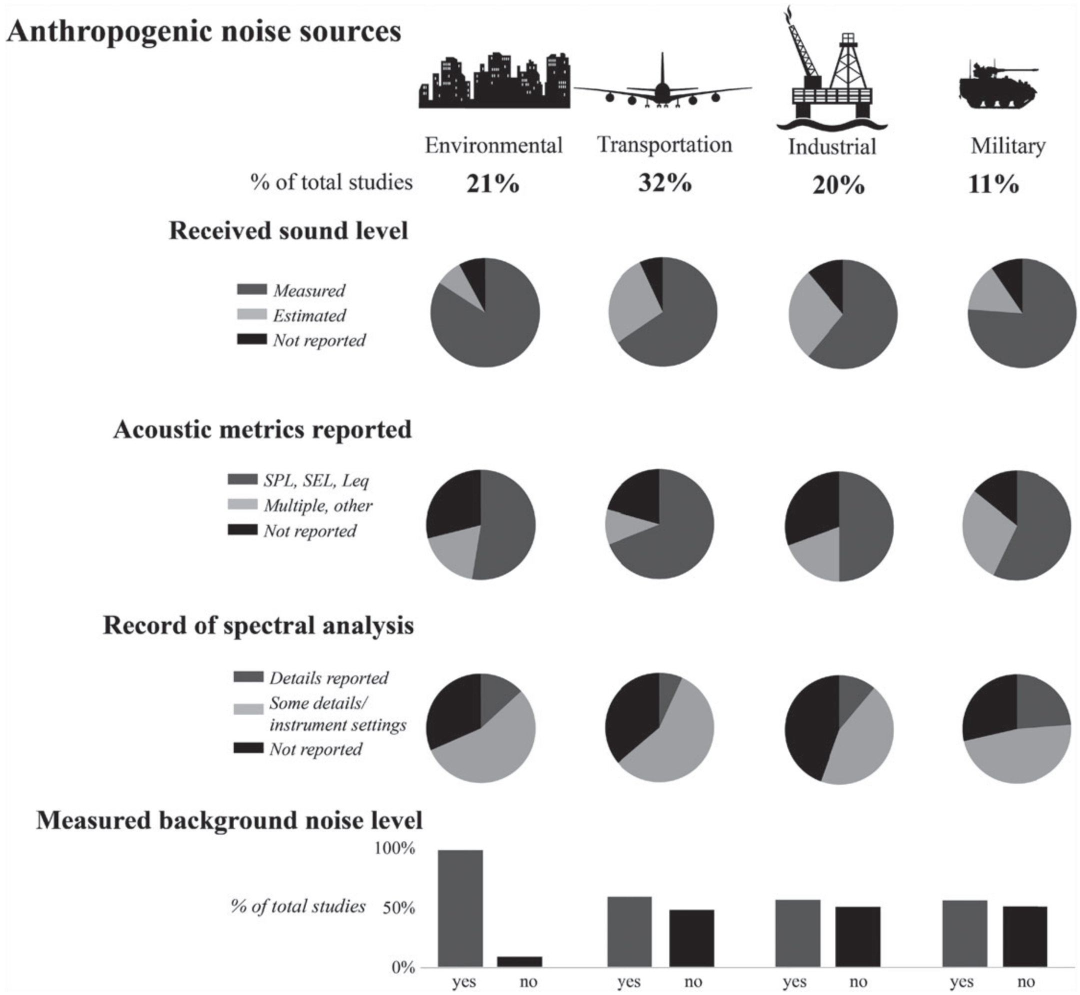

Fig. 2. Reporting of acoustic noise-source measurements. The chart divides all of the studies into noise source categories and highlights different components of acoustic analysis, including whether the received sound level was measured, the types of acoustic metric reported (see online Appendices S1 and S2 for acoustic metric definitions), whether details of the spectral analysis were provided and whether background noise was measured (note that background noise provided the noise source for most studies in the environmental category). Black-filled graphics indicate the proportion of studies in which details were not reported.

reproduction, abundance, stress hormone levels, and species richness at levels ≥45 dBA SPL (re 20 μPa). Terrestrial mammals exhibited increased stress levels and decreased reproductive efficiency at noise levels between 52 and 68 dBA SPL (re 20 μPa). Traffic noise exceeding 60 dBA SPL (re 20 μPa) impacted the vocal behaviour of male anurans and traffic noise exceeding 80 dBA SPL (re 20 μPa) reduced the foraging efficiency of gleaning bats.

The diversity of responses and metrics creates opportunities for misinterpretation. For example, it might seem reasonable to utilise the median of this cumulative distribution as a noise-impact criterion that is robustly supported by this body of literature. This would yield a value of 60 dB. This level would be cause for concern in a community setting: it causes conversational speech interference. The EPA (1974) recommended a 55 dB criterion to protect the health and welfare of the American public. The inflated character of this median can be explained by examining the metrics associated with the points in Fig. 3A. Many of the studies that fall above the median utilised metrics that typically exceed LAeq (SPL max, SEL), or the studies did not specify the metric and measurement procedure. Accordingly, the most useful portion of this curve lies to the left of the median.

To provide insight into the relative effects of noise on humans and wildlife, the cumulative curve for the terrestrial wildlife studies was compared against human responses to noise derived from a meta-analysis of human survey data on annoyance at different noise levels (ANSI, 2005). The human response curve represents the predicted percentage of residents in quiet rural communities predicted to be highly annoyed by a new or unfamiliar noise source. Despite the heterogeneity in the wildlife noise metrics and responses, the range of noise levels documented to induce annoyance in humans and responses in terrestrial wildlife are similar (40–100 dB SPL re 20 μPa). Evidence

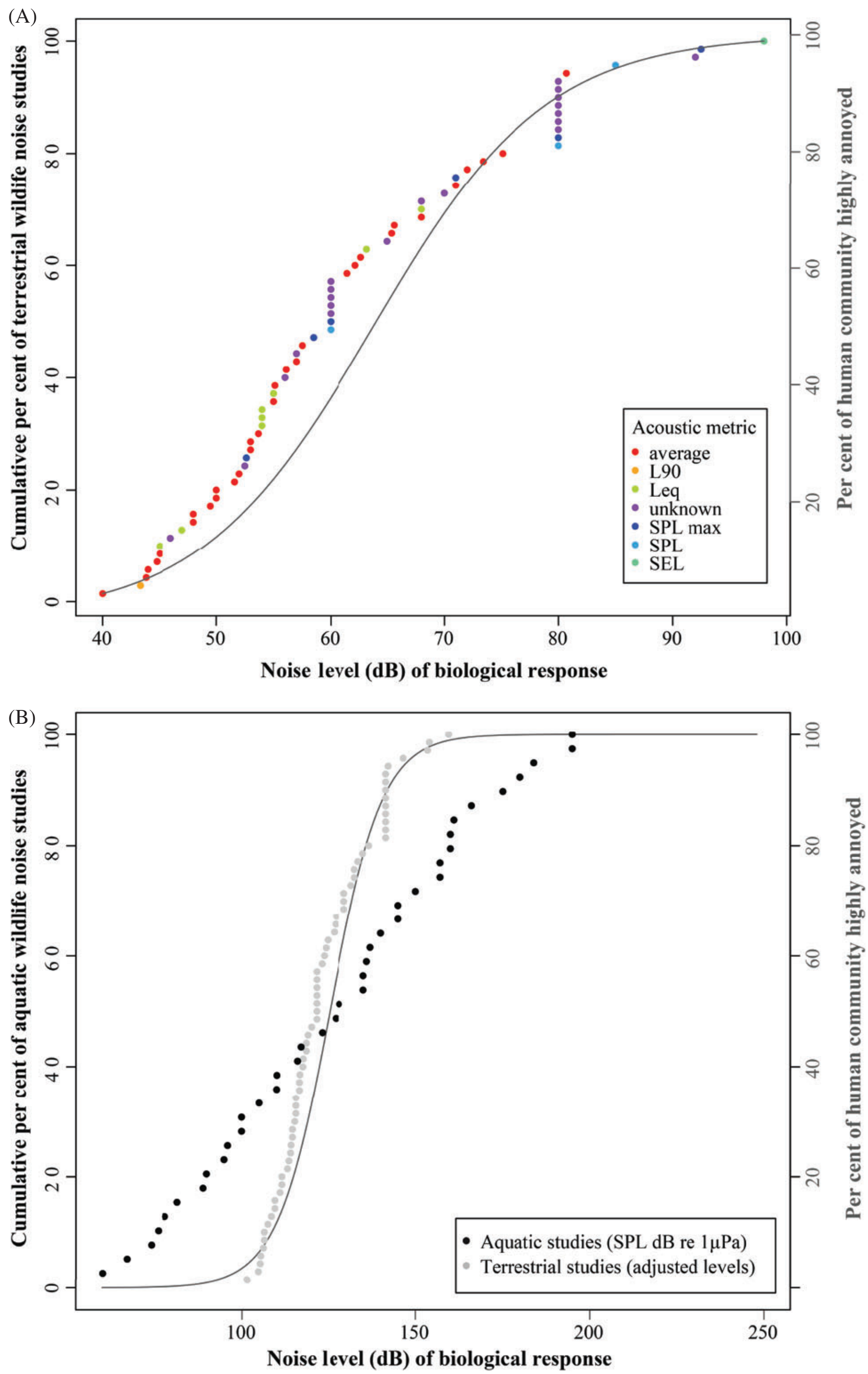

Fig. 3. Cumulative per cent of studies reporting biological responses by wildlife for a given noise level. Only studies that reported acoustic measurements are included (N = 131). See Appendices S1 and S2 for additional details on the noise levels, acoustic metric definitions, frequency weighting and bandwidths for each study used to generate these curves. (A) Results from terrestrial studies. Coloured symbols are used to reveal the potential influence of different metrics on the shape of the terrestrial curve. The human response curve (solid line) represents the predicted percentage of residents in quiet rural communities predicted to be highly annoyed by a new or unfamiliar noise source. (B) Results from the aquatic studies. Only SPL dB values were used to generate the cumulative curve. For comparison, received levels from the terrestrial wildlife studies and the human response curves (right *y* axis) are also plotted. The noise levels in the terrestrial wildlife and human studies were adjusted to the same scale as the aquatic studies. This was done by adding 61.5 dB to the sound level values to account for the difference in reference pressure and impedance.

for wildlife responses to noise accumulates at lower exposure levels than the rural human annoyance curve, although the slopes are similar. Another connection between human and wildlife noise studies is the onset of health effects. Epidemiological studies suggest that humans may experience elevated risk of hypertension when LAeq is greater than 55 dB (Stansfeld & Matheson, 2003). Physiological and fitness effects were documented by five papers included in this review at noise exposure levels of 52, 52, 58, 60, and 68 dBA SPL.

The aquatic studies generally provided better descriptions of their measurements, although in this literature variation in the bandwidth of the noise stimulus varies and presents a challenge for interpretation of the cumulative evidence curves. Fifty per cent of the aquatic studies measured a biological response at or below 125 dB (re 1 μPa) (Fig. 3B). The different reference pressure and acoustic impedances between air and water account for 61.5 dB of the differences in levels between terrestrial and aquatic studies (Leighton, 2012). The terrestrial data and human annoyance curves are included in Fig. 3B after accounting for this correction factor.

The studies contributing to the aquatic weight-of-evidence curve include all noise source categories and species groups (Table 6). Manatees shifted their foraging and movement behaviour when one-third octave band levels (4 kHz) exceeded 60 dB SPL, a notably low level. Otherwise, fishes, mammals, and invertebrates responded to noise across a wide range of noise levels (67–195 dB SPL re 1 μPa) (see online Appendix S2). Industrial noise, particularly high-intensity sound sources such as seismic air guns, impacted the physiology, vocal communication, and activity budgets of aquatic species, with reduced abundance and catch rates of fishes during relatively high levels of industrial noise (248 dB SPL re 1 μPa). Marine mammals responded to industrial noise by altering spatial movement patterns (107 dB Leq re 1 μPa), hearing thresholds (226 dB peak–peak re 1 μPa), and calling behaviour (82 dB SPL re 1 μPa) (Table 6). Naval sonar was the main source of concern in the military category (92% of aquatic studies with military sources). Sonar caused active avoidance, disrupted foraging, and temporary hearing loss among marine mammals in close proximity to the source (67 dB SPL re 1 μPa), yet showed limited effects on fish with all documented responses occurring at higher noise levels (195 dB SPL re 1 μPa) (Table 6).

V. RESEARCH RECOMMENDATIONS

Our review has highlighted the substantial body of information concerning the effects of anthropogenic noise on wildlife. Such research can assist scientists, natural resource managers, industry, and policy makers in both predicting potential outcomes of noise exposure as well as implementing meaningful thresholds and mitigation measures. Refinement and focus on several key research areas will further strengthen the conclusions and inferences that can be drawn regarding the impacts of noise on wildlife.

(1) Expand geographic and taxonomic sampling

Research on the effects of anthropogenic noise on terrestrial systems has been taxonomically and geographically biased, with 65% of studies conducted on birds and marine mammals and 81% of research carried out in either North America or Europe (includes all theoretical and laboratory-based studies). Investigating the effects of noise across a broader array of species and habitats is crucial for developing theories that explain variations in response to noise in terms of unique auditory capabilities, social structure, life history, ecological role, and evolutionary adaptation. Greater knowledge of taxon-level responses to noise will also be useful in predicting the likely responses of species that are too rare or elusive to study directly and may reveal responses in species previously thought unaffected because they occupy noisy areas (Shannon *et al.*, 2014) or have peak hearing sensitivities outside of a particular noise source (Goldbogen *et al.*, 2013).

(2) Explore interacting effects

In most cases, it remains unclear whether responses to noise will be further compounded by the introduction of potentially heterotypic stressors such as artificial light and habitat fragmentation. Designing studies that explore and quantify how the addition of other stressors influences observed biological responses to noise will facilitate evaluation of the benefit of reducing noise in environments facing multiple threats.

(3) Remove or reduce noise

Documenting biological responses in environments that have experienced a reduction in noise, such as closure of a road, closure of an energy facility, or a change in ship traffic routes, may reveal how systems recover from chronic noise exposure. Successful design requires knowledge and coordination with proposed changes in order to capture conditions prior to the reduction in noise levels.

(4) Invest in large-scale studies

To date there are very few studies that have attempted to explore the effects of noise at the landscape scale and/or over long temporal periods (e.g. seasonal, yearly), likely due to the logistical and experimental challenges that it presents, particularly in isolating the effects of noise from other sources of disturbance (e.g. habitat fragmentation, human presence). Nonetheless, in contrast to single-exposure, single-species research, larger-scale approaches can provide direct insight into the cumulative effects of noise exposure related to population persistence, ecological integrity, and evolutionary processes. Developing a systematic approach to sampling of multiple species within a community and multiple metrics of biological responses will therefore require coordination across scientific disciplines and organisations.

Table 5. Biological responses to different noise-source categories by terrestrial taxa. Studies in this table are included in Fig. 3A

	Environmental		Transportation		Industrial		Military	
Birds	Changes in frequency components of vocalisations [1–22]	44–73 dBA# 54 dBA** 60 dBA* 59 dBA† 53–80 dBA?	Changes in frequency components of vocalisations [33–35]	60–65 dBA? 50 dBA#	Changes in song frequency and length [53]	45 dBA**	Increase in vigilance and alert behaviour [64, 65]	63 dBA** 80 dBA†
	Changes in call rate and duration [14–18]	60 dBA* 48–66 dBA# 57 dBA?	Increase in amplitude of vocalisations [36]	57 dBA#	Increase in physiological stress levels [54]	52 dBA#		
	Increase in amplitude of vocalisations [19–23]	54 dB$,** 53-62 dBA# 80 dB$?	Shifts in timing of vocalisations [37]	80 dBA?	Reduced breeding success [55]	68 dBA#		
	Shifts in timing of vocalisations [24]	63 dBA#	Preference for roosting in quieter areas [38]	47 dBA**	Decline in occupancy and abundance [56–58]	48 dBA# 55 dBA# 45 dBA#		
	Decreases in acoustic complexity of songbird community [25]	53 dBA†	Reduction in reproductive success in presence of road noise [39]	68 dBA?	Changes in community and species interactions [59, 60]	60 dBC? 50 dBC#		
	Decline in species diversity [26, 27]	40 dB$# 45 dBA*	Effects on physiology and development [40]	60 dBA†				
	Avoidance of noisy environments [28]	70 dBA?	Changes in abundance, species richness, distribution and occupancy [41–43]	46 dBA? 45 dBA# 55 dBA**				
	Decline in reproductive success [29, 30]	58 dBA* 43 dBA***						
Mammals	Shifts in call frequency and amplitude for echolocating bats [31]	80 dB$	Disruption of foraging in gleaning bats [44, 45]	80 dBA*	Increase in physiological stress from construction noise [61, 62]	52 dBL# 92 dBA?	Short–term increase in heart rates and shifts in resting and movement behaviours of ungulates [66–68]	85 dB$* 98 dBA‡ 92 dB$†
					Reduced reproductive efficiency of laboratory mammals exposed to construction noise [63]	68 dBA**		

Table 5. Continued

	Environmental		Transportation		Industrial		Military	
Reptiles and amphibians	Shifts in energy distribution of cicadas songs towards higher frequency [32]	62 dBC#	Reduction in chorus tenure and duration by male anurans exposed to traffic noise [46–48]	72 dBA# 60–80 dBC?				
			Difficulty locating mates [49]	75 dBC#				
			Increased minimum frequency of vocalisations [50]	60 dBA?				
			Change in calling time [51]	71 dBC†				
Inverte–brates			Higher frequency components in courtship signal of grasshoppers [52]	81 dBA?				

Symbols: * sound pressure level (SPL); ** equivalent continuous sound level (Leq or LAeq); † SPL max; ‡ sound exposure level (SEL); # average; ? unknown.
See Appendices S1 and S2 for acoustic metric definitions. ***A-weighting***, like the human ear, cuts off the lower and higher frequencies that the average person cannot hear. At higher sound levels (100 dB and above), the ear's response is flatter, as shown in the **C-weighting**. **L** (linear) or **unweighted** (also known as Z-weighting) is a flat frequency response of 10–20 kHz ±1.5 dB.

$ indicates studies where it was unclear if a frequency weighting function was applied.

[1] Pohl *et al.* (2012); [2] Seger-Fullam, Rodewald & Soha (2011); [3] Bermúdez-Cuamatzin *et al.* (2011); [4] Dowling, Luther & Marra (2012); [5] Bermúdez-Cuamatzin *et al.* (2009); [6] Mendes, Colino-Rabanal & Peris (2011); [7] Nemeth & Brumm (2010); [8] Hu & Cardoso (2010); [9] Proppe *et al.* (2012); [10] Slabbekoorn & Peet (2003); [11] Goodwin & Podos (2013); [12] Montague, Danek-Gontard & Kunc (2013); [13] Nemeth & Brumm (2009); [14] Mockford & Marshall (2009); [15] Halfwerk & Slabbekoorn (2009); [16] Ríos-Chelén *et al.* (2013); [17] Potvin, Parris & Mulder (2011); [18] Gross, Pasinelli & Kunc, 2010); [19] Redondo, Barrantes & Sandoval (2013); [20] Pohl *et al.* (2009); [21] Nemeth *et al.* (2013); [22] Wood & Yezerinac (2006); [23] Lowry, Lill & Wong (2012); [24] Fuller *et al.* (2007); [25] Pieretti & Farina (2013); [26] Patón *et al.* (2012); [27] Proppe *et al.* (2013*b*); [28] McLaughlin & Kunc (2013); [29] Kight *et al.* (2012); [30] González-Oreja *et al.* (2012); [31] Hage *et al.* (2013); [32] Shieh *et al.* (2012); [33] Halfwerk *et al.* (2011*b*); [34] Potvin & Mulder (2013); [35] Verzijden *et al.* (2010); [36] Brumm (2004); [37] Arroyo-Solís *et al.* (2013); [38] Zhang *et al.* (2012); [39] Halfwerk *et al.* (2011*a*); [40] Crino *et al.* (2013); [41] Arévalo & Newhard (2011); [42] Goodwin & Shriver (2011); [43] McClure *et al.* (2013); [44] Schaub *et al.* (2008); [45] Siemers & Schaub (2011); [46] Lengagne (2008); [47] Sun & Narins (2005); [48] Kaiser *et al.* (2011); [49] Bee & Swanson (2007); [50] Cunnington & Fahrig (2010); [51] Lampe *et al.* (2012); [52] Vargas-Salinas & Amézquita (2013); [53] Francis, Ortega, & Cruz (2011*a*); [54] Blickley *et al.* (2012*b*); [55] Schroeder *et al.* (2012); [56] Bayne *et al.* (2008); [57] Blickley *et al.* (2012*a*); [58] Francis, Ortega, & Cruz (2011*c*); [59] Francis *et al.* (2009); [60] Francis *et al.* (2012); [61] Powell *et al.* (2006); [62] Westlund *et al.* (2012); [63] Rasmussen *et al.* (2009); [64] Conomy *et al.* (1998); [65] Goudie & Jones (2004); [66] Krausman *et al.* (1998); [67] Maier *et al.* (1998); [68] Weisenberger *et al.* (1996).

Table 6. Biological responses to different noise-source categories by aquatic taxa. Studies in this table are included in Fig. 3B

	Environmental		Transportation		Industrial		Military	
Fishes			Decrease in detection of communication signals and increase in stress hormones [5–7]	135 dBL** 111 dBL** 153 dB**	Change in the movement behaviour of fishes [23, 24]	195 dB* 147 dB‡	Change in movement behaviour in the presence of sonar signals [39]	137 dB*
			Changes in spatial movement and orientation [8–10]	142 dB** 135 dB* 90 dB*	Reduction in local abundance and catch rate [25]	248 dB†	Auditory threshold shift in fish exposed to low frequency active (LFA) sonar [40, 41]	193 dB† 195 dB*
			Changes in territorial and social behaviour [11, 12]	161 dBL** 127 dB*	Damage to fish ears [26, 27]	180 dB* 174 dB‡		
			Temporary loss in hearing [13]	142 dBL**				
Mammals	Adjustments to vocalisation and singing behaviour [1–3]	110 dB# 105 dB* 117 dB#	Loss of communication space [14]	166 dB*	Changes in movement behaviour [28–32]	184 dB* 170 dB? 116 dB** 107 dB** 139 dB‡	Change in auditory response [42–45]	196 dB+ 67 dB* 75 dB* 210 dB‡
	Changes in the proportion of time spent feeding and milling [4]	60 dB*	Adjustment to vocalisation and singing behaviour [15, 16]	110 dB* 135 dB* 95 dB*	Shifts in hearing thresholds after exposure to seismic airguns [33]	226 dB+	Disruption in trained behaviour [46, 47]	150 dB* 175 dB*
			Increase in stress hormones [17]		Changes in vocalisations [34, 35]	82 dB# 116 dB#		
			Change in spatial movement patterns [18–20]	78 dB* 161 dB* 74 dB*			Change in spatial distribution and behaviour [48–51]	128 dB# 140 dB* 89 dB* 116 dB+
Invertebrates			Increase in larvae settlement [21]	100 dB*	Damage to sensory systems in cephalopod [36]	157 dB*		
			Disruption of foraging and anti-predator behaviour [22]	145 dB*	Development delays and body malformations [37, 38]	136 dB* 145 dB*		

Symbols: * sound pressure level (SPL); ** equivalent continuous sound level (Leq); † SPL max (Lmax, peak SPL); ‡ sound exposure level (SEL); + SPL peak–peak.

See Appendices S1 and S2 for acoustic metric definitions.

[1] Holt, Noren, & Emmons (2011); [2] Parks *et al.* (2011); [3] Scheifele *et al.* (2005); [4] Miksis-Olds & Wagner (2011); [5] Codarin *et al.* (2009); [6] Vasconcelos, Amorim, & Ladich (2007); [7] Wysocki, Dittami, & Ladich (2006); [8] Picciulin *et al.* (2010); [9] Sarà *et al.* (2007); [10] Holles *et al.* (2013); [11] Sebastianutto *et al.* (2011); [12] Bruintjes & Radford (2013); [13] Liu *et al.* (2013); [14] Hatch *et al.* (2012); [15] Holt *et al.* (2009); [16] Melcón *et al.* (2012); [17] Rolland *et al.* (2012); [18] Lemon *et al.* (2006); [19] de Soto *et al.* (2006); [20] Tripovich *et al.* (2012); [21] Wilkens, Stanley, & Jeffs (2012); [22] Wale *et al.* (2013); [23] Wardle *et al.* (2001); [24] Fewtrell & McCauley (2012); [25] Engås *et al.* (1996); [26] McCauley, Fewtrell, & Popper (2003); [27] Casper *et al.* (2013); [28] Brandt *et al.* (2011); [29] Goold (1996); [30] Kastelein *et al.* (2005); [31] Kastelein *et al.* (2006); [32] Dähne *et al.* (2013); [33] Finneran *et al.* (2002); [34] Risch *et al.* (2012); [35] Blackwell *et al.* (2013); [36] Solé *et al.* (2013); [37] de Soto *et al.* (2013); [38] Pine *et al.* (2012); [39] Doksæter *et al.* (2012); [40] Popper *et al.* (2007); [41] Halvorsen *et al.* (2013); [42] Finneran *et al.* (2000); [43] Kastelein, Hoek, & de Jong (2011*a*); [44] Kastelein, Hoek, & de Jong (2011*b*); [45] Mooney *et al.* (2009); [46] Houser, Martin, & Finneran (2013*a*); [47] Houser *et al.* (2013*b*); [48] McCarthy *et al.* (2011); [49] Tyack *et al.* (2011); [50] Deruiter *et al.* (2013*a*); [51] Deruiter *et al.* (2013*b*).

(5) Measure responses over a gradient of noise levels

Additional studies are needed that investigate a gradient of noise exposure rather than quiet *versus* loud treatments. A gradient design provides insight on the levels of noise at which a response is initiated and how the response changes with increasing noise levels. This design can also reveal how animals recover from exposure to noise, while exploring the relationship between levels and duration of noise exposure and habituation or sensitisation by different species.

(6) Evaluate mitigation measures

There is a need to evaluate the ecological benefit of mitigation measures in both terrestrial and aquatic environments. Technological innovations (such as quieter ship propellers, car and aeroplane engines, tyres, and asphalt), modifications to standard operations (e.g. slower ship and vehicle speeds, traffic flow control, road closures), and sound barriers can significantly reduce noise levels in a particular habitat; however the benefits to wildlife are not fully understood. For example, how long does a road need to be closed for the biological community to recover from traffic noise? Do the unintended consequences of sound barriers (e.g. fragmentation or acoustically reflective surfaces) outweigh the benefits (Parris & Schneider, 2009)? Further, design and implementation of mitigation methods should match the timing and locations of biological activity, particularly during biologically sensitive periods, such as breeding (e.g. lekking behaviour in sage grouse *Centrocercus urophasianus*; Blickley *et al.*, 2012*a,b*) or seasonal movement (e.g. spring migration in cetaceans; Patenaude *et al.*, 2002).

(7) Improve reporting of acoustic metrics

Identifying the conditions that elicit biological responses is impossible without exposure information. Relevant details should include specification of acoustic metrics, temporal characteristics of the measurement (duration of recordings), frequency range measured, weighting filters applied, and the reference pressure used. Additionally, recording equipment and measurement procedures (distances and duration) should be documented for the source and received levels. Spectral descriptions or graphics provide important detail on the dominant frequencies of the noise source and can be compared to the hearing sensitivities of different species. The current state of the literature limits proper meta-analytical approaches that would allow compilation, comparison, and projection.

VI. CONCLUSIONS

(1) The substantial body of scientific research reviewed here provides considerable evidence that anthropogenic noise is detrimental to wildlife and natural ecosystems.

(2) Expertise from a diverse range of disciplines is required to improve understanding of the impacts associated with noise, especially considering that the effects may be expressed from the cellular to the ecosystem level.

(3) It is essential that research on the effects of anthropogenic noise evolves to report acoustic metrics accurately, test gradients of noise exposure, measure long-term consequences of responses to noise, assess cumulative effects of disturbance, investigate effectiveness of mitigation measures and recovery from chronic noise exposure, and fill in gaps with more diverse taxonomic groups and noise sources.

(4) We provide a cumulate weight-of-evidence summary of the recent literature, an initial step in providing guidance for natural resource managers when evaluating anthropogenic impacts or developing conservation policy.

(5) The interface between marine mammal research, regulation, and mitigation regarding noise provides an exemplar for controlling impacts for other taxa and ecosystems (Southall *et al.*, 2007; Stokstad, 2014). While the strides taken in the past decades have been impressive and provide a solid basis for shaping this critically important field of research, future activities should attempt to manage these impacts on temporal and spatial scales relevant to wildlife.

VII. ACKNOWLEDGEMENTS

The National Park Service, Natural Sounds and Night Skies Division funded this study. We thank two anonymous referees for their helpful comments and A. Cooper and W. Foster for their editorial assistance.

VIII. REFERENCES

**References marked with asterisk have been cited within the supporting information*

*American National Standards Institute-ANSI (2004). Acoustical terminology. ANSI S1.1-1994 (R2004). Available at http://www.ansi.org/ Accessed 15.08.2014.

American National Standards Institute-ANSI (2005). Quantities and procedures for description and measurement of environmental sound, noise assessment and prediction of long-term community response). ANSI S12.9-4. Available at http://www.ansi.org/ Accessed 15.08.2014.

*Amoser, S., Wysocki, L. E. & Ladich, F. (2004). Noise emission during the first powerboat race in an Alpine lake and potential impact on fish communities. *The Journal of the Acoustical Society of America* **116**, 3789–3797.

*Anderson, P. A., Berzins, I. K., Fogarty, F., Hamlin, H. J. & Guillette, L. J. (2011). Sound, stress, and seahorses: the consequences of a noisy environment to animal health. *Aquaculture* **311**, 129–138.

*André, M., Solé, M., Lenoir, M., Durfort, M., Quero, C., Mas, A., Lombarte, A., van der Schaar, M., López-Bejar, M., Morell, M., Zaugg, S. & Houégnigan, L. (2011). Low-frequency sounds induce acoustic trauma in cephalopods. *Frontiers in Ecology and the Environment* **9**, 489–493.

Arévalo, J. E. & Newhard, K. (2011). Traffic noise affects forest bird species in a protected tropical forest. *Revista de Biología Tropical* **59**, 969–980.

Arroyo-Solís, A., Castillo, J. M., Figueroa, E., López-Sánchez, J. L. & Slabbekoorn, H. (2013). Experimental evidence for an impact of anthropogenic noise on dawn chorus timing in urban birds. *Journal of Avian Biology* **44**, 288–296.

Babisch, W., Beule, B., Schust, M., Kersten, N. & Ising, H. (2005). Traffic noise and risk of myocardial infarction. *Epidemiology* **16**, 33–40.

*Baldwin, A. L., Primeau, R. L. & Johnson, W. E. (2006). Effect of noise on the morphology of the intestinal mucosa in laboratory rats. *Journal of the American Association for Laboratory Animal Science* **45**, 74–82.

Barber, J. R., Crooks, K. R. & Fristrup, K. M. (2010). The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology & Evolution* **25**, 180–189.

Bayne, E. M., Habib, L. & Boutin, S. (2008). Impacts of chronic anthropogenic noise from energy-sector activity on abundance of songbirds in the boreal forest. *Conservation Biology* **22**, 1186–1193.

*Becker, A., Whitfield, A. K., Cowley, P. D., Järnegren, J. & Næsje, T. F. (2013). Does boat traffic cause displacement of fish in estuaries? *Marine Pollution Bulletin* **75**, 168–173.

Bee, M. A. & Swanson, E. M. (2007). Auditory masking of anuran advertisement calls by road traffic noise. *Animal Behaviour* **74**, 1765–1776.

Bermúdez-Cuamatzin, E., Ríos-Chelén, A. A., Gil, D. & Garcia, C. M. (2009). Strategies of song adaptation to urban noise in the house finch: syllable pitch plasticity or differential syllable use? *Behaviour* **146**, 1269–1286.

Bermúdez-Cuamatzin, E., Ríos-Chelén, A. A., Gil, D. & Garcia, C. M. (2011). Experimental evidence for real-time song frequency shift in response to urban noise in a passerine bird. *Biology Letters* **7**, 36–38.

*Birke, L. (2002). Effects of browse, human visitors and noise on the behaviour of captive orang utans. *Animal Welfare* **11**, 189–202.

Blackwell, S. B., Nations, C. S., McDonald, T. L., Greene, C. R., Thode, A. M., Guerra, M. & Michael Macrander, A. (2013). Effects of airgun sounds on bowhead whale calling rates in the Alaskan Beaufort Sea. *Marine Mammal Science* **29**, 342–365.

Blickley, J. L., Blackwood, D. & Patricelli, G. L. (2012*a*). Experimental evidence for the effects of chronic anthropogenic noise on abundance of greater sage-grouse at leks. *Conservation Biology* **26**, 461–471.

Blickley, J. L., Word, K. R., Krakauer, A. H., Phillips, J. L., Sells, S. N., Taff, C. C., Wingfield, J. C. & Patricelli, G. L. (2012*b*). Experimental chronic noise is related to elevated fecal corticosteroid metabolites in lekking male greater sage-grouse (*Centrocercus urophasianus*). *PLoS ONE* **7**, e50462.

Bloom, D. E. (2011). 7 billion and counting. *Science* **333**, 562–569.

*Bowles, A. E., Smultea, M., Würsig, B., DeMaster, D. P. & Palka, D. (1994). Relative abundance and behavior of marine mammals exposed to transmissions from the Heard Island Feasibility Test. *The Journal of the Acoustical Society of America* **96**, 2469–2484.

Boyd, I., Brownell, B., Cato, D., Clarke, C., Costa, D., Eveans, P. G. H., Gedamke, J., Genrty, R., Gisiner, B., Gordon, J., Jepson, P., Miller, P., Rendell, L., Tasker, M., Tyack, P., Vos, E., Whitehead, H., Wartzok, D. & Zimmer, W. (2008). *The Effects of Anthropogenic Sound on Marine Mammals – A Draft Research Strategy*. European Science Foundation and Marine Board, Oxford.

Bracciali, C., Campobello, D., Giacoma, C. & Sarà, G. (2012). Effects of nautical traffic and noise on foraging patterns of Mediterranean damselfish (*Chromis chromis*). *PLoS ONE* **7**, e40582.

Brandt, M. J., Diederichs, A., Betke, K. & Nehls, G. (2011). Responses of harbour porpoises to pile driving at the Horns Rev II offshore wind farm in the Danish North Sea. *Marine Ecology Progress Series* **421**, 205–216.

*Branstetter, B. K., Trickey, J. S., Bakhtiari, K., Black, A., Aihara, H. & Finneran, J. J. (2013). Auditory masking patterns in bottlenose dolphins (*Tursiops truncatus*) with natural, anthropogenic, and synthesized noise. *The Journal of the Acoustical Society of America* **133**, 1811–1818.

*Breeden, J. B., Hernández, F., Bingham, R. L., Silvy, N. J. & Waggerman, G. L. (2008). Effects of traffic noise on auditory surveys of urban White-winged Doves. *The Wilson Journal of Ornithology* **120**, 384–389.

*Brown, A. L. (1990). Measuring the effect of aircraft noise on sea birds. *Environment International* **16**, 587–592.

Brown, C. L., Hardy, A. R., Barber, J. R., Fristrup, K. M., Crooks, K. R. & Angeloni, L. M. (2012). The effect of human activities and their associated noise on ungulate behavior. *PLoS ONE* **7**, e40505.

Bruintjes, R. & Radford, A. N. (2013). Context-dependent impacts of anthropogenic noise on individual and social behaviour in a cooperatively breeding fish. *Animal Behaviour* **85**, 1343–1349.

Brumm, H. (2004). The impact of environmental noise on song amplitude in a territorial bird. *Journal of Animal Ecology* **73**, 434–440.

Brumm, H. & Slabbekoorn, H. (2005). Acoustic communication in noise. *Advances in the Study of Behavior* **35**, 151–209.

*Buckstaff, K. C. (2004). Effects of watercraft noise on the acoustic behavior of bottlenose dolphins, Tursiops truncatus, in Sarasota Bay, Florida. *Marine Mammal Science* **20**, 709–725.

*Byrnes, P., Goosem, M. & Turton, S. M. (2012). Are less vocal rainforest mammals susceptible to impacts from traffic noise? *Wildlife Research* **39**, 355–365.

Casper, B. M., Smith, M. E., Halvorsen, M. B., Sun, H., Carlson, T. J. & Popper, A. N. (2013). Effects of exposure to pile driving sounds on fish inner ear tissues. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* **166**, 352–360.

*Castellote, M., Clark, C. W. & Lammers, M. O. (2012). Acoustic and behavioural changes by fin whales (*Balaenoptera physalus*) in response to shipping and airgun noise. *Biological Conservation* **147**, 115–122.

Chan, A. A. Y. H., Giraldo-Perez, P., Smith, S. & Blumstein, D. T. (2010). Anthropogenic noise affects risk assessment and attention: the distracted prey hypothesis. *Biology Letters* **6**, 458–461.

Chapman, D. M. & Ellis, D. D. (1998). The elusive decibel: thoughts on sonars and marine mammals. *Canadian Acoustics* **26**, 29–31.

Chepesiuk, R. (2005). Decibel hell. *Environmental Health Perspectives* **113**, 35–41.

Codarin, A., Wysocki, L. E., Ladich, F. & Picciulin, M. (2009). Effects of ambient and boat noise on hearing and communication in three fish species living in a marine protected area (Miramare, Italy). *Marine Pollution Bulletin* **58**, 1880–1887.

Conomy, J. T., Dubovsky, J. A., Collazo, J. A. & Fleming, W. J. (1998). Do black ducks and wood ducks habituate to aircraft disturbance? *The Journal of Wildlife Management* **62**, 1135–1142.

Crino, O. L., Johnson, E. E., Blickley, J. L., Patricelli, G. L. & Breuner, C. W. (2013). Effects of experimentally elevated traffic noise on nestling white-crowned sparrow stress physiology, immune function and life history. *The Journal of Experimental Biology* **216**, 2055–2062.

*Croll, D. A., Clark, C. W., Calambokidis, J., Ellison, W. T. & Tershy, B. R. (2001). Effect of anthropogenic low-frequency noise on the foraging ecology of Balaenoptera whales. *Animal Conservation* **4**, 13–27.

*Culik, B. M., Koschinski, S., Tregenza, N. & Ellis, G. M. (2001). Reactions of harbor porpoises *Phocoena phocoena* and herring *Clupea harengus* to acoustic alarms. *Marine Ecology Progress Series* **211**, 255–260.

Cunnington, G. M. & Fahrig, L. (2010). Plasticity in the vocalizations of anurans in response to traffic noise. *Acta Oecologica* **36**, 463–470.

Dähne, M., Gilles, A., Lucke, K., Peschko, V., Adler, S., Krügel, K., Sundermeyer, J. & Siebert, U. (2013). Effects of pile-driving on harbour porpoises (*Phocoena phocoena*) at the first offshore wind farm in Germany. *Environmental Research Letters* **8**, 025002.

David, J. A. (2006). Likely sensitivity of bottlenose dolphins to pile-driving noise. *Water and Environment Journal* **20**, 48–54.

*Delaney, D. K., Grubb, T. G., Beier, P., Pater, L. L. & Reiser, M. H. (1999). Effects of helicopter noise on Mexican spotted owls. *The Journal of Wildlife Management* **63**, 60–76.

Delaney, D. K., Pater, L. L., Carlile, L. D., Spadgenske, E. W., Beaty, T. A. & Melton, R. H. (2011). Response of red-cockaded woodpeckers to military training operations. *Wildlife Monographs* **177**, 1–38.

*De Robertis, A., Hjellvik, V., Williamson, N. J. & Wilson, C. D. (2008). Silent ships do not always encounter more fish: comparison of acoustic backscatter recorded by a noise-reduced and a conventional research vessel. *ICES Journal of Marine Science* **65**, 623–635.

DeRuiter, S. L., Boyd, I. L., Claridge, D. E., Clark, C. W., Gagnon, C., Southall, B. L. & Tyack, P. L. (2013*a*). Delphinid whistle production and call matching during playback of simulated military sonar. *Marine Mammal Science* **29**, 46–59.

DeRuiter, S. L., Southall, B. L., Calambokidis, J., Zimmer, W. M. X., Sadykova, D., Falcone, E. A., Friedlaender, A. S., Joseph, J. E., Moretti, D., Schorr, G. S., Thomas, L. & Tyack, P. L. (2013*b*). First direct measurements of behavioural responses by Cuvier's beaked whales to mid-frequency active sonar. *Biology Letters* **9**, 20130223.

Diaz, M., Parra, A. & Gallardo, C. (2011). Serins respond to anthropogenic noise by increasing vocal activity. *Behavioral Ecology* **22**, 332–336.

Di' Iorio, L. & Clark, C. W. (2010). Exposure to seismic survey alters blue whale acoustic communication. *Biology Letters* **6**, 51–54.

Doksæter, L., Handegard, N. O., Godø, O. R., Kvadsheim, P. H. & Nordlund, N. (2012). Behavior of captive herring exposed to naval sonar transmissions (1.0–1.6 kHz) throughout a yearly cycle. *The Journal of the Acoustical Society of America* **131**, 1632–1642.

Doksæter, L., Rune Godø, O., Olav Handegard, N., Kvadsheim, P. H., Lam, F.-P. A., Donovan, C. & Miller, P. J. O. (2009). Behavioral responses of herring (*Clupea harengus*) to 1–2 and 6–7 kHz sonar signals and killer whale feeding sounds. *The Journal of the Acoustical Society of America* **125**, 554–564.

*Doresky, J., Morgan, K., Ragsdale, L., Townsend, H., Barron, M. & West, M. (2001). Effects of military activity on reproductive success of red-cockaded woodpeckers. *Journal of Field Ornithology* **72**, 305–311.

Dowling, J. L., Luther, D. A. & Marra, P. P. (2012). Comparative effects of urban development and anthropogenic noise on bird songs. *Behavioral Ecology* **23**, 201–209.

*Duarte, M. H., Vecci, M. A., Hirsch, A. & Young, R. J. (2011). Noisy human neighbours affect where urban monkeys live. *Biology Letters* **7**, 840–842.

*Egnor, S. R., Wickelgren, J. G. & Hauser, M. D. (2007). Tracking silence: adjusting vocal production to avoid acoustic interference. *Journal of Comparative Physiology A* **193**, 477–483.

*Ellis, D. H., Ellis, C. H. & Mindell, D. P. (1991). Raptor responses to low-level jet aircraft and sonic booms. *Environmental Pollution* **74**, 53–83.

Ellison, W. T., Southall, B. L., Clark, C. W. & Frankel, A. S. (2012). A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds. *Conservation Biology* **26**, 21–28.

Engås, A., Løkkeborg, S., Ona, E. & Soldal, A. V. (1996). Effects of seismic shooting on local abundance and catch rates of cod (*Gadus morhua*) and haddock) (*Melanogrammus aeglefinus*). *Canadian Journal of Fisheries and Aquatic Sciences* **53**, 2238–2249.

EPA (1974). Information on levels of environmental noise requisite to protect public health and welfare with an adequate margin of safety. EPA/ONAC 550/9-74-004. United States Environmental Protection Agency, Washington, DC.

Fewtrell, J. L. & McCauley, R. D. (2012). Impact of air gun noise on the behaviour of marine fish and squid. *Marine Pollution Bulletin* **64**, 984–993.

*Filiciotto, F., Giacalone, V. M., Fazio, F., Buffa, G., Piccione, G., Maccarrone, V., Di Stefano, V., Mazzola, S. & Buscaino, G. (2013). Effect of acoustic environment on gilthead sea bream (*Sparus aurata*): sea and onshore aquaculture background noise. *Aquaculture* **414**, 36–45.

Finneran, J. J., Schlundt, C. E., Carder, D. A., Clark, J. A., Young, J. A., Gaspin, J. B. & Ridgway, S. H. (2000). Auditory and behavioral responses of bottlenose dolphins (*Tursiops truncatus*) and a beluga whale (*Delphinapterus leucas*) to impulsive sounds resembling distant signatures of underwater explosions. *The Journal of the Acoustical Society of America* **108**, 417–431.

Finneran, J. J., Schlundt, C. E., Dear, R., Carder, D. A. & Ridgway, S. H. (2002). Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. *The Journal of the Acoustical Society of America* **111**, 2929–2940.

Fontana, C. S., Burger, M. I. & Magnusson, W. E. (2011). Bird diversity in a subtropical South-American City: effects of noise levels, arborisation and human population density. *Urban Ecosystems* **14**, 341–360.

*Foote, A. D., Osborne, R. W. & Hoelzel, A. R. (2004). Environment: whale-call response to masking boat noise. *Nature* **428**, 910.

Francis, C. D. & Barber, J. R. (2013). A framework for understanding noise impacts on wildlife: an urgent conservation priority. *Frontiers in Ecology and the Environment* **11**, 305–313.

Francis, C. D., Kleist, N. J., Ortega, C. P. & Cruz, A. (2012). Noise pollution alters ecological services: enhanced pollination and disrupted seed dispersal. *Proceedings of the Royal Society of London B: Biological Sciences* **279**, 2727–2735.

Francis, C. D., Ortega, C. P. & Cruz, A. (2009). Noise pollution changes avian communities and species interactions. *Current Biology* **19**, 1415–1419.

*Francis, C. D., Ortega, C. P. & Cruz, A. (2011*a*). Different behavioural responses to anthropogenic noise by two closely related passerine birds. *Biology Letters* **7**, 850–852.

*Francis, C. D., Ortega, C. P. & Cruz, A. (2011*b*). Noise pollution filters bird communities based on vocal frequency. *PLoS ONE* **6**, e27052.

*Francis, C. D., Ortega, C. P. & Cruz, A. (2011*c*). Vocal frequency change reflects different responses to anthropogenic noise in two suboscine tyrant flycatchers. *Proceedings of the Royal Society B: Biological Sciences* **278**, 2025–2031.

*Francis, C. D., Paritsis, J., Ortega, C. P. & Cruz, A. (2011*d*). Landscape patterns of avian habitat use and nest success are affected by chronic gas well compressor noise. *Landscape Ecology* **26**, 1269–1280.

*Frantzis, A. (1998). Does acoustic testing strand whales? *Nature* **392**, 29.

*Fristrup, K. M., Hatch, L. T. & Clark, C. W. (2003). Variation in humpback whale (*Megaptera novaeangliae*) song length in relation to low-frequency sound broadcasts. *The Journal of the Acoustical Society of America* **113**, 3411–3424.

Fritschi, L., Brown, A. L., Kim, R., Schwela, D. H. & Kephalopoulos, S. (2011). *Burden of Disease from Environmental Noise – Quantification of Healthy Life Years Lost in Europe*. WHO European Centre for Environment and Health, Bonn Office, Copenhagen, Denmark. Available at http://www.who.int/quantifying_ehimpacts/publications/e94888/en/ Accessed 15.08.2014.

Fuller, R. A., Warren, P. H. & Gaston, K. J. (2007). Daytime noise predicts nocturnal singing in urban robins. *Biology Letters* **3**, 368–370.

Fyhri, A. & Aasvang, G. M. (2010). Noise, sleep and poor health: modeling the relationship between road traffic noise and cardiovascular problems. *Science of the Total Environment* **408**, 4935–4942.

*Gailey, G., Würsig, B. & McDonald, T. L. (2007). Abundance, behavior, and movement patterns of western gray whales in relation to a 3-D seismic survey, Northeast Sakhalin Island, Russia. *Environmental Monitoring and Assessment* **134**, 75–91.

Gill, S. A., Job, J. R., Myers, K., Naghshineh, K. & Vonhof, M. J. (2015). Toward a broader characterization of anthropogenic noise and its effects on wildlife. *Behavioral Ecology* **26**, 328–333.

Goerlitz, H. R., Greif, S. & Siemers, B. M. (2008). Cues for acoustic detection of prey: insect rustling sounds and the influence of walking substrate. *Journal of Experimental Biology* **211**, 2799–2806.

Goldbogen, J. A., Southall, B. L., DeRuiter, S. L., Calambokidis, J., Friedlaender, A. S., Hazen, E. L., Falcone, E. A., Schorr, G. S., Douglas, A., Moretti, D. J., Kyburg, C., McKenna, M. F. & Tyack, P. L. (2013). Blue whales respond to simulated mid-frequency military sonar. *Proceedings of the Royal Society of London B: Biological Sciences* **280**, 20130657.

González-Oreja, J. A., De La Fuente-Díaz, A. A., Hernández-Santín, L., Bonache-Regidor, C. & Buzo-Franco, D. (2012). Can human disturbance promote nestedness? Songbirds and noise in urban parks as a case study. *Landscape and Urban Planning* **104**, 9–18.

Goodwin, S. E. & Podos, J. (2013). Shift of song frequencies in response to masking tones. *Animal Behaviour* **85**, 435–440.

Goodwin, S. E. & Shriver, W. G. (2011). Effects of traffic noise on occupancy patterns of forest birds. *Conservation Biology* **25**, 406–411.

Goold, J. C. (1996). Acoustic assessment of populations of common dolphin Delphinus delphis in conjunction with seismic surveying. *Journal of the Marine Biological Association of the United Kingdom* **76**, 811–820.

Goudie, R. & Jones, I. L. (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.

*Graham, A. L. & Cooke, S. J. (2008). The effects of noise disturbance from various recreational boating activities common to inland waters on the cardiac physiology of a freshwater fish, the largemouth bass (*Micropterus salmoides*). *Aquatic Conservation: Marine and Freshwater Ecosystems* **18**, 1315–1324.

Gross, K., Pasinelli, G. & Kunc, H. P. (2010). Behavioral plasticity allows short-term adjustment to a novel environment. *The American Naturalist* **176**, 456–464.

*Grubb, T. G., Pater, L. L., Gatto, A. E. & Delaney, D. K. (2013). Response of nesting northern goshawks to logging truck noise in northern Arizona. *The Journal of Wildlife Management* **77**, 1618–1625.

*Gutscher, M., Wysocki, L. E. & Ladich, F. (2011). Effects of aquarium and pond noise on hearing sensitivity in an otophysine fish. *Bioacoustics* **20**, 117–136.

Habib, L., Bayne, E. M. & Boutin, S. (2006). Chronic industrial noise affects pairing success and age structure of ovenbirds *Seiurus aurocapilla*. *Journal of Applied Ecology* **44**, 176–184.

Hage, S. R., Jiang, T., Berquist, S. W., Feng, J. & Metzner, W. (2013). Ambient noise induces independent shifts in call frequency and amplitude within the Lombard effect in echolocating bats. *Proceedings of the National Academy of Sciences* **110**, 4063–4068.

Halfwerk, W., Bot, S., Buikx, J., van der Velde, M., Komdeur, J., ten Cate, C. & Slabbekoorn, H. (2011*a*). Low-frequency songs lose their potency in noisy urban conditions. *Proceedings of the National Academy of Sciences* **108**, 14549–14554.

Halfwerk, W., Holleman, L. J., Lessells, C. K. & Slabbekoorn, H. (2011*b*). Negative impact of traffic noise on avian reproductive success. *Journal of Applied Ecology* **48**, 210–219.

Halfwerk, W. & Slabbekoorn, H. (2009). A behavioural mechanism explaining noise-dependent frequency use in urban birdsong. *Animal Behaviour* **78**, 1301–1307.

Halpern, B. S., Walbridge, S., Selkoe, K. A., Kappel, C. V., Micheli, F., D'Agrosa, C., Bruno, J. F., Casey, K. S., Ebert, C., Fox, H. E., Fujita, R., Heinemann, D., Lenihan, H. S., Madin, E. M. P., et al. (2008). A global map of human impact on marine ecosystems. *Science* **319**, 948–952.

Halvorsen, M. B., Zeddies, D. G., Chicoine, D. & Popper, A. N. (2013). Effects of low-frequency naval sonar exposure on three species of fish. *The Journal of the Acoustical Society of America* **134**, 205–210.

Hansell, A. L., Blangiardo, M., Fortunato, L., Floud, S., de Hoogh, K., Fecht, D., Ghosh, R. E., Laszlo, H. E., Pearson, C., Beale, L., Beevers, S., Gulliver, J., Best, N., Richardson, S. & Elliott, P. (2013). Aircraft noise and cardiovascular disease near Heathrow airport in London: small area study. *British Medical Journal* **347**, f5432.

*Harris, R. E., Miller, G. W. & Richardson, W. J. (2001). Seal responses to airgun sounds during summer seismic surveys in the Alaskan Beaufort Sea. *Marine Mammal Science* **17**, 795–812.

Hatch, L. T., Clark, C. W., Van Parijs, S. M., Frankel, A. S. & Ponirakis, D. W. (2012). Quantifying loss of acoustic communication space for right whales in and around a U.S. National Marine Sanctuary. *Conservation Biology* **26**, 983–994.

*Herrera-Montes, M. I. & Aide, T. M. (2011). Impacts of traffic noise on anuran and bird communities. *Urban Ecosystems* **14**, 415–427.

Hildebrand, J. A. (2009). Anthropogenic and natural sources of ambient noise in the ocean. *Marine Ecology Progress Series* **395**, 5–20.

Holles, S., Simpson, S. D., Radford, A. N., Berten, L. & Lecchini, D. (2013). Boat noise disrupts orientation behaviour in a coral reef fish. *Marine Ecology Progress Series* **485**, 295–300.

Holt, M. M., Noren, D. P. & Emmons, C. K. (2011). Effects of noise levels and call types on the source levels of killer whale calls. *The Journal of the Acoustical Society of America* **130**, 3100–3106.

Holt, M. M., Noren, D. P., Veirs, V., Emmons, C. K. & Veirs, S. (2009). Speaking up: killer whales (*Orcinus orca*) increase their call amplitude in response to vessel noise. *The Journal of the Acoustical Society of America* **125**, 27–32.

Hotchkin, C. & Parks, S. (2013). The Lombard effect and other noise-induced vocal modifications: insight from mammalian communication systems. *Biological Reviews* **4**, 809–824.

Houser, D. S., Martin, S. W. & Finneran, J. J. (2013*a*). Behavioral responses of California sea lions to mid-frequency (3250–3450 Hz) sonar signals. *Marine Environmental Research* **92**, 268–278.
Houser, D. S., Martin, S. W. & Finneran, J. J. (2013*b*). Exposure amplitude and repetition affect bottlenose dolphin behavioral responses to simulated mid-frequency sonar signals. *Journal of Experimental Marine Biology and Ecology* **443**, 123–133.
*Hovem, J. M., Tronstad, T. V., Karlsen, H. E. & Lokkeborg, S. (2012). Modeling propagation of seismic airgun sounds and the effects on fish behavior. *IEEE Journal of Oceanic Engineering* **37**, 576–588.
*Hu, Y. & Cardoso, G. C. (2009). Are bird species that vocalize at higher frequencies preadapted to inhabit noisy urban areas? *Behavioral Ecology* **20**, 1268–1273.
Hu, Y. & Cardoso, G. C. (2010). Which birds adjust the frequency of vocalizations in urban noise? *Animal Behaviour* **79**, 863–867.
*Huffeldt, N. P. & Dabelsteen, T. (2013). Impact of a noise-polluted urban environment on the song frequencies of a cosmopolitan songbird, the Great Tit (*Parus major*), in Denmark. *Ornis Fennica* **90**, 94–102.
*Iglesias, C., Mata, C. & Malo, J. E. (2012). The influence of traffic noise on vertebrate road crossing through underpasses. *Ambio* **41**, 193–201.
Jenkins, C. N., Pimm, S. L. & Joppa, L. N. (2013). Global patterns of terrestrial vertebrate diversity and conservation. *Proceedings of the National Academy of Sciences of the United States of America* **110**, 2602–2610.
*Jung, C. A. & Swearer, S. E. (2011). Reactions of temperate reef fish larvae to boat sound. *Aquatic Conservation: Marine and Freshwater Ecosystems* **21**, 389–396.
Kaiser, K., Scofield, D. G., Alloush, M., Jones, R. M., Marczak, S., Martineau, K., Oliva, M. A. & Narins, P. M. (2011). When sounds collide: the effect of anthropogenic noise on a breeding assemblage of frogs in Belize, Central America. *Behaviour* **148**, 215–232.
*Kane, A. S., Song, J., Halvorsen, M. B., Miller, D. L., Salierno, J. D., Wysocki, L. E., Zeddies, D. & Popper, A. N. (2010). Exposure of fish to high-intensity sonar does not induce acute pathology. *Journal of Fish Biology* **76**, 1825–1840.
*Karp, D. S. & Guevara, R. (2011). Conversational noise reduction as a win–win for ecotourists and rain forest birds in Peru. *Biotropica* **43**, 122–130.
Karp, D. S. & Root, T. L. (2009). Sound the stressor: how Hoatzins (*Opisthocomus hoazin*) react to ecotourist conversation. *Biodiversity and Conservation* **18**, 3733–3742.
Kaseloo, P. A. & Tyson, K. O. (2004). *Synthesis of Noise Effects on Wildlife Populations*. US Department of Transportation, Federal Highway Administration, Washington, DC.
*Kastak, D., Schusterman, R. J., Southall, B. L. & Reichmuth, C. J. (1999). Underwater temporary threshold shift induced by octave-band noise in three species of pinniped. *The Journal of the Acoustical Society of America* **106**, 1142–1148.
*Kastelein, R. A., De Haan, D., Vaughan, N., Staal, C. & Schooneman, N. M. (2001). The influence of three acoustic alarms on the behaviour of harbour porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research* **52**, 351–371.
Kastelein, R. A., Hoek, L. & de Jong, C. A. (2011*a*). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for helicopter dipping sonar signals (1.43–1.33 kHz) (L). *The Journal of the Acoustical Society of America* **130**, 679–682.
Kastelein, R. A., Hoek, L. & de Jong, C. A. (2011*b*). Hearing thresholds of a harbor porpoise (*Phocoena phocoena*) for sweeps (1–2 kHz and 6–7 kHz bands) mimicking naval sonar signals. *The Journal of the Acoustical Society of America* **129**, 3393–3399.
Kastelein, R. A., van der Heul, S., van der Veen, J., Verboom, W. C., Jennings, N., de Haan, D. & Reijnders, P. J. (2007). Effects of acoustic alarms, designed to reduce small cetacean bycatch in gillnet fisheries, on the behaviour of North Sea fish species in a large tank. *Marine Environmental Research* **64**, 160–180.
*Kastelein, R. A., van der Heul, S., Verboom, W. C., Jennings, N., van der Veen, J. & de Haan, D. (2008). Startle response of captive North Sea fish species to underwater tones between 0.1 and 64 kHz. *Marine Environmental Research* **65**, 369–377.
Kastelein, R. A., van der Heul, S., Verboom, W. C., Triesscheijn, R. J. & Jennings, N. V. (2006). The influence of underwater data transmission sounds on the displacement behaviour of captive harbour seals (*Phoca vitulina*). *Marine Environmental Research* **61**, 19–39.
*Kastelein, R. A., Verboom, W. C., Muijsers, M., Jennings, N. V. & Van der Heul, S. (2005). The influence of acoustic emissions for underwater data transmission on the behaviour of harbour porpoises (*Phocoena phocoena*) in a floating pen. *Marine Environmental Research* **59**, 287–307.
Kight, C. R., Saha, M. S. & Swaddle, J. P. (2012). Anthropogenic noise is associated with reductions in the productivity of breeding Eastern bluebirds (*Sialia sialis*). *Ecological Applications* **22**, 1989–1996.
Kight, C. R. & Swaddle, J. P. (2011). How and why environmental noise impacts animals: an integrative, mechanistic review. *Ecology Letters* **14**, 1052–1061.
*Klinck, H., Nieukirk, S. L., Mellinger, D. K., Klinck, K., Matsumoto, H. & Dziak, R. P. (2012). Seasonal presence of cetaceans and ambient noise levels in polar waters of the North Atlantic. *The Journal of the Acoustical Society of America* **132**, 176–181.
*Koschinski, S., Culik, B. M., Henriksen, O. D., Tregenza, N., Ellis, G., Jansen, C. & Kathe, G. (2003). Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. *Marine Ecology Progress Series* **265**, 263–273.
*Krausman, P. R., Harris, L. K., Blasch, C. L., Koenen, K. K. & Francine, J. (2004). Effects of military operations on behavior and hearing of endangered Sonoran pronghorn. *Wildlife Monographs* **157**, 1–41.
Krausman, P. R., Wallace, M. C., Hayes, C. L. & DeYoung, D. W. (1998). Effects of jet aircraft on mountain sheep. *The Journal of Wildlife Management* **62**, 1246–1254.
Kuningas, S., Kvadsheim, P. H., Lam, F. P. A. & Miller, P. J. O. (2013). Killer whale presence in relation to naval sonar activity and prey abundance in northern Norway. *ICES Journal of Marine Science* **70**, 1287–1293.
*Kvadsheim, P. H., Sevaldsen, E. M., Folkow, L. P. & Blix, A. S. (2010). Behavioural and physiological responses of hooded seals (*Cystophora cristata*) to 1 to 7 kHz sonar signals. *Aquatic Mammals* **36**, 239–247.
*Ladich, F. & Schulz-Mirbach, T. (2013). Hearing in cichlid fishes under noise conditions. *PLoS ONE* **8**, e57588.
*La Manna, G., Manghi, M., Pavan, G., Lo Mascolo, F. & Sarà, G. (2013). Behavioural strategy of common bottlenose dolphins (*Tursiops truncatus*) in response to different kinds of boats in the waters of Lampedusa Island (Italy). *Aquatic Conservation: Marine and Freshwater Ecosystems* **23**, 745–757.
Lampe, U., Schmoll, T., Franzke, A. & Reinhold, K. (2012). Staying tuned: grasshoppers from noisy roadside habitats produce courtship signals with elevated frequency components. *Functional Ecology* **26**, 1348–1354.
*Leader, N., Wright, J. & Yom-Yov, Y. (2005). Acoustic properties of two urban song dialects in the orange-tufted sunbird (*Nectarinia osea*). *The Auk* **122**, 231–245.
Leighton, T. G. (2012). How can humans, in air, hear sound generated underwater (and can goldfish hear their owners talking)? *The Journal of the Acoustical Society of America* **131**, 2539–2542.
Lemon, M., Lynch, T. P., Cato, D. H. & Harcourt, R. G. (2006). Response of travelling bottlenose dolphins (*Tursiops aduncus*) to experimental approaches by a powerboat in Jervis Bay, New South Wales, Australia. *Biological Conservation* **127**, 363–372.
Lengagne, T. (2008). Traffic noise affects communication behaviour in a breeding anuran, *Hyla arborea*. *Biological Conservation* **141**, 2023–2031.
*Leonard, M. L. & Horn, A. G. (2008). Does ambient noise affect growth and begging call structure in nestling birds? *Behavioral Ecology* **19**, 502–507.
*Leonard, M. L. & Horn, A. G. (2012). Ambient noise increases missed detections in nestling birds. *Biology Letters* **8**, 530–532.
*Le Roux, D. S. L. & Waas, J. R. (2012). Do long-tailed bats alter their evening activity in response to aircraft noise? *Acta Chiropterologica* **14**, 111–120.
*Lesage, V., Barrette, C., Kingsley, M. & Sjare, B. (1999). The effect of vessel noise on the vocal behavior of belugas in the St. Lawrence River estuary, Canada. *Marine Mammal Science* **15**, 65–84.
Liu, M., Wei, Q. W., Du, H., Fu, Z. Y. & Chen, Q. C. (2013). Ship noise-induced temporary hearing threshold shift in the Chinese sucker *Myxocyprinus asiaticus* (Bleeker, 1864). *Journal of Applied Ichthyology* **29**, 1416–1422.
*Lowry, H., Lill, A. & Wong, B. (2011). Tolerance of auditory disturbance by an avian urban adapter, the noisy miner. *Ethology* **117**, 490–497.
Lowry, H., Lill, A. & Wong, B. B. (2012). How noisy does a noisy miner have to be? Amplitude adjustments of alarm calls in an avian urban 'adapter'. *PLoS ONE* **7**, e29960.
Luther, D. & Baptista, L. (2010). Urban noise and the cultural evolution of bird songs. *Proceedings of the Royal Society B: Biological Sciences* **277**, 469–473.
*Luther, D. A. & Derryberry, E. P. (2012). Birdsongs keep pace with city life: changes in song over time in an urban songbird affects communication. *Animal Behaviour* **83**, 1059–1066.
Luther, D. & Gentry, K. (2013). Sources of background noise and their influence on vertebrate acoustic communication. *Behaviour* **150**, 1045–1068.
Madsen, P. T. (2005). Marine mammals and noise: problems with root mean square sound pressure levels for transients. *The Journal of the Acoustical Society of America* **117**, 3952–3957.
*Madsen, P. T. & Møhl, B. (2000). Sperm whales (*Physeter catodon* L. 1758) do not react to sounds from detonators. *The Journal of the Acoustical Society of America* **107**, 668–671.
*Madsen, P. T., Møhl, B., Nielsen, B. K. & Wahlberg, M. (2002). Male sperm whale behaviour during exposures to distant seismic survey pulses. *Aquatic Mammals* **28**, 231–240.
*Maes, J. H. R. & de Groot, G. (2003). Effects of noise on the performance of rats in an operant discrimination task. *Behavioural Processes* **61**, 57–68.

Maier, J. A., Murphy, S. M., White, R. G. & Smith, M. D. (1998). Responses of caribou to overflights by low-altitude jet aircraft. *The Journal of Wildlife Management* **62**, 752–766.

McCarthy, E., Moretti, D., Thomas, L., DiMarzio, N., Morrissey, R., Jarvis, S., Ward, J., Izzi, A. & Dilley, A. (2011). Changes in spatial and temporal distribution and vocal behavior of Blainville's beaked whales (*Mesoplodon densirostris*) during multiship exercises with mid-frequency sonar. *Marine Mammal Science* **27**, 206–226.

McCauley, R. D., Fewtrell, J. & Popper, A. N. (2003). High intensity anthropogenic sound damages fish ears. *The Journal of the Acoustical Society of America* **113**, 638–642.

McClure, C. J. W., Ware, H. E., Carlisle, J., Kaltenecker, G. & Barber, J. R. (2013). An experimental investigation into the effects of traffic noise on distributions of birds: avoiding the phantom road. *Proceedings of the Royal Society of London B: Biological Sciences* **280**, 20132290.

*McDonald, M. A., Hildebrand, J. A. & Webb, S. C. (1995). Blue and fin whales observed on a seafloor array in the Northeast Pacific. *The Journal of the Acoustical Society of America* **98**, 712–721.

McGregor, P. K., Horn, A. G., Leonard, M. L. & Thomsen, F. (2013). Anthropogenic noise and conservation. In *Animal Signals and Communication*, pp. 409–444. Springer, Berlin, Heidelberg.

McLaughlin, K. E. & Kunc, H. P. (2013). Experimentally increased noise levels change spatial and singing behaviour. *Biology Letters* **9**, 20120771.

Melcón, M. L., Cummins, A. J., Kerosky, S. M., Roche, L. K., Wiggins, S. M. & Hildebrand, J. A. (2012). Blue whales respond to anthropogenic noise. *PLoS ONE* **7**, e32681.

Mendes, S., Colino-Rabanal, V. J. & Peris, S. J. (2011). Bird song variations along an urban gradient: the case of the European blackbird (*Turdus merula*). *Landscape and Urban Planning* **99**, 51–57.

Mennitt, D., Fristrup, K. M. & Nelson, L. (2013). Mapping the extent of noise on a national scale. http://acoustics.org/pressroom/httpdocs/166th/4aNS5-Mennitt.html Accessed 15.08.2014.

*Merrill, S. B. & Erickson, C. R. (2003). A GPS-based method to examine wolf response to loud noise. *Wildlife Society Bulletin* **31**, 769–773.

*Miksis-Olds, J. L., Donaghay, P. L., Miller, J. H., Tyack, P. L. & Reynolds, J. E. (2007). Simulated vessel approaches elicit differential responses from manatees. *Marine Mammal Science* **23**, 629–649.

Miksis-Olds, J. L. & Wagner, T. (2011). Behavioral response of manatees to variations in environmental sound levels. *Marine Mammal Science* **27**, 130–148.

*Miller, P. J., Biassoni, N., Samuels, A. & Tyack, P. L. (2000). Whale songs lengthen in response to sonar. *Nature* **405**, 903.

Mockford, E. J. & Marshall, R. C. (2009). Effects of urban noise on song and response behaviour in great tits. *Proceedings of the Royal Society of London B: Biological Sciences* **276**, 2979–2985.

Mockford, E. J., Marshall, R. C. & Dabelsteen, T. (2011). Degradation of rural and urban great tit song: testing transmission efficiency. *PLoS ONE* **6**, e28242.

Montague, M. J., Danek-Gontard, M. & Kunc, H. P. (2013). Phenotypic plasticity affects the response of a sexually selected trait to anthropogenic noise. *Behavioral Ecology* **24**(2), 343–348.

Mooney, T. A., Nachtigall, P. E. & Vlachos, S. (2009). Sonar-induced temporary hearing loss in dolphins. *Biology Letters* **5**, 565–567.

Moore, S. E., Reeves, R. R., Southall, B. L., Ragen, T. J., Suydam, R. S. & Clark, C. W. (2012). A new framework for assessing the effects of anthropogenic sound on marine mammals in a rapidly changing arctic. *BioScience* **62**, 289–295.

Morley, E. L., Jones, G. & Radford, A. N. (2013). The importance of invertebrates when considering the impacts of anthropogenic noise. *Proceedings of the Royal Society of London B: Biological Sciences* **281**, 20132683.

*Morton, A. B. & Symonds, H. K. (2002). Displacement of Orcinus orca (L.) by high amplitude sound in British Columbia, Canada. *ICES Journal of Marine Science* **59**, 715–780.

Murphy, E. & King, E. A. (2011). Scenario analysis and noise action planning: modelling the impact of mitigation measures on population exposure. *Applied Acoustics* **72**, 487–494.

*Nachtigall, P. E., Supin, A. Y., Pawloski, J. & Au, W. W. (2004). Temporary threshold shifts after noise exposure in the bottlenose dolphin (*Tursiops truncatus*) measured using evoked auditory potentials. *Marine Mammal Science* **20**, 673–687.

*Naguib, M., van Oers, K., Braakhuis, A., Griffioen, M., de Goede, P. & Waas, J. R. (2013). Noise annoys: effects of noise on breeding great tits depend on personality but not on noise characteristics. *Animal Behaviour* **85**, 949–956.

Nemeth, E. & Brumm, H. (2009). Blackbirds sing higher-pitched songs in cities: adaptation to habitat acoustics or side-effect of urbanization? *Animal Behaviour* **78**, 637–641.

Nemeth, E. & Brumm, H. (2010). Birds and anthropogenic noise: are urban songs adaptive? *The American Naturalist* **176**, 465–475.

Nemeth, E., Pieretti, N., Zollinger, S. A., Geberzahn, N., Partecke, J., Miranda, A. C. & Brumm, H. (2013). Bird song and anthropogenic noise: vocal constraints may explain why birds sing higher-frequency songs in cities. *Proceedings of the Royal Society of London B: Biological Sciences* **280**, 20122798.

Nowacek, D. P., Thorne, L. H., Johnston, D. W. & Tyack, P. L. (2007). Responses of cetaceans to anthropogenic noise. *Mammal Review* **37**, 81–115.

Ortega, C. P. (2012). Effects of noise pollution on birds: a brief review of our knowledge. *Ornithological Monographs* **74**, 6–22.

*Owen, M. A., Swaisgood, R. R., Czekala, N. M., Steinman, K. & Lindburg, D. G. (2004). Monitoring stress in captive giant pandas (*Ailuropoda melanoleuca*): behavioral and hormonal responses to ambient noise. *Zoo Biology* **23**, 147–164.

*Owens, J. L., Stec, C. L. & O'Hatnick, A. (2012). The effects of extended exposure to traffic noise on parid social and risk-taking behavior. *Behavioural Processes* **91**, 61–69.

*Parks, S. E., Clark, C. W. & Tyack, P. L. (2007). Short-and long-term changes in right whale calling behavior: the potential effects of noise on acoustic communication. *The Journal of the Acoustical Society of America* **122**, 3725–3731.

Parks, S. E., Johnson, M., Nowacek, D. & Tyack, P. L. (2011). Individual right whales call louder in increased environmental noise. *Biology Letters* **7**, 33–35.

*Parks, S. E., Urazghildiiev, I. & Clark, C. W. (2009). Variability in ambient noise levels and call parameters of North Atlantic right whales in three habitat areas. *The Journal of the Acoustical Society of America* **125**, 1230–1239.

Parris, K. M. & McCarthy, M. A. (2013). Predicting the effect of urban noise on the active space of avian vocal signals. *The American Naturalist* **182**, 452–464.

Parris, K. M. & Schneider, A. (2009). Impacts of traffic noise and traffic volume on birds of roadside habitats. *Ecology and Society* **14**, 29.

Parris, K. M., Velik-Lord, M., North, J. M. & Function, L. (2009). Frogs call at a higher pitch in traffic noise. *Ecology and Society* **14**, 25.

Patenaude, N. J., Richardson, W. J., Smultea, M. A., Koski, W. R., Miller, G. W., Wursig, B. & Greene, C. R. (2002). Aircraft sound and disturbance to bowhead and beluga whales during spring migration in the Alaskan Beaufort Sea. *Marine Mammal Science* **18**(2), 309–335.

Patón, D., Romero, F., Cuenca, J. & Escudero, J. C. (2012). Tolerance to noise in 91 bird species from 27 urban gardens of Iberian Peninsula. *Landscape and Urban Planning* **104**, 1–8.

Patricelli, G. L. & Blickley, J. L. (2006). Avian communication in urban noise: causes and consequences of vocal adjustment. *The Auk* **123**, 639–649.

*Payne, C. J., Jessop, T. S., Guay, P. J., Johnstone, M., Feore, M. & Mulder, R. A. (2012). Population, behavioural and physiological responses of an urban population of black swans to an intense annual noise event. *PLoS ONE* **7**, e45014.

*Penna, M. & Hamilton-West, C. (2007). Susceptibility of evoked vocal responses to noise exposure in a frog of the temperate austral forest. *Animal Behaviour* **74**, 45–56.

*Penna, M., Pottstock, H. & Velasquez, N. (2005). Effect of natural and synthetic noise on evoked vocal responses in a frog of the temperate austral forest. *Animal Behaviour* **70**, 639–651.

*Perry, E. A., Boness, D. J. & Insley, S. J. (2002). Effects of sonic booms on breeding gray seals and harbor seals on Sable Island, Canada. *The Journal of the Acoustical Society of America* **111**, 599–609.

Picciulin, M., Sebastianutto, L., Codarin, A., Farina, A. & Ferrero, E. A. (2010). In situ behavioural responses to boat noise exposure of *Gobius cruentatus* (Gmelin, 1789; fam. *Gobiidae*) and *Chromis chromis* (Linnaeus, 1758; fam. *Pomacentridae*) living in a Marine Protected Area. *Journal of Experimental Marine Biology and Ecology* **386**, 125–132.

Pieretti, N. & Farina, A. (2013). Application of a recently introduced index for acoustic complexity to an avian soundscape with traffic noise. *The Journal of the Acoustical Society of America* **134**, 891–900.

Pine, M. K., Jeffs, A. G. & Radford, C. A. (2012). Turbine sound may influence the metamorphosis behaviour of estuarine crab megalopae. *PLoS ONE* **7**, e51790.

*Pirotta, E., Milor, R., Quick, N., Moretti, D., Di Marzio, N., Tyack, P., Boyd, I. & Hastie, G. (2012). Vessel noise affects beaked whale behavior: results of a dedicated acoustic response study. *PLoS ONE* **7**, e42535.

Pohl, N. U., Leadbeater, E., Slabbekoorn, H., Klump, G. M. & Langemann, U. (2012). Great tits in urban noise benefit from high frequencies in song detection and discrimination. *Animal Behaviour* **83**, 711–721.

Pohl, N. U., Slabbekoorn, H., Klump, G. M. & Langemann, U. (2009). Effects of signal features and environmental noise on signal detection in the great tit, *Parus major*. *Animal Behaviour* **78**, 1293–1300.

van *Polanen Petel, T. D., Terhune, J. M., Hindell, M. A. & Giese, M. A. (2006). An assessment of the audibility of sound from human transport by breeding Weddell seals (*Leptonychotes weddellii*). *Wildlife Research* **33**, 275–291.

Popper, A. N., Halvorsen, M. B., Kane, A., Miller, D. L., Smith, M. E., Song, J., Stein, P. & Wysocki, L. E. (2007). The effects of high-intensity, low-frequency active sonar on rainbow trout. *The Journal of the Acoustical Society of America* **122**, 623–635.

*Popper, A. N., Smith, M. E., Cott, P. A., Hanna, B. W., MacGillivray, A. O., Austin, M. E. & Mann, D. A. (2005). Effects of exposure to seismic airgun use on hearing of three fish species. *The Journal of the Acoustical Society of America* **117**, 3958–3971.

Potvin, D. A. & Mulder, R. A. (2013). Immediate, independent adjustment of call pitch and amplitude in response to varying background noise by silvereyes (*Zosterops lateralis*). *Behavioral Ecology* **24**, 1363–1368.

Potvin, D. A., Parris, K. M. & Mulder, R. A. (2011). Geographically pervasive effects of urban noise on frequency and syllable rate of songs and calls in silvereyes (*Zosterops lateralis*). *Proceedings of the Royal Society of London B: Biological Sciences* **278**, 2464–2469.

Powell, D. M., Carlstead, K., Tarou, L. R., Brown, J. L. & Monfort, S. L. (2006). Effects of construction noise on behavior and cortisol levels in a pair of captive giant pandas (*Ailuropoda melanoleuca*). *Zoo Biology* **25**, 391–408.

Proppe, D. S., Avey, M. T., Hoeschele, M., Moscicki, M. K., Farrell, T., St Clair, C. C. & Sturdy, C. B. (2012). Black-capped chickadees *Poecile atricapillus* sing at higher pitches with elevated anthropogenic noise, but not with decreasing canopy cover. *Journal of Avian Biology* **43**, 325–332.

Proppe, D. S., Byers, K. A., Sturdy, C. B. & St Clair, C. C. (2013*a*). Physical condition of Black-capped Chickadees (*Poecile atricapillus*) in relation to road disturbance. *Canadian Journal of Zoology* **91**, 842–845.

Proppe, D. S., Sturdy, C. B. & St Clair, C. C. (2013*b*). Anthropogenic noise decreases urban songbird diversity and may contribute to homogenization. *Global Change Biology* **19**, 1075–1084.

Quinn, J. L., Whittingham, M. J., Butler, S. J. & Cresswell, W. (2006). Noise, predation risk compensation and vigilance in the chaffinch *Fringilla coelebs*. *Journal of Avian Biology* **37**, 601–608.

Rabin, L. A., Coss, R. G. & Owings, D. H. (2006). The effects of wind turbines on antipredator behavior in California ground squirrels (*Spermophilus beecheyi*). *Biological Conservation* **131**, 410–420.

Radford, A. N., Kerridge, E. & Simpson, S. D. (2014). Acoustic communication in a noisy world: can fish compete with anthropogenic noise? *Behavioral Ecology* **25**, 1022–1030.

Rasmussen, S., Glickman, G., Norinsky, R., Quimby, F. W. & Tolwani, R. J. (2009). Construction noise decreases reproductive efficiency in mice. *Journal of the American Association for Laboratory Animal Science* **48**, 363–370.

Read, J., Jones, G. & Radford, A. N. (2014). Fitness costs as well as benefits are important when considering responses to anthropogenic noise. *Behavioral Ecology* **25**, 4–7.

Redondo, P., Barrantes, G. & Sandoval, L. (2013). Urban noise influences vocalization structure in the house wren *Troglodytes aedon*. *Ibis* **155**, 621–625.

*Rendell, L. E. & Gordon, J. C. D. (1999). Vocal responses of long-finned pilot whales (*Globicephala melas*) to military sonar in the Ligurian sea. *Marine Mammal Science* **15**, 198–204.

*Rheindt, F. E. (2003). The impact of roads on birds: does song frequency play a role in determining susceptibility to noise pollution? *Journal für Ornithologie* **144**, 295–306.

Richardson, W. J., Greene, C. R. Jr., Malme, C. I. & Thomson, D. H. (1995). *Marine Mammals and Noise*. Academic Press, San Diego.

Ríos-Chelén, A. A., Quirós-Guerrero, E., Gil, D. & Garcia, C. M. (2013). Dealing with urban noise: vermilion flycatchers sing longer songs in noisier territories. *Behavioral Ecology and Sociobiology* **67**, 145–152.

Ríos-Chelén, A. A., Salaberria, C., Barbosa, I., Macías Garcia, C. & Gil, D. (2012). The learning advantage: bird species that learn their song show a tighter adjustment of song to noisy environments than those that do not learn. *Journal of Evolutionary Biology* **25**, 2171–2180.

*Ripmeester, E. A., Kok, J. S., van Rijssel, J. C. & Slabbekoorn, H. (2010). Habitat-related birdsong divergence: a multi-level study on the influence of territory density and ambient noise in European blackbirds. *Behavioral Ecology and Sociobiology* **64**, 409–418.

Risch, D., Corkeron, P. J., Ellison, W. T. & Van Parijs, S. M. (2012). Changes in humpback whale song occurrence in response to an acoustic source 200 km away. *PLoS ONE* **7**, e29741.

Rolland, R. M., Parks, S. E., Hunt, K. E., Castellote, M., Corkeron, P. J., Nowacek, D. P., Wasser, S. K. & Kraus, S. D. (2012). Evidence that ship noise increases stress in right whales. *Proceedings of the Royal Society of London B: Biological Sciences* **279**, 2363–2368.

*Romano, T. A., Keogh, M. J., Kelly, C., Feng, P., Berk, L., Schlundt, C. E., Carder, D. A. & Finneran, J. J. (2004). Anthropogenic sound and marine mammal health: measures of the nervous and immune systems before and after intense sound exposure. *Canadian Journal of Fisheries and Aquatic Sciences* **61**, 1124–1134.

Rossing, T. D. (2007). *Springer Handbook of Acoustics*. Springer, New York.

*Saha, D. C. & Padhy, P. K. (2011). Effect of air and noise pollution on species diversity and population density of forest birds at Lalpahari, West Bengal, India. *Science of the Total Environment* **409**, 5328–5336.

*Salaberria, S. & Gill, D. (2010). Increase in song frequency in response to urban noise in the great tit Parus major as shown by data from the Madrid (Spain) city noise map. *Ardeola* **57**, 3–11.

Sarà, G., Dean, J. M., D'Amato, D., Buscaino, G., Oliveri, A., Genovese, S., Ferro, S., Buffa, G., Lo Martire, M. & Mazzola, S. (2007). Effect of boat noise on the behaviour of bluefin tuna *Thunnus thynnus* in the Mediterranean Sea. *Marine Ecology Progress Series* **331**, 243–253.

Schaub, A., Ostwald, J. & Siemers, B. M. (2008). Foraging bats avoid noise. *Journal of Experimental Biology* **211**, 3174–3180.

Scheifele, P. M., Andrew, S., Cooper, R. A., Darre, M., Musiek, F. E. & Max, L. (2005). Indication of a Lombard vocal response in the St. Lawrence River beluga. *The Journal of the Acoustical Society of America* **117**, 1486–1492.

*Scholik, A. R. & Yan, H. Y. (2002*a*). Effects of boat engine noise on the auditory sensitivity of the fathead minnow, *Pimephales promelas*. *Environmental Biology of Fishes* **63**, 203–209.

*Scholik, A. R. & Yan, H. Y. (2002*b*). The effects of noise on the auditory sensitivity of the bluegill sunfish, Lepomis macrochirus. *Comparative Biochemistry and Physiology Part A: Molecular & Integrative Physiology* **133**, 43–52.

Schroeder, J., Nakagawa, S., Cleasby, I. R. & Burke, T. (2012). Passerine birds breeding under chronic noise experience reduced fitness. *PLoS ONE* **7**, e39200.

Sebastianutto, L., Picciulin, M., Costantini, M. & Ferrero, E. A. (2011). How boat noise affects an ecologically crucial behaviour: the case of territoriality in *Gobius cruentatus* (Gobiidae). *Environmental Biology of Fishes* **92**, 207–215.

Seger-Fullam, K. D., Rodewald, A. D. & Soha, J. A. (2011). Urban noise predicts song frequency in Northern Cardinals and American Robins. *Bioacoustics* **20**, 267–276.

*Sembulingam, K., Sembulingam, P. & Namasivayam, A. (1998). Effect of chronic noise stress on some selected stress indices in albino rats. *Journal of Environmental Biology* **19**, 63–66.

*Shamoun-Baranes, J., Dokter, A. M., van Gasteren, H., van Loon, E. E., Leijnse, H. & Bouten, W. (2011). Birds flee en mass from New Year's Eve fireworks. *Behavioral Ecology* **22**, 1173–1177.

Shannon, G., Angeloni, L. M., Wittemyer, G., Fristrup, K. M. & Crooks, K. R. (2014). Road traffic noise modifies behaviour of a keystone species. *Animal Behaviour* **94**, 135–141.

Shieh, B. S., Liang, S. H., Chen, C. C., Loa, H. H. & Liao, C. Y. (2012). Acoustic adaptations to anthropogenic noise in the cicada Cryptotympana takasagona Kato (*Hemiptera: Cicadidae*). *Acta Ethologica* **15**, 33–38.

*Shier, D. M., Lea, A. J. & Owen, M. A. (2012). Beyond masking: endangered Stephen's kangaroo rats respond to traffic noise with footdrumming. *Biological Conservation* **150**, 53–58.

Siemers, B. M. & Schaub, A. (2011). Hunting at the highway: traffic noise reduces foraging efficiency in acoustic predators. *Proceedings of the Royal Society of London B: Biological Sciences* **278**, 1646–1652.

*Sivle, L. D., Kvadsheim, P. H., Fahlman, A., Lam, F. P. A., Tyack, P. L. & Miller, P. J. (2012). Changes in dive behavior during naval sonar exposure in killer whales, long-finned pilot whales, and sperm whales. *Frontiers in Physiology* **3**, 1–11.

Slabbekoorn, H. (2013). Songs of the city: noise-dependent spectral plasticity in the acoustic phenotype of urban birds. *Animal Behaviour* **85**, 1089–1099.

*Slabbekoorn, H. & den Boer-Visser, A. (2006). Cities change the songs of birds. *Current Biology* **16**, 2326–2331.

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

Slabbekoorn, H. & Peet, M. (2003). Ecology: birds sing at a higher pitch in urban noise. *Nature* **424**, 267.

Slabbekoorn, H. & Ripmeester, E. A. P. (2008). Birdsong and anthropogenic noise: implications and applications for conservation. *Molecular Ecology* **17**, 72–83.

*Smith, M. E., Kane, A. S. & Popper, A. N. (2004). Noise-induced stress response and hearing loss in goldfish (*Carassius auratus*). *Journal of Experimental Biology* **207**, 427–435.

Solé, M., Lenoir, M., Durfort, M., López-Bejar, M., Lombarte, A., Van der Schaar, M. & André, M. (2013). Does exposure to noise from human activities compromise sensory information from cephalopod statocysts? *Deep Sea Research Part II: Topical Studies in Oceanography* **95**, 160–181.

de Soto, N. A., Delorme, N., Atkins, J., Howard, S., Williams, J. & Johnson, M. (2013). Anthropogenic noise causes body malformations and delays development in marine larvae. *Scientific Reports* **3**, 2831.

de Soto, N. A., Johnson, M., Madsen, P. T., Tyack, P. L., Bocconcelli, A. & Fabrizio Borsani, J. (2006). Does intense ship noise disrupt foraging in deep-diving Cuvier's beaked whales (*Ziziphus cavirostris*)? *Marine Mammal Science* **22**, 690–699.

Southall, B. L., Berkson, J., Bowen, D., Brake, R., Eckman, J., Field, J., Gisiner, R., Gregerson, S., Lang, W. & Lewandowski, J. (2009). *Addressing the Effects of Human-Generated Sound on Marine Life: An Integrated Research Plan for US Federal Agencies*. Interagency Task Force on Anthropogenic Sound and the Marine Environment of the Joint Subcommittee on Ocean Science and Technology, Washington.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. L., Greene, C. R. Jr., Kastak, D., Ketten, D. R., Miller, J. H. & Nachtigall, P. E.

(2007). Marine mammal noise exposure criteria: initial scientific recommendations. *Aquatic Mammals* **33**, 411–509.

Stansfeld, S. A. & Matheson, M. P. (2003). Noise pollution: non-auditory effects on health. *British Medical Bulletin* **68**, 243–257.

Stokstad, E. (2014). US regulators unveil new ocean noise rules for marine mammals. *Science* **343**, 128.

Summers, P. D., Cunnington, G. M. & Fahrig, L. (2011). Are the negative effects of roads on breeding birds caused by traffic noise? *Journal of Applied Ecology* **48**, 1527–1534.

Sun, J. W. & Narins, P. M. (2005). Anthropogenic sounds differentially affect amphibian call rate. *Biological Conservation* **121**, 419–427.

*Swaddle, J. P. & Page, L. C. (2007). High levels of environmental noise erode pair preferences in zebra finches: implications for noise pollution. *Animal Behaviour* **74**, 363–368.

Szalma, J. L. & Hancock, P. A. (2011). Noise effects on human performance: a meta-analytic synthesis. *Psychological Bulletin* **137**, 682–707.

Tabarelli, M. & Gascon, C. (2005). Lessons from fragmentation research: improving management and policy guidelines for biodiversity conservation. *Conservation Biology* **19**, 734–739.

*Thompson, P. M., Lusseau, D., Barton, T., Simmons, D., Rusin, J. & Bailey, H. (2010). Assessing the responses of coastal cetaceans to the construction of offshore wind turbines. *Marine Pollution Bulletin* **60**, 1200–1208.

*Todd, S., Lien, J., Marques, F., Stevick, P. & Ketten, D. (1996). Behavioural effects of exposure to underwater explosions in humpback whales (*Megaptera novaeangliae*). *Canadian Journal of Zoology* **74**, 1661–1672.

Tripovich, J. S., Hall-Aspland, S., Charrier, I. & Arnould, J. P. (2012). The behavioural response of Australian fur seals to motor boat noise. *PLoS ONE* **7**, e37228.

Tyack, P. L. (2008). Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy* **89**, 549–558.

Tyack, P. L., Zimmer, W. M. X., Moretti, D., Southall, B. L., Claridge, D. E., Durban, J. W., Clark, C. W., D'Amico, A., DiMarzio, N., Jarvis, S., McCarthy, E., Morrissey, R., Ward, J. & Boyd, I. L. (2011). Beaked whales respond to simulated and actual navy sonar. *PLoS ONE* **6**, e17009.

*Uran, S. L., Aon-Bertolino, M. L., Caceres, L. G., Capani, F. & Guelman, L. R. (2012). Rat hippocampal alterations could underlie behavioral abnormalities induced by exposure to moderate noise levels. *Brain Research* **1471**, 1–12.

Vargas-Salinas, F. & Amézquita, A. (2013). Traffic noise correlates with calling time but not spatial distribution in the threatened poison frog *Andinobates bombetes*. *Behaviour* **150**, 569–584.

Vasconcelos, R. O., Amorim, M. C. P. & Ladich, F. (2007). Effects of ship noise on the detectability of communication signals in the Lusitanian toadfish. *Journal of Experimental Biology* **210**, 2104–2112.

Verzijden, M. N., Ripmeester, E. A. P., Ohms, V. R., Snelderwaard, P. & Slabbekoorn, H. (2010). Immediate spectral flexibility in singing chiffchaffs during experimental exposure to highway noise. *The Journal of Experimental Biology* **213**, 2575–2581.

*Wada, Y., Mogi, T., Inoue, H. & Koizumi, A. (1995). A mouse model of a sudden death induced by noise exposure is useful to investigate human responses to physical stress. *Industrial Health* **33**, 29–33.

*Wahlberg, M. & Westerberg, H. (2005). Hearing in fish and their reactions to sounds from offshore wind farms. *Marine Ecology Progress Series* **288**, 295–309.

Wale, M. A., Simpson, S. D. & Radford, A. N. (2013). Noise negatively affects foraging and antipredator behaviour in shore crabs. *Animal Behaviour* **86**, 111–118.

Wardle, C. S., Carter, T. J., Urquhart, G. G., Johnstone, A. D. F., Ziolkowski, A. M., Hampson, G. & Mackie, D. (2001). Effects of seismic air guns on marine fish. *Continental Shelf Research* **21**, 1005–1027.

*Weir, C. R. (2007). Observations of marine turtles in relation to seismic airgun sound off Angola. *Marine Turtle Newsletter* **116**, 17–20.

*Weir, C. R. (2008). Overt responses of humpback whales (*Megaptera novaeangliae*), sperm whales (*Physeter macrocephalus*), and Atlantic spotted dolphins (*Stenella frontalis*) to seismic exploration off Angola. *Aquatic Mammals* **34**, 71–83.

Weisenberger, M. E., Krausman, P. R., Wallace, M. C., De Young, D. W. & Maughan, O. E. (1996). Effects of simulated jet aircraft noise on heart rate and behavior of desert ungulates. *The Journal of Wildlife Management* **60**, 52–61.

Westlund, K., Fernström, A. L., Wergård, E. M., Fredlund, H., Hau, J. & Spångberg, M. (2012). Physiological and behavioural stress responses in cynomolgus macaques (*Macaca fascicularis*) to noise associated with construction work. *Laboratory Animals* **46**, 51–58.

Wilkens, S. L., Stanley, J. A. & Jeffs, A. G. (2012). Induction of settlement in mussel (*Perna canaliculus*) larvae by vessel noise. *Biofouling* **28**, 65–72.

Wood, W. E. & Yezerinac, S. M. (2006). Song sparrow (*Melospiza melodia*) song varies with urban noise. *The Auk* **123**, 650–659.

Wright, A. J., Aguilar Soto, N., Baldwin, A. L., Bateson, M., Beale, C., Clark, C., Deak, T., Edwards, E. F., Fernández, A., Godinho, A., Hatch, L., Kakuschke, A., Lusseau, D., Martineau, D., Romero, L. M., et al. (2007). Anthropogenic noise as a stressor in animals: a multidisciplinary perspective. *International Journal of Comparative Psychology* **20**, 250–273.

Würsig, B. B., Greene, C. R. C. & Jefferson, T. A. T. (2000). Development of an air bubble curtain to reduce underwater noise of percussive piling. *Marine Environmental Research* **49**, 79–93.

Wysocki, L. E., Dittami, J. P. & Ladich, F. (2006). Ship noise and cortisol secretion in European freshwater fishes. *Biological Conservation* **128**, 501–508.

Zhang, M., Cheong, K., Leong, K. & Zou, F. (2012). Effect of traffic noise on black-faced spoonbills in the Taipa–Coloane Wetland Reserve, Macao. *Wildlife Research* **39**, 603–610.

Zurcher, A. A., Sparks, D. W. & Bennett, V. J. (2010). Why the bat did not cross the road? *Acta Chiropterologica* **12**, 337–340.

IX. SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

Appendix S1. Summary of information gathered from all studies used in this review.

Appendix S2. Summary of information gathered from studies used to generate Fig. 3.

(*Received 1 October 2014; revised 28 May 2015; accepted 5 June 2015; published online 26 June 2015*)