

Anthropogenic Noise and Animal Behaviour: A Review of Effects on Communication, Foraging, Physiology, and Fitness

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Abstract

Noise from transport, industry, and resource extraction now pervades terrestrial and aquatic habitats, and a rapidly growing literature shows that it alters the behaviour of animals. This review synthesises published evidence on how anthropogenic noise affects acoustic communication, foraging and antipredator behaviour, physiology, reproduction, and the structure of animal communities. Noise acts through three perceptual mechanisms: masking of signals and cues, distraction, and perception of noise as a threat. Birds, frogs, insects, and whales modify the frequency, amplitude, or timing of their signals in noise, but such adjustments are constrained and can carry costs. Noise reduces the foraging efficiency of acoustic predators, distracts prey, increases vigilance at the expense of feeding, and can raise predation mortality. Chronic exposure is associated with altered glucocorticoid physiology, reduced pairing and hatching success, and smaller broods. Experiments that isolate noise from other disturbance, including playback of traffic noise in roadless habitat, demonstrate that noise alone reduces bird abundance and body condition and can alter pollination and seed dispersal. Responses occur across a wide range of taxa and begin at modest sound levels. However, research remains concentrated on songbirds and marine mammals in Europe and North America, acoustic exposure is often poorly reported, and long-term population consequences are seldom measured. Because noise ceases when its source is removed, it is among the more tractable pollutants. Mitigation options and research priorities are outlined, with attention to understudied tropical regions.

Keywords:- Anthropogenic Noise, Noise Pollution, Acoustic Communication, Masking, Lombard Effect, Foraging Behaviour, Stress Physiology, Soundscape, Behavioural Ecology.

I. INTRODUCTION

Sound is a primary channel through which animals find mates, defend territories, detect predators and prey, maintain contact with offspring, and orient in space. Human activity has changed the acoustic environment in which these functions evolved. Road, rail, and air traffic, industrial plant, construction, and recreation have raised background sound levels on land (Barber et al., 2010), while shipping, seismic exploration, pile driving, and sonar have done so in the sea (Hildebrand, 2009; Duarte et al., 2021). Shipping alone is estimated to have raised low-frequency ambient levels in the ocean by about 12 dB over recent decades (Shannon et al., 2016). Noise now reaches areas set aside for conservation. Modelling for the contiguous United States indicated that anthropogenic noise doubled background sound levels in 63% of protected area units and produced a ten-fold or greater increase in 21% (Buxton et al., 2017).

Since the demonstration that urban great tits (*Parus major*) sing at a higher pitch in noisier territories (Slabbekoorn & Peet, 2003), research on the biological effects of noise has expanded rapidly. A systematic review identified 242 empirical studies published between 1990 and 2013, of which 88% reported a statistically significant biological response (Shannon et al., 2016). A phylogenetically controlled meta-analysis subsequently found that noise affects amphibians, arthropods, birds, fishes, mammals, molluscs, and reptiles, and that the pattern reflects most species responding to noise and not merely a few sensitive ones (Kunc & Schmidt, 2019).

The objectives of this review are to:

- Describe the sources of anthropogenic noise and the mechanisms by which it affects animals
- Summarise evidence for noise-induced changes in acoustic communication
- Evaluate effects on foraging, vigilance, and predator–prey interactions
- Examine physiological, reproductive, and fitness consequences
- Assess effects on distribution, communities, and ecological processes
- Identify limitations, mitigation options, and research priorities.

II. NOISE AS A SENSORY POLLUTANT

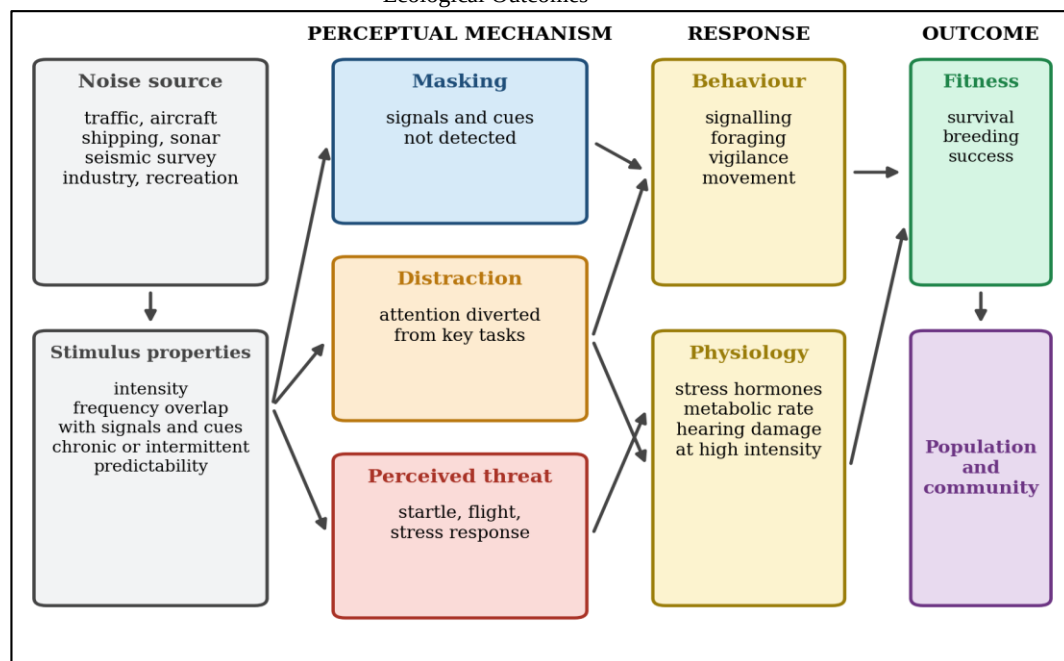
2.1. Sources and Characteristics

Anthropogenic noise differs from most natural sound in being concentrated at low frequencies, often loud, and either chronic, as beside a highway or shipping lane, or intermittent and unpredictable, as with aircraft overflights and seismic airguns (Barber et al., 2010; Hildebrand, 2009). Its biological effect depends on intensity, on the overlap between its frequency spectrum and the hearing range and signals of the animal, and on its temporal pattern (Francis & Barber, 2013). Because sound travels far and fast in water, underwater sources can influence very large areas (Slabbekoorn et al., 2010; Duarte et al., 2021).

2.2. Mechanisms of Effect

Francis and Barber (2013) proposed that responses depend on how noise is perceived. Three mechanisms are generally recognised (Figure 1). Masking occurs when noise overlaps a signal or cue in frequency and time and so prevents its detection. Even a modest rise in background level substantially reduces the area over which an animal can hear a sound of interest (Barber et al., 2010). Distraction occurs when noise occupies limited attention, reducing the ability to respond to other stimuli even when these are not masked (Chan et al., 2010). Finally, sudden or unfamiliar noise may be perceived as a threat and elicit startle, flight, and physiological stress responses similar to those evoked by predators (Francis & Barber, 2013). These mechanisms are not mutually exclusive, and their behavioural and physiological consequences were reviewed by Kight and Swaddle (2011).

Figure 1: Conceptual Framework Linking Anthropogenic Noise to Behavioural, Physiological, and Ecological Outcomes



Source: Author's schematic adapted from the frameworks of Francis and Barber (2013) and Kight and Swaddle (2011)

The properties of the noise stimulus determine whether it masks signals and cues, distracts the animal, or is perceived as a threat. These mechanisms alter behaviour and physiology, with consequences for individual fitness and, ultimately, for populations and communities.

III. APPROACH AND SCOPE OF THE REVIEW

This article is a narrative synthesis of peer-reviewed literature on the responses of animals to anthropogenic noise in terrestrial and aquatic habitats. We drew principally on systematic reviews and meta-analyses, on experiments that isolated noise from other forms of disturbance by means of playback or natural contrasts, and on studies that measured reproductive success, survival, or community-level outcomes. No new empirical data are presented, and all figures are

conceptual schematics that illustrate published ideas without plotting data. As a narrative review, the article does not claim exhaustive coverage. Its conclusions should be read as an integration of the main lines of evidence.

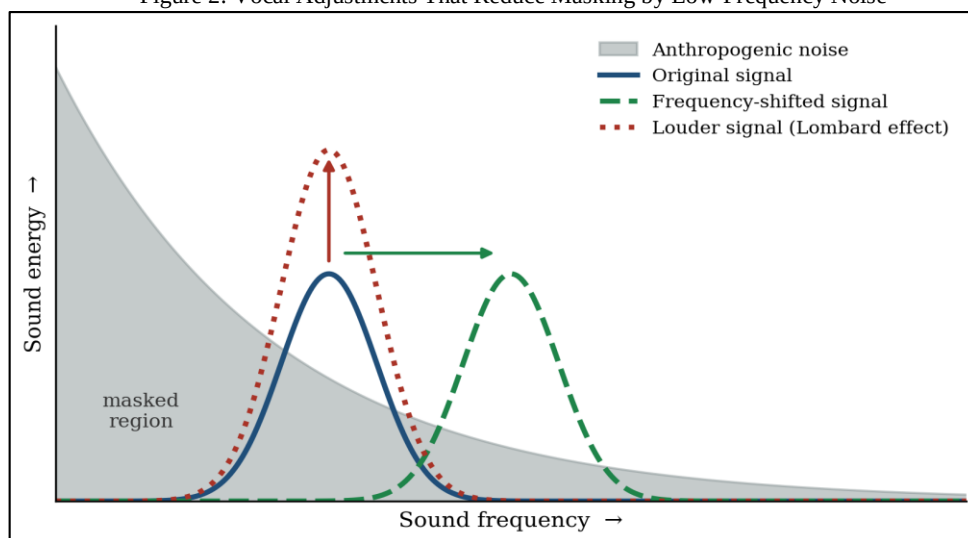
IV. EFFECTS ON ACOUSTIC COMMUNICATION

4.1. Birds

Vocal adjustment in birds is the most thoroughly documented response to noise (Brumm & Slabbekoorn, 2005; Patricelli & Blickley, 2006; Slabbekoorn & Ripmeester, 2008). Three kinds of adjustment have been described (Figure 2). First, birds raise the minimum frequency of their songs, reducing overlap with low-frequency traffic noise, as shown in great tits in Leiden (Slabbekoorn & Peet, 2003). In San Francisco, the minimum frequency of white-crowned sparrow (*Zonotrichia leucophrys*) song rose over a 30-year period during which noise levels increased (Luther & Baptista, 2010). Second, birds sing louder. Territorial nightingales (*Luscinia megarhynchos*) in Berlin sang with higher amplitude at noisier sites, an example of the Lombard effect (Brumm, 2004). Third, birds shift the timing of song. European robins (*Erithacus rubecula*) sang at night in places that were noisy by day (Fuller et al., 2007).

The relative benefit of these strategies has been debated. Calculations suggest that increasing amplitude improves communication distance far more than the observed shifts in pitch, which may partly be a by-product of singing louder (Nemeth & Brumm, 2010). The flexibility of song was illustrated during the COVID-19 shutdown of 2020, when traffic noise in the San Francisco Bay Area fell to levels characteristic of the 1950s and white-crowned sparrows responded by producing higher-performance songs at lower amplitude (Derryberry et al., 2020).

Figure 2: Vocal Adjustments That Reduce Masking by Low-Frequency Noise



Source: Author's schematic based on Slabbekoorn and Peet (2003), Brumm (2004), and Nemeth and Brumm (2010); axes unscaled, no empirical data plotted

Anthropogenic noise (shaded) is concentrated at low frequencies. A signal that overlaps this region is masked. Animals may reduce masking by shifting the signal to higher frequencies (dashed line) or by increasing its amplitude, the Lombard effect (dotted line).

4.2. Anurans and Insects

Frogs calling beside roads face similar problems. Two frog species in Melbourne called at a higher pitch in traffic noise (Parris et al., 2009). In grey treefrogs (*Hyla chrysoscelis*), playback experiments showed that traffic noise masks the male advertisement call and impairs the ability of females to locate calling males (Bee & Swanson, 2007). Among insects, male grasshoppers (*Chorthippus biguttulus*) from roadside habitats produced courtship signals with elevated frequency components compared with males from quiet sites (Lampe et al., 2012). Invertebrates nevertheless remain greatly under-represented in noise research relative to their diversity and ecological importance (Morley et al., 2014).

4.3. Marine Mammals

Baleen whales communicate with low-frequency calls that overlap the noise of large ships. North Atlantic right whales (*Eubalaena glacialis*) have shifted their calls to higher frequencies over both short and long timescales (Parks et al., 2007), and individuals call louder as background noise increases (Parks et al., 2011). Responses of cetaceans to noise, which also include changes in diving, movement, and habitat use, were reviewed by Nowacek et al. (2007). Blue whales (*Balaenoptera musculus*) exposed to simulated mid-frequency military sonar ceased deep feeding and moved away from the source, even though the sonar frequencies lie well above those of their own calls (Goldbogen et al., 2013).

4.4. Costs and Limits of Adjustment

Vocal adjustment does not remove the cost of noise. Female great tits prefer low-frequency songs, but these are the songs most strongly masked, so that in noisy conditions males must sing higher-pitched and less attractive songs to

be heard (Halfwerk, Bot, et al., 2011). Species differ in their capacity for adjustment, and those that cannot adjust may be excluded from noisy habitat (Francis et al., 2009). Vocal adjustments are summarised in Table 1.

Table 1. Documented Adjustments of Acoustic Signals in Response to Anthropogenic Noise

Study	Species	Adjustment
Slabbekoorn & Peet (2003)	Great tit	Higher minimum song frequency in noisier urban territories
Brumm (2004)	Common nightingale	Higher song amplitude at noisier sites (Lombard effect)
Fuller et al. (2007)	European robin	Nocturnal singing where daytime noise is high
Parks et al. (2007)	North Atlantic right whale	Upward shift in call frequency over short and long timescales
Parris et al. (2009)	Two frog species, Melbourne	Higher call pitch in traffic noise
Luther & Baptista (2010)	White-crowned sparrow	Rise in minimum song frequency over 30 years
Parks et al. (2011)	North Atlantic right whale	Individuals call louder as background noise rises
Lampe et al. (2012)	Grasshopper <i>Chorthippus biguttulus</i>	Elevated frequency components in roadside males
Derryberry et al. (2020)	White-crowned sparrow	Lower amplitude, higher performance song when traffic noise fell in 2020

Notes: Adjustments are paraphrased from the cited sources.

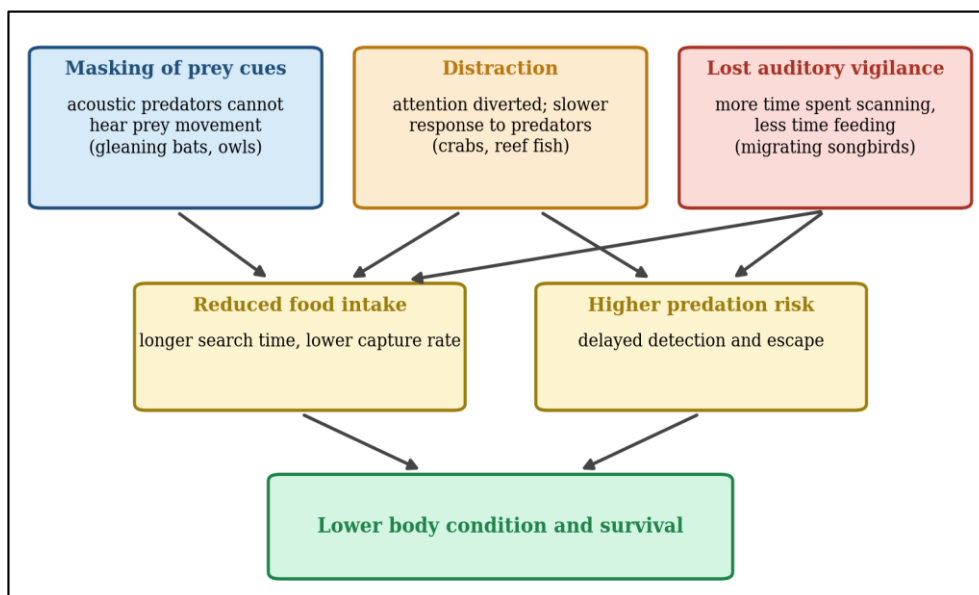
V. FORAGING, VIGILANCE, AND PREDATOR-PREY INTERACTIONS

Noise affects the acquisition of food and the avoidance of predators through all three perceptual mechanisms (Figure 3). Predators that hunt by listening are vulnerable to masking. Greater mouse-eared bats (*Myotis myotis*) locate ground-running arthropods by their rustling sounds, and in a laboratory experiment simulating different distances from a highway, search time increased five-fold at 7.5 m from the road, implying a 25-fold reduction in the ground area a bat could survey (Siemers & Schaub, 2011). Field experiments with wild owls in Japan likewise showed that prey detection declined with increasing traffic noise, with effects extending more than 120 m from a road (Senzaki et al., 2016).

Distraction affects prey. Caribbean hermit crabs (*Coenobita clypeatus*) allowed a simulated predator to approach more closely during playback of boat noise, consistent with attention being diverted (Chan et al., 2010). Shore crabs (*Carcinus maenas*) exposed to ship noise were more likely to have feeding disrupted and were slower to retreat to shelter after a simulated attack (Wale et al., 2013). On a coral reef, motorboat noise raised the metabolic rate of juvenile Ambon damselfish (*Pomacentrus amboinensis*) and reduced their response to predatory strikes, and more than twice as many were consumed by a natural predator when motorboats were passing (Simpson et al., 2016).

Noise can also force a trade-off between feeding and vigilance. When traffic noise was broadcast along a roadless ridge in Idaho to create a phantom road, 31% of the migrating bird community avoided the area, and the body condition of birds that remained fell markedly. Laboratory trials indicated that birds in noise spent more time scanning for predators and less time feeding (Ware et al., 2015).

Figure 3: Pathways by Which Noise Alters Foraging and Predation Risk



Source: Author's schematic based on Siemers and Schaub (2011), Chan et al. (2010), Wale et al. (2013), Ware et al. (2015), and Simpson et al. (2016)

Masking of prey-generated sounds, distraction, and loss of auditory vigilance each reduce food intake or increase exposure to predators, with consequences for body condition and survival.

VI. PHYSIOLOGY, REPRODUCTION, AND FITNESS

Noise can act as a physiological stressor. Following the events of 11 September 2001, reduced ship traffic in the Bay of Fundy produced a 6 dB decrease in underwater noise, and this was accompanied by lower concentrations of stress-related glucocorticoid metabolites in the faeces of North Atlantic right whales (Rolland et al., 2012). In greater sage-grouse (*Centrocercus urophasianus*), experimental playback of noise from natural gas drilling and roads at leks reduced peak male attendance by 29% and 73% respectively (Blickley, Blackwood, & Patricelli, 2012) and raised faecal corticosteroid metabolites in males that remained (Blickley, Word, et al., 2012). In cavity-nesting birds breeding near gas compressors in New Mexico, noise exposure was associated with lower baseline corticosterone in adults and nestlings, a pattern indicative of chronic stress, and with reduced hatching success in western bluebirds (*Sialia mexicana*) (Kleist et al., 2018).

Effects on reproduction have been shown in several systems. Male ovenbirds (*Seiurus aurocapilla*) holding territories beside noisy compressor stations in the Canadian boreal forest had lower pairing success than males at quiet well pads, probably because song was masked (Habib et al., 2007). Great tits breeding in noisier areas beside a Dutch motorway laid smaller clutches and fledged fewer young (Halfwerk, Holleman, et al., 2011). At continental scale, an analysis of 58,506 nest records of 142 bird species across the contiguous United States found that noise was negatively associated with nest success in species of closed habitats and that species-specific responses were explained by vocal frequency, nest location, and diet (Senzaki et al., 2020). Effects on foraging, physiology, and reproduction are summarised in Table 2.

Table 2. Selected Studies of the Effects of Noise on Foraging, Physiology, and Reproduction

Study	Species and noise source	Principal finding
Habib et al. (2007)	Ovenbird; gas compressor stations	Lower pairing success at noisy sites
Chan et al. (2010)	Caribbean hermit crab; boat noise	Distracted crabs allowed closer approach by a simulated predator
Halfwerk, Holleman, et al. (2011)	Great tit; motorway traffic	Smaller clutches and fewer fledglings in noisier areas
Siemers & Schaub (2011)	Greater mouse-eared bat; traffic noise	Five-fold increase in prey search time close to a simulated highway
Blickley, Blackwood, & Patricelli (2012)	Greater sage-grouse; drilling and road noise	Lek attendance reduced by 29% and 73%
Rolland et al. (2012)	North Atlantic right whale; shipping	Stress hormone metabolites fell when ship noise dropped by 6 dB
Wale et al. (2013)	Shore crab; ship noise	Feeding disrupted and retreat to shelter slowed
Ware et al. (2015)	Migrating songbirds; traffic noise playback	31% of community avoided noise; body condition of remaining birds declined
Simpson et al. (2016)	Ambon damselfish; motorboat noise	Predation by a natural predator more than doubled
Kleist et al. (2018)	Cavity-nesting birds; gas compressors	Altered corticosterone and reduced hatching success
Senzaki et al. (2020)	142 bird species; continental noise model	Nest success negatively related to noise in closed habitats

Notes: Findings are paraphrased from the cited sources.

VII. DISTRIBUTION, COMMUNITIES, AND ECOLOGICAL PROCESSES

A long-standing difficulty in this field is that noise usually accompanies other disturbance, such as habitat loss, collision mortality, and visual intrusion. Two approaches have overcome this. The first exploits industrial sites that differ in noise but not in other respects. In the boreal forest of Alberta, passerine density was about one and a half times higher around noiseless well pads than around noisy compressor stations (Bayne et al., 2008). In New Mexico woodland, noisy gas-well sites supported fewer nesting bird species than quiet ones, yet nests at noisy sites were more successful because a major nest predator, the western scrub-jay, avoided noise (Francis et al., 2009). This rearrangement of the community had further consequences. Hummingbird pollination increased at noisy sites, whereas the dispersal and recruitment of piñon pine seeds declined because scrub-jays, which cache the seeds, were scarce there (Francis et al., 2012).

The second approach is experimental playback at landscape scale. The phantom road in Idaho reduced bird abundance by more than a quarter during periods when the speakers were on, with some species avoiding the area almost completely (McClure et al., 2013). Because nothing but sound was altered, this is direct evidence that noise alone degrades habitat. Ware et al. (2015) emphasised a further implication: the continued presence of a species in noisy habitat does not show that it is unaffected.

In the ocean, anthropogenic sound has been shown to affect marine animals at multiple levels, from behaviour and physiology to, in extreme cases, survival (Duarte et al., 2021). For fishes, the potential effects of chronic, moderate noise from vessels over large areas are of greater concern than those of rare, intense events (Slabbekoorn et al., 2010). Community-level studies are summarised in Table 3.

Table 3. Studies Isolating the Effect of Noise on Distribution, Communities, and Ecological Processes

Study	System and design	Principal finding
Bayne et al. (2008)	Boreal songbirds; noisy vs noiseless energy sites	Passerine density about 1.5 times higher at noiseless sites
Francis et al. (2009)	Woodland birds; gas wells with and without compressors	Fewer nesting species but higher nest success at noisy sites owing to predator avoidance of noise
Francis et al. (2012)	Same system; plants and their animal mutualists	Pollination by hummingbirds increased and piñon pine seed dispersal decreased in noise
McClure et al. (2013)	Migrating birds; phantom road playback	Bird abundance fell by more than a quarter when noise was on
Ware et al. (2015)	Migrating birds; phantom road playback	Habitat use and body condition reduced by noise alone
Buxton et al. (2017)	Protected areas of the contiguous USA; sound models	Noise doubled background levels in 63% of protected area units

Notes: Findings are paraphrased from the cited sources.

VIII. DISCUSSION

8.1. Integration of Evidence

The evidence reviewed shows that anthropogenic noise is a genuine pollutant and not merely a nuisance. Its effects have been demonstrated experimentally, in isolation from other disturbance (McClure et al., 2013; Ware et al., 2015), they extend from signalling behaviour to survival and reproduction (Halfwerk, Holleman, et al., 2011; Simpson et al., 2016; Kleist et al., 2018), and they occur across most animal groups tested (Kunc & Schmidt, 2019). Responses of terrestrial wildlife begin at sound levels of about 40 dBA, and one-fifth of the studies reviewed by Shannon et al. (2016) documented effects below 50 dBA, levels that are commonplace near roads and settlements. Behavioural flexibility allows some species to persist in noise, but flexibility has limits and costs (Halfwerk, Bot, et al., 2011; Nemeth & Brumm, 2010), and the capacity of species to adjust influences which of them remain (Francis et al., 2009). Because species differ in sensitivity, noise can reorganise communities and alter ecological processes in ways that are not predictable from the responses of single species (Francis et al., 2012).

8.2. Limitations of Current Knowledge

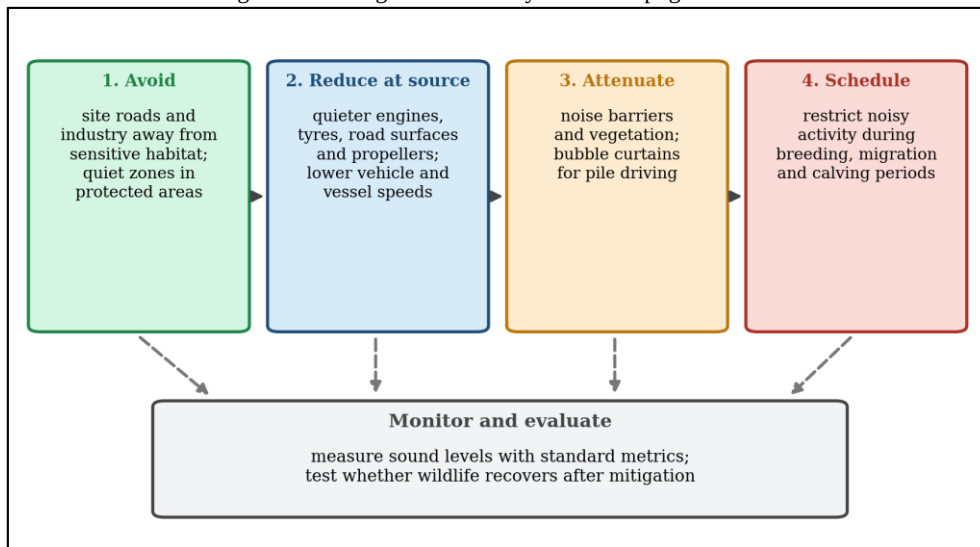
Several limitations should be noted. Research is taxonomically biased. Birds and aquatic mammals accounted for 37% and 28% of studies respectively, whereas invertebrates contributed only 4% (Shannon et al., 2016; Morley et al., 2014). It is also geographically biased. About 81% of terrestrial studies came from North America or Europe, or were laboratory-based, and only 4% were from Asia (Shannon et al., 2016). Acoustic exposure is frequently poorly described. Thirty per cent of studies gave no received sound level, which hampers comparison and the setting of thresholds (Shannon et al., 2016). Most studies are short-term and measure behaviour in a single species, so that evidence for long-term population consequences is largely indirect. Finally, noise commonly co-occurs with artificial light and other stressors, and their combined effects are little known (Senzaki et al., 2020).

8.3. Mitigation and Research Priorities

Unlike chemical pollutants, noise leaves no residue, and the environment becomes quieter as soon as the source is reduced (Rolland et al., 2012; Derryberry et al., 2020). Mitigation is therefore feasible, and options can be arranged as a hierarchy (Figure 4). Noise can be avoided by siting roads and industrial plant away from sensitive habitat and by managing noise within protected areas, which are quieter where regulation is more stringent (Buxton et al., 2017). It can be reduced at source through quieter engines, tyres, road surfaces, and ship propellers and through lower vehicle and vessel speeds (Shannon et al., 2016; Duarte et al., 2021). It can be attenuated along its path by barriers on land and by bubble curtains around pile driving at sea, and noisy activities can be scheduled outside breeding and migration periods (Shannon et al., 2016). Few studies, however, have tested whether such measures benefit wildlife. Only 9% of the studies reviewed by Shannon et al. (2016) offered specific mitigation recommendations.

Research priorities, summarised in Table 4, include studies of neglected taxa and regions. Road networks and shipping are expanding fastest in tropical Asia, Africa, and South America, which hold much of the world's biodiversity but have contributed little to the literature. In India, for example, the effects of traffic, railway, and festival noise on forest birds, anurans, and bats in and around protected areas remain largely unstudied and would repay investigation.

Figure 4: A Mitigation Hierarchy for Anthropogenic Noise



Source: Author's schematic based on the mitigation measures reviewed by Shannon et al. (2016), Buxton et al. (2017), and Duarte et al. (2021)

Measures are ordered from avoidance of noise in sensitive habitat, through reduction at source and attenuation along the transmission path, to seasonal and daily scheduling. Monitoring with standard acoustic metrics is needed to evaluate whether wildlife benefits.

Table 4. Knowledge Gaps and Research Priorities

Knowledge gap	Recommended action	Supporting sources
Taxonomic bias	Extend research to invertebrates, amphibians, reptiles, and fishes	Morley et al. (2014); Shannon et al. (2016)
Geographic bias	Establish studies in tropical Asia, Africa, and South America	Shannon et al. (2016)
Poor acoustic reporting	Report received levels, frequency weighting, and measurement procedures	Shannon et al. (2016)
Short-term, single-species focus	Measure survival, reproduction, and population trends over several years	Kleist et al. (2018); Senzaki et al. (2020)
Untested mitigation	Monitor wildlife before and after noise reduction	Rolland et al. (2012); Derryberry et al. (2020)
Interacting stressors	Test combined effects of noise, artificial light, and habitat change	Senzaki et al. (2020)

Notes: Recommendations are the authors' synthesis of the cited literature.

IX. CONCLUSION

This review integrates evidence on the effects of anthropogenic noise on animal behaviour and its consequences. Key conclusions include:

- Noise affects animals by masking signals and cues, by distracting them, and by being perceived as a threat
- Birds, frogs, insects, and whales alter the frequency, amplitude, or timing of their signals in noise, but these adjustments are limited and can reduce signal attractiveness
- Noise reduces the hunting success of acoustic predators, distracts prey, and shifts time from feeding to vigilance, and it can increase predation mortality
- Chronic noise is associated with altered stress physiology and with reduced pairing, clutch size, and hatching success
- Playback experiments show that noise alone reduces bird abundance and body condition, and natural contrasts show that it can alter pollination and seed dispersal
- Effects occur in most taxa tested and at modest sound levels, but knowledge is biased towards birds and marine mammals of temperate regions
- Noise is reversible at source, which makes mitigation practicable.

The acoustic environment should be treated as a component of habitat quality in conservation planning and environmental impact assessment. Extending research to tropical faunas and testing the ecological benefit of mitigation are the most pressing needs.

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