NOISE POLLUTION

Noise pollution is pervasive in U.S. protected areas

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Anthropogenic noise threatens ecological systems, including the cultural and biodiversity resources in protected areas. Using continental-scale sound models, we found that anthropogenic noise doubled background sound levels in 63% of U.S. protected area units and caused a 10-fold or greater increase in 21%, surpassing levels known to interfere with human visitor experience and disrupt wildlife behavior, fitness, and community composition. Elevated noise was also found in critical habitats of endangered species, with 14% experiencing a 10-fold increase in sound levels. However, protected areas with more stringent regulations had less anthropogenic noise. Our analysis indicates that noise pollution in protected areas is closely linked with transportation, development, and extractive land use, providing insight into where mitigation efforts can be most effective.

Over the past century, human activities have increased the magnitude and distribution of anthropogenic noise, raising concerns about the potential impacts of noise pollution (*1*). Anthropogenic noise reduces the capacity to perceive natural sounds, which are fundamental to survival and reproduction of wildlife (*2*) and provide human health benefits (*3*, *4*). Noise pollution causes cognitive impairment, distraction, stress, and altered behavior and physiology in ways that directly influence both wildlife and humans (*5*–*9*). Moreover, noise pollution that alters the distribution or behavior of key species can have cascading effects on ecosystem integrity (*10*).

Noise pollution is often considered to be an urban problem, but expanding human development and activities in rural landscapes are extending its reach. Thus, assessments of the spatial distribution of noise pollution are needed, particularly in the context of protected land. Protected areas (PAs) cover more than 13% of the world's total land area and are an important tool for conserving biodiversity (*11*) and providing economic and health benefits for humans (*12*). PAs have a range of conservation goals, including the reduction of anthropogenic disturbance (*13*), yet PA objectives rarely include the management of noise pollution (*14*, *15*). We quantified the degree and extent of noise pollution in PAs and critical habitat for endangered species across the continental United States. We compared noise pollution among land management and protection status and investigated sources responsible for generating noise across PAs.

To quantify noise pollution, we used changes in environmental sound levels caused by anthropogenic factors, extrapolated with machine learning algorithms that analyzed the relationship between sound measurements at 492 sites and geospatial features (*16*). Our metric, "noise exceedance," is the difference between predicted A-weighted sound levels (LA_{50}) of the full model and predicted sound levels that result from minimizing the influence of anthropogenic noise. In

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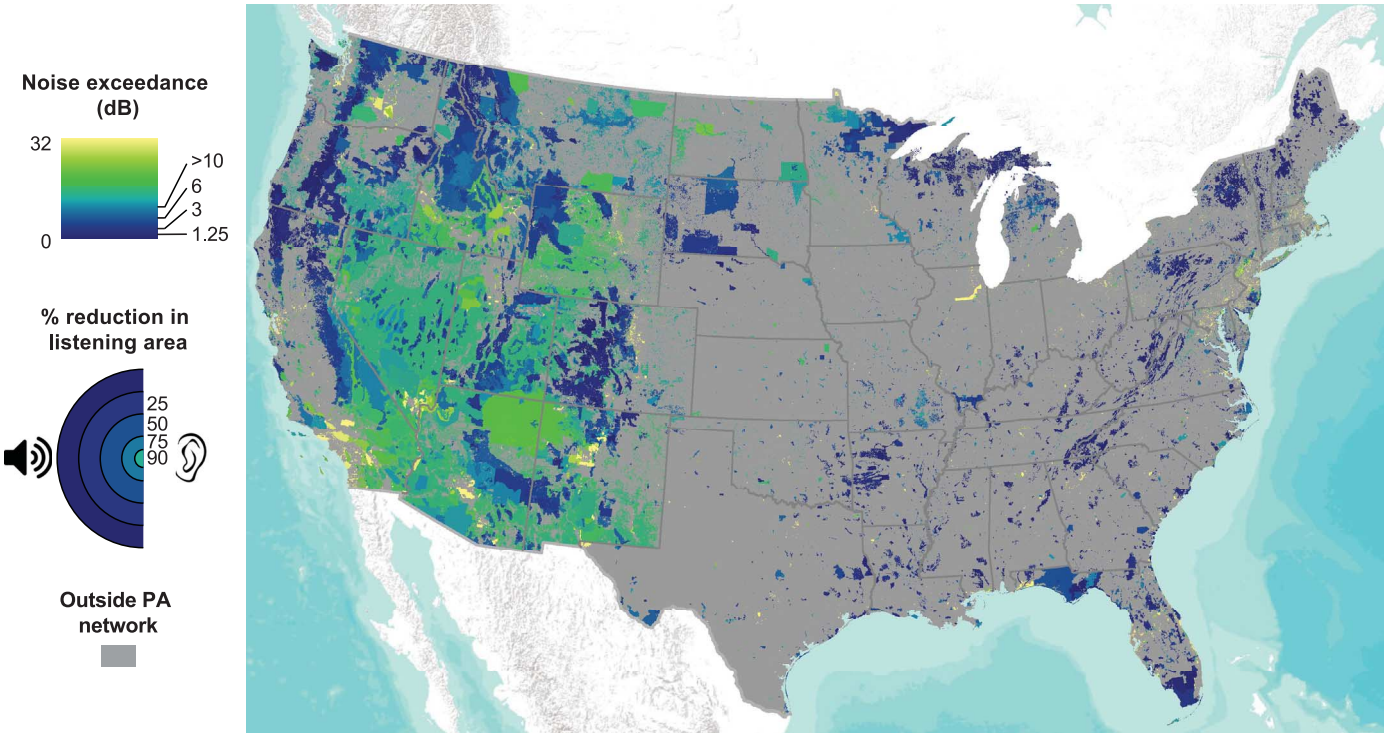

Fig. 1. Median noise exceedance (the amount that anthropogenic noise increases sound levels above the natural level) in protected area units across the contiguous United States. Noise exceedance of 1.25, 3.01, 6.02, and 10 dB corresponds, respectively, to 25, 50, 75, and 90% reductions in listening area (the area at which an acoustic signal can be detected) for humans. Gray areas are outside the protected area network.

effect, noise exceedance is the amount that anthropogenic noise raises sound above natural levels. A-weighting is the most widely used measurement in terrestrial noise studies, emphasizing sound energy at frequencies where many vertebrates have their most sensitive hearing thresholds (*17*). Threshold noise exceedance values of 3 and 10 dB were used to summarize noise pollution, indicating a doubling and 10-fold increase in acoustic energy due to anthropogenic noise and a 50 and 90% decline in listening area (the spatial extent of acoustic signal detection, fig. S1) (*18*). Anthropogenic noise 3 and 10 dB above natural sound levels is known to reduce visitor enjoyment of parks through annoyance and interference with natural quiet (*19*), and noise in this range has documented effects on wildlife species richness, abundance, reproductive success, behavior, and physiology (fig. S2) (*1*, *6*).

Noise exceedance was greater than 3 and 10 dB in 34.4 and 1.2% of all PA land area within the contiguous United States. The median noise exceedance within PA boundaries was greater than 3 and 10 dB in 62.8 and 20.9% of PA units (Fig. 1), demonstrating the prevalence of noise pollution. Most PAs either had low noise exceedance or were inundated with high exceedance. Thus, future efforts to manage noise in ecologically sensitive areas fit into two strategies: reducing noise in areas with high noise pollution and prioritizing the protection of quiet areas (Fig. 2A) (*20*). Using bootstrapped general additive models (GAMs) (*18*), we found that PAs experienced 34.9% less anthropogenic noise than adjacent 5-km buffers of unprotected land (Fig. 2B and table S1), even though noise management has not been a focus of PA creation, legislation, or management.

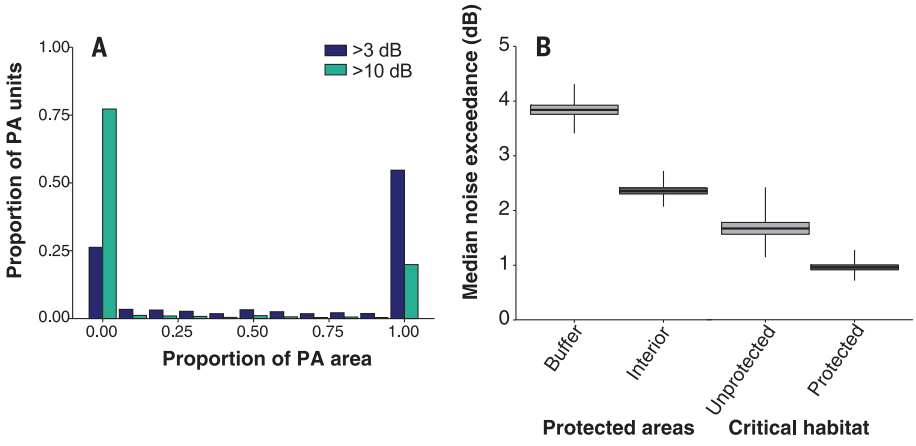

Fig. 2. Spatial extent of noise exceedance in PAs and degree of noise exceedance in PAs, adjacent unprotected areas, and critical habitat of U.S. endangered species. Most PA units were either inundated with anthropogenic noise 3 and 10 dB above natural or largely unaffected by noise (**A**). Noise exceedance within PAs (interior) was lower than within unprotected 5-km buffer zones adjacent to PAs (buffer) and lower in protected versus unprotected critical habitat (**B**). Data presented are from all protected land and critical habitat across the contiguous United States.

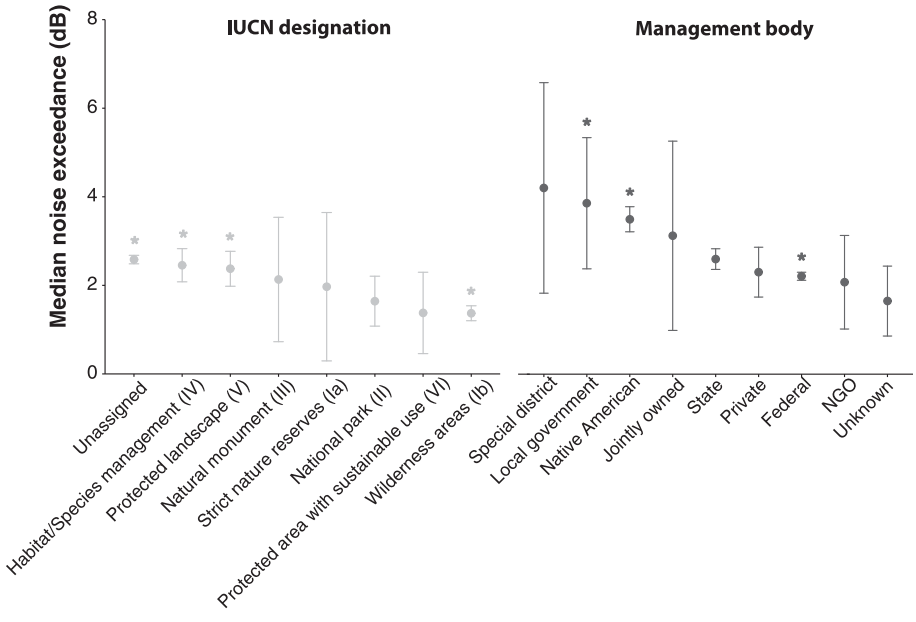

Fig. 3. Noise exceedance (± bootstrapped standard error) was higher in PAs without an International Union for Conservation of Nature (IUCN) designation, in areas where species or habitat are intensively managed (IV), in protected landscapes (V), in PAs managed by local government, and on Native American land. Noise exceedance was lower in wilderness areas and in PAs managed by the federal government. Asterisks indicate PA categories where the standard error around model parameter estimates did not overlap with 0, indicating a significant effect on noise exceedance.

To identify PA types with higher levels of noise pollution, we quantified noise exceedance in different PA classes based on International Union for Conservation of Nature (IUCN) categories and PA management bodies using a bootstrapped GAM fitting procedure (*18*). Noise exceedance was highest in PAs lacking IUCN designation, where median exceedance was more likely to surpass levels in surrounding unprotected buffer areas (Fig. 3 and tables S2 and S3). Among management bodies, lands managed by local governments had the highest noise exceedance (Fig. 3), often because these PAs were in or near urban areas. The severe degradation of the acoustical environment likely compromises the protective efficacy and diminishes visitor experience of these urban PAs.

Wilderness areas, which have one of the highest level of IUCN protection (category Ib) (*21*), experienced the lowest noise exceedance (Fig. 3 and table S2). Nonetheless, 12.1% of wilderness areas still experienced anthropogenic sound levels 3 dB above predicted natural levels, indicating that they are not entirely "untrammeled by man" as defined by the Wilderness Act (U.S. C. 1131-1136, sec. 3c, 1964). Wilderness areas are often remote sites with low background sound levels that enhance the audibility of distant sound sources; thus, minimizing the intrusion of anthropogenic noise in wilderness will require noise management at larger scales.

For species listed under the U.S. Endangered Species Act, designated critical habitat within PAs experienced 55.9% lower noise exceedance than those of unprotected areas (Fig. 2B and table S4). However, median noise exceedance was above 3 and 10 dB within critical habitat for 57.8 and 13.7% of endangered species (fig. S3). Noise exceedance varied across critical habitat for different taxa, with plants and invertebrates experiencing the highest noise exceedance (Fig. 4). The effects of anthropogenic noise are least understood for these taxa (*22*), but there is evidence of impacts across a wide range of species (fig. S1) (*6*) regardless of hearing sensitivity, including direct effects on invertebrates that lack ears (*23*) and indirect effects on plants and entire ecological communities (e.g., reduced seedling recruitment due to altered behavior of seed distributors) (*10*). Of endangered species with median noise exceedance above 10 dB in their critical habitats, 63% were partially within federal PA boundaries. Given the mandate of federal agencies to maintain

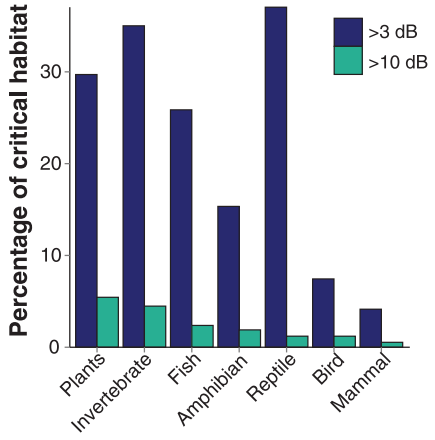

Fig. 4. For each taxon of species listed under the U.S. Endangered Species Act, the percentage of critical habitat where anthropogenic noise increased sound levels 3 and 10 dB above the natural level. We include plant species and animal species with less sensitive hearing thresholds (e.g., invertebrates), as they can be indirectly affected by anthropogenic noise if they interact with key organisms that respond to noise.

and enhance critical habitat, these areas offer the most feasible opportunity for noise management (fig. S4).

We found that human transportation networks, development, and extraction, all of which were correlated with proximity to cities, resulted in high noise exceedance in PAs (tables S3 and S5 to S7). Median noise exceedance values were more likely to surpass those in unprotected buffers for PAs with >16% of land occupied by roads, >40% used for extraction (timber, mining, oil, and gas), and >7% used for development (fig. S5 and table S3).

Our analyses show that PAs experience less anthropogenic noise than unprotected areas, likely because they limit human activity. Nonetheless, anthropogenic noise is present in most PAs and is pervasive in PAs near developed areas, where noise surpassed levels known to affect humans and wildlife. Given the widespread distribution of anthropogenic noise and extensive research documenting its negative impacts (*6*, *8*), noise pollution merits consideration in combination with other major threats when assessing PA effectiveness, management of endangered species, and enhancing human experience. Other than the soundscape management of the U.S. National Park Service (*24*, *25*), PA legislation does not include policies for the monitoring or management of anthropogenic noise. This is a conspicuous missed opportunity, as techniques to manage noise pollution are readily available (*26*) and noise management could improve ecological resilience and enhance quality of habitats facing multiple threats (*27*).

Despite the expansion of the PA network in the past few decades, biodiversity has continued to decline, emphasizing the importance of identifying factors that influence PA effectiveness (*14*). As human development expands within and surrounding PA boundaries, the identification of areas with high noise pollution presents an opportunity to reduce the interactive and cumulative impacts of anthropogenic noise and other stressors on natural systems (*28*).

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/356/6337/531/suppl/DC1
Materials and Methods
Figs. S1 to S5
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Editor's Summary

Shhh, you're disturbing the ecosystem

Species in nature reserves are experiencing increased pressure from human encroachment in many forms. One type of pressure that is rarely discussed but perennial is human-produced noise. Buxton *et al.* looked at the degree to which such noise has affected protected areas across the United States. Human-produced noise doubled background noise levels in a majority of protected areas and substantially affected critical habitat areas for endangered species.

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