www.sciencemag.org/content/356/6337/531/suppl/DC1

Supplementary Materials for

Noise pollution is pervasive in U.S. protected areas

Rachel T. Buxton,* Megan F McKenna, Daniel Mennitt, Kurt Fristrup, Kevin Crooks, Lisa Angeloni, George Wittemyer

*Corresponding author. Email: rachel.buxton@colostate.edu

Published 5 May 2017, *Science* **356**, 531 (2017)
DOI: 10.1126/science.aah4783

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Materials and Methods

Our analysis involved multiple steps. First, we extracted predictions of the change in sound levels due to anthropogenic noise from previously published geospatial models (*16*) as a measure of noise pollution in protected areas (PAs) across the contiguous United States (total number of cells = 31,680,065). We identified the number of protected areas with noise pollution above 3 and 10 dB thresholds, levels that are known to impact humans and wildlife based on a literature review. We summarized noise pollution levels among PA management bodies and IUCN designations. We then compared protected areas with unprotected areas by extracting and summarizing noise pollution levels in 5 km unprotected areas around each protected area unit and comparing them to median noise pollution levels within each protected area. We also summarized noise pollution levels in critical habitat of species listed under the Endangered Species Act. Lastly, to evaluate which anthropogenic sources were associated with high noise pollution in protected areas, we compared median noise pollution values and the difference between noise pollution in protected areas and adjacent unprotected areas with a suite of anthropogenic features in an information theoretic approach.

Anthropogenic noise levels

Summary of previously published geospatial model of sound levels. Georeferenced maps of sound levels across the contiguous U.S. were accessed from the National Park Service data store (*29*). These maps were generated by machine learning algorithms which analyzed the relationship between >1.5 million hours of sound measurements from 492 sites and geospatial features such as vegetation, topography, climate, hydrology, and anthropogenic activity (*16*). To account for temporal and seasonal variation in the acoustic environment, time of day and day of year were included as model covariates, allowing for projections to be made for a given time of day and year. To overlap with the breeding season of most North American species and peak visitation in National Parks, models projected the median A-weighted sound levels re 20 µPa (L_{A50}) for an average summer day. A-weighting is the most widely used composite measure of sound in human and wildlife noise studies, where sound energy is summed across the frequency spectrum, emphasizing frequencies in which many terrestrial vertebrates have their most sensitive thresholds of hearing (*1, 30*). The L_{A50} is a robust statistic (50^{th} percentile sound levels, or median sound levels) that is less sensitive to infrequent, loud events, whereas the L_{A10} (10^{th} percentile sound levels) or the L_{Aeq} (equivalent level of energy integrated over time) would yield larger estimates of anthropogenic noise impacts. L_{A50} were expressed in decibels (dB), a ratio of summed, squared pressure deviations to squared reference pressure transformed using the base 10 logarithm and multiplied by 10. Note that the modeled L_{A50} are projections of generic geospatial patterns expressed by numerous measurement sites, rather than values calculated from sound source levels or physical models of sound propagation.

Noise exceedance. In addition to predicting expected sound levels ($L_{existing}$), the geospatial model can evaluate changes from current acoustic conditions by modifying model inputs. By changing model inputs from their current values to values that minimize anthropogenic factors, models can generate approximate natural sound levels (L_{nat}; *31*). This enables the evaluation of the amount that anthropogenic sound energy raises the existing sound levels above natural, by calculating the difference between existing sound levels and sound levels that result from minimizing the influence of anthropogenic noise:

$$noise\ exceedance = 10log10\left({10^{(L_{existing}/10)}} \Big/ {10^{(L_{nat}/10)}} \right) = \boldsymbol{L_{existing}} - \boldsymbol{L_{nat}} \qquad \text{Eq. 1}$$

We describe this value as "noise exceedance" and use it as an index of noise pollution in all further analysis as it measures changes in sound levels due to anthropogenic noise and estimates the consequent decrease in distance at which sounds of interest can be heard by an animal (decreased "listening area"). We note that for the same level of anthropogenic noise, a site with high levels of natural sounds – waterfalls, river rapids, and frequent rainfall – will generate a lower noise exceedance value than a site with low levels of natural sound. Also, levels of natural sound tend to be higher in summer than winter, so our analysis will typically underestimate winter noise exceedances.

Noise exceedance thresholds. We examined the proportion of PAs and critical habitat of U.S. endangered species with median noise exceedance above 3 and 10 dB. We selected these thresholds because a 3 dB noise exceedance indicates a doubling of sound energy (e.g. 40 dB $\boldsymbol{L_{nat}}$ + 40 dB $\boldsymbol{L_{anthropogenic}}$ = 43 dB $\boldsymbol{L_{existing}}$ = 3 dB noise exceedance), and a 10 dB noise exceedance indicates a ten-fold increase.

Noise exceedance values of 3 and 10 dB also correspond to 50% and 90% reductions in listening area (*1*) if natural sound levels are higher than an organism's threshold of hearing. To test this assumption, we summarized sound measurements from national parks across the contiguous U.S. (*31*). We used L_{90} (90^{th} percentile sound levels) at each site, which provides a lower bound for sound conditions in the absence of anthropogenic noise, approximating natural sound levels. We found that L_{90} values in almost all acoustic monitoring locations exceed human hearing thresholds between 160 and 8000 Hz (Fig. S1). Even if an organism's hearing thresholds were 10 dB worse than humans, a level which encompasses most mammals and birds (*32*), they would still satisfy this assumption at >50% of sites for frequencies between 315 and 5000 Hz. Notably, many species have more sensitive hearing than humans (e.g., owls; *33*). Because the listening area assumption is met within frequencies that encompass the most sensitive hearing thresholds for many vertebrate species, it is likely that a broad suite of animals in a variety of habitats have diminished auditory capability at noise exceedance thresholds of 3 dB and 10 dB. Moreover, increasing evidence suggests that anthropogenic noise may affect animals with drastically different hearing thresholds than humans, even when noise does not spectrally overlap with acoustic communication signals and sensitive hearing ranges (*34, 35*).

In addition to the consequences for acoustic signal detection, there are other substantial effects of noise on humans and wildlife. Other costs of anthropogenic noise are increases in distraction (*36, 37*), stress (*38, 39*), and cognitive impairment (*40*). For humans, exposure to noise in a park setting leads to degraded visitor experience: noise exceedance values of 3 and 10 dB result in approximately 25% and 50% of park visitors reporting annoyance and interference with their experience of natural quiet (*19*). Although the effects of noise pollution on wildlife may depend on several aspects of the noise stimulus (e.g., temporal patterns, frequency, novelty) and the animal species (e.g., tolerance, tendency to habituate), there is growing evidence that increases in anthropogenic noise often result in changes in behavior and physiology, lower fitness, changes in distribution, and altered community composition (*6*). For organisms that do not perceive sound (e.g., plants), anthropogenic noise may have indirect effects, through changed behavior or distribution of key, sensitive species with which they interact (*10*). To highlight the tangible effects of an increase in noise exceedance on wildlife, we compiled studies from a recent literature review of the effects of anthropogenic noise on terrestrial wildlife (*6*) where authors reported control sound levels (n=41). To generate a similar anthropogenic noise metric to noise exceedance, we calculated the difference between the treatment and control sound levels (parallel to $L_{existing}$ - L_{nat}) and summarized levels that resulted in a response across studies. Some studies used L_{eq} values (rather than L_{50}) and no weighting or C-weighting sound adjustments (rather than A-weighting); thus, figure S2 represents an approximation of noise exceedances that result in wildlife response. With this caveat, we show that 68% of studies demonstrated a response when treatment sound levels were >10 dB above the control (Fig. S2). These studies did not assess responses across a range of noise values, thus, it is possible that many species may react to noise at lower levels than were studied. In other words, 32% of studies detecting responses at values less than 10 dB does not imply that responses at these lower noise levels are uncommon.

Geospatial data

Maps of predicted noise exceedance have a raster resolution of 270m; thus all other geospatial layers were rasterized to the same resolution to allow overlaying. We obtained protected area (PA) boundaries from the USGS Gap Analysis Program's PAs database (GAP PAD-US version 3; *41*). PAs were dissolved by standardized name and rasterized for further analysis. We excluded PA units awaiting official declaration (i.e. proposed sites). PAs <1 km^2 were excluded from analysis, as they were below the spatial resolution of the noise exceedance layer, leaving 73,552 PAs. We extracted all noise exceedance values within PAs, generating a total of 31,680,065 raster cells. To compare noise exceedance values in PAs with adjacent unprotected areas we summarized noise in buffers around each PA. We chose the maximum buffer radius that was computationally feasible, 5 km, to ensure we adequately sampled sounds in the landscape surrounding each PA. Buffer areas overlapping adjacent PAs were excluded. We compared noise exceedance between PAs and buffers and between different PA designations and management types (Table S2-3, 6).

We obtained critical habitat boundaries of U.S. endangered species from the U.S. Fish and Wildlife Service environmental conservation online system (*42*). To capture noise exceedance in each species' critical habitat, we rasterized each species' habitat polygon individually, joined PA attributes, and compiled all data for further analysis.

We ranked and compared noise exceedance in each type of PA and among designated critical habitat of animals listed under the U.S. Endangered Species act using 3 and 10 dB as thresholds of noise exceedance.

To determine what sources of noise were most responsible for higher median predicted noise exceedance in PAs, we used fourteen anthropogenic geospatial data layers (Table S7). These included PA designation and level of protection, and distance to, density, and size of nearby anthropogenic features (e.g., cities, roads, airports, land use). We calculated the density of anthropogenic land use type (crops, grazing, extractive, industrial, and developed), oil and gas production, oil wells, roads, and railways by rasterizing each feature and calculating the proportion of rasters with each feature present within each PA. We obtained georeferenced frequency of commercial and military flights (*29*). Because we were unable to obtain levels of watercraft traffic, we used the presence of large bodies of water as a correlate of higher motorized boat activity. To view and process all geospatial data layers we used ArcGIS for Desktop (10.3, ESRI Inc., USA) and R statistical software v. 3.2.0 (*43*).

Quantitative analysis

We performed all statistical analyses using R statistical software v. 3.2.0. Because noise exceedance values within PAs were not normally distributed we present summary statistics as medians ± standard deviation or inter-quartile ranges (*44*). Because noise exceedance values appeared to be clustered in distribution, we tested for spatial autocorrelation among noise exceedance values within PAs by calculating Moran's I in the *raster* package (*45*). We used values >0.9 to indicate strong spatial autocorrelation (*46*).

Noise exceedance values in different PA categories. To compare noise exceedance values among PA management bodies (e.g., federal, state, private, etc.), among PA IUCN designations, between critical habitat for endangered species within and outside PA boundaries, and between PAs and 5 km radius unprotected buffer zones we used a bootstrapped general additive model (GAM) fitting procedure.

Moran's I for noise exceedance raster values were ≥ 0.95, indicating that noise exceedance values were highly autocorrelated. Typically, to control for autocorrelation, models require a correlation matrix between each pair of spatial locations, increasing the computational cost according to the cube of the sample size (*47*). Because such models would be prohibitive given our large data set, we fit GAMs with thin plate regression spline smoothed x,y coordinates (mgcv package; *47, 48*). In this case, the number of dimensions is reduced by smoothing the spatial process (i.e. x,y values) over a finite number of representative locations (*49*):

$$y \sim \mathrm{N}(\mathrm{X}\beta + \mathrm{Z}\alpha,\ \sigma^2 \mathrm{I}) \,, \qquad \text{Eq. 2}$$

where y is a vector of noise exceedance, X are the covariates, β are the coefficients, σ^2I is the normally distributed error and Zα is a basis function for x,y coordinates:

$$\mathrm{Z} \equiv \mathrm{C}(\phi)\mathrm{R}(\phi)^{-1} \qquad \text{Eq. 3}$$
$$\alpha \sim \mathrm{N}(0, \sigma^2\mathrm{R}(\phi)) \,,$$

where R(ϕ) is the correlation matrix for preselected knots and C(ϕ) is the cross-correlation matrix between observed data and knots. Because there were multiple noise exceedance values (cell values) within the same PA, we controlled for variation in values by including the ridge penalized PA unit name as a covariate in Eq. 2. In order to determine the best model structure we fit the model in Eq. 2 with different knot sizes and link structures to a random subset (n_{sub} = 500) of the full dataset (with replacement) 1000 times and determined the highest mean R^2 and mean estimated degreed of freedom of the spatial smooth furthest from the number of knots minus 1 (*50*). Using these criteria, we selected a knot size of 30, a Gaussian error structure, and an identity link. Because loud sound sources produce large variation in noise exceedance with distance (SPL attenuates as distance from the source increases), there were large inequalities of variance among categorical covariates. To reduce inequalities of variance we log transformed noise exceedance values.

Despite attempts to reduce dimensions, we obtained over 31 million noise exceedance estimates in PAs, and thus were unable to fit a model to all the data (i.e. using a bam procedure;

47). Instead, we used non-parametric bootstrapping of the model fitting process to estimate the distribution and true standard error of coefficients (*51*). We fit the model in Eq. 2 to a random subset (n_{sub} = 500) of the full dataset (with replacement) 5000 times.

We ran four bootstrapped GAM models where we included each covariate as a separate set of binary dummy variables (X; Eq. 2): 1) IUCN designation, where we combined 'permanently unassigned' with 'unassigned'; 2) management body; 3) buffer zone with PA set as a reference class; and 4) critical habitat outside of protected area boundaries, with critical habitat within protected areas set as a reference class (*52*).

Noise sources associated with high median noise exceedance in PAs vs unprotected buffers. To investigate which noise sources and land designation types were most associated with higher median noise exceedance in PAs and higher median noise exceedance in PAs versus corresponding 5 km buffer zones, we used an information theoretic approach. For median PA noise exceedance, all Moran's I were ≤ 0.810, indicating weak evidence of spatial autocorrelation; thus, we did not include a spatial component in the following models.

We constructed two separate model sets with the following response variables: 1) a binary response variable where PAs with a median noise exceedance greater than or equal to adjacent buffers were scored as 1, and PAs with a median noise exceedance less than adjacent buffers were scored as 0; and 2) median noise exceedance in PAs. Global models were generalized linear models (GLM) with a Laplace approximation; the first model set had a binomial distribution and logit link and the second model set had a Gaussian distribution and identity link. We included the following covariates: management body and IUCN designation as dummy variables (with one class set as a reference; Table S7); GAP status code (measure of management intent to conserve biodiversity; *53*); area of the PA unit; distance to and number of enplanements of the nearest airport; distance to and size of the nearest city; distance to and type of nearest large water body; distance to the nearest railway; population density, road density, rail density, and density of oil wells within the PA; weekly flight frequency and military flight path density; number of mines; oil and gas production; and proportion of the PA land used for different types of anthropogenic activity ("land use": crops, grazing, extractive, industrial, and developed; Table S7). We computed a Spearman's correlation matrix to assess collinearity among explanatory variables and omitted one of each covariate randomly when correlation coefficients (R) were greater than 0.5 (GAP status code; population size; distance to city and roads; and IUCN category V and IV were removed from further analysis). For the binomial buffer model set we removed distance to rail, flight frequency, and military flight path density from this analysis, as their distance component made buffer comparison results difficult to interpret (i.e., if the nearest rail was within the buffer, a smaller 'distance to rail' may result in a quieter PA vs buffer). To ensure the resulting parameter estimates would be comparable, all variables were scaled by subtracting the mean and dividing by one standard deviation (*54*).

We considered two sets of 20 *a priori* candidate models (Table S7), where important sets of covariates were constructed based on other studies examining noise sources in U.S. parks (*16, 24, 55*). For models with a binary response variable, comparing noise exceedance levels in protected areas to buffers, we found the model including park area; density of oil wells; oil and gas production; number of mines; the proportion of PA land used for crops, grazing, extractive, industrial, and developed; density of rail lines and roads; enplanements of the nearest airport; distance to a large body of water; federal, local government, Native American, non-governmental organization, private, and state management bodies; and Ib, II, VI, and Unassigned

IUCN designations (model #19; Table S7) received 99% of the total weight. For models examining median noise exceedance in each PA, the global model received 99% of the total weight. We used model averaging of all candidate models to generate parameter estimates, unconditional standard errors, and 95% confidence intervals using the package *MuMIn* (*56*). Because our sample size was so large and all covariates were scaled, we used the size of parameter estimates rather than summed Akaike weights when estimating the effect size for each predictor variable (*57*). We considered covariates with large parameter estimates and 95% confidence intervals that did not overlap zero to be the most influential (Table S3, S6).

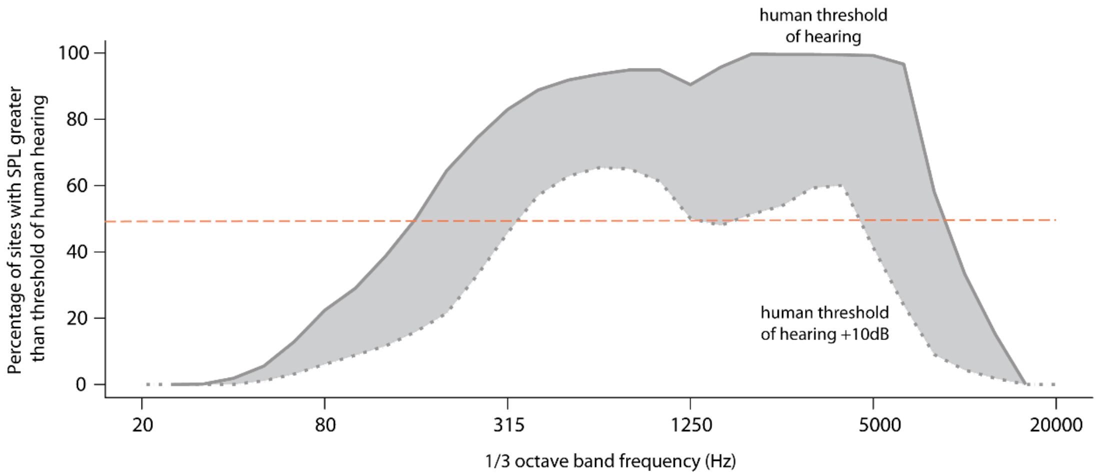

Fig. S1

Nearly 100% of national park recording sites (for site details see *16*) are at or above the threshold of human hearing (dark grey line), while >50% (pink stippled line) of sites are at or above most vertebrate species hearing thresholds between 315 and 5000 Hz. Thus, for species whose hearing thresholds are within 10 dB of humans (grey area), additional sound within these frequencies is detectable and could mask natural sound signals at most sites. Sound levels exceeded 90 percent of the time (L_{90}) in each 1/3 octave frequency band approximate natural sound levels.

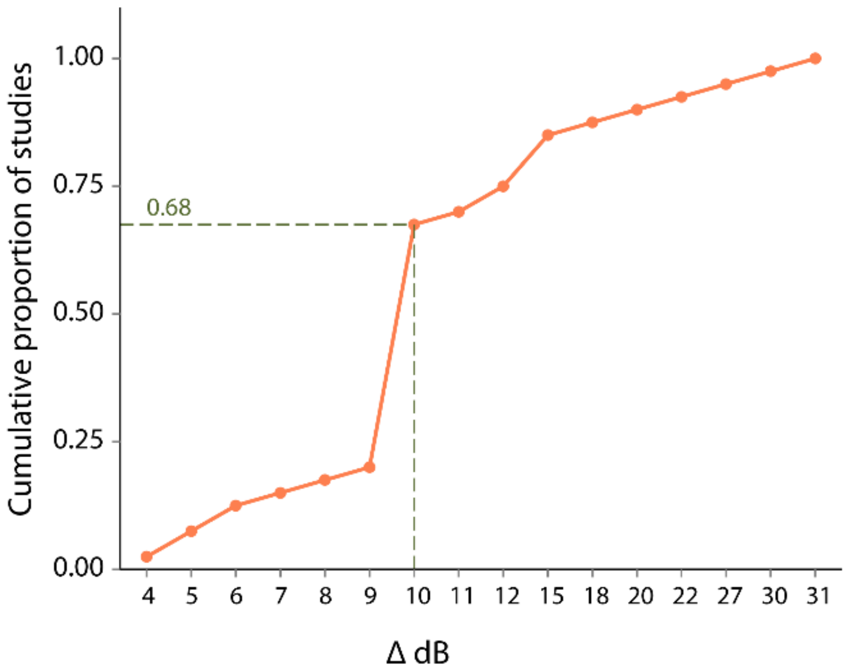

Fig. S2.

Proportion of studies found in the literature from 1990-2013 (altered from *6*) demonstrating a response to each level of increase in anthropogenic noise above background (Δ dB = sound pressure levels during anthropogenic noise treatment – sound pressure levels at control, parallel to our 'noise exceedance' metric). Response was defined as a significant change in behavior, distribution, reproductive success, species richness, or physiology.

*Data summarized from the following references: (*58*) (*59*) (*38*) (*60*) (*61*) (*62*) *(63) (33) (64) (65)* (*66*) (*67*) (*68*) (*69*) (*10*) (*70*) (*71*) (*72*) *(73)* (*74*) (*75*) *(76)* (*77*) (*78*) (*79*) (*80*) (*81*) (*82*) (*83*) (*84*) (*85*) (*86*) (*87*) *(88)* (*89*) (*90*) (*91*) (*92*) (*93*)

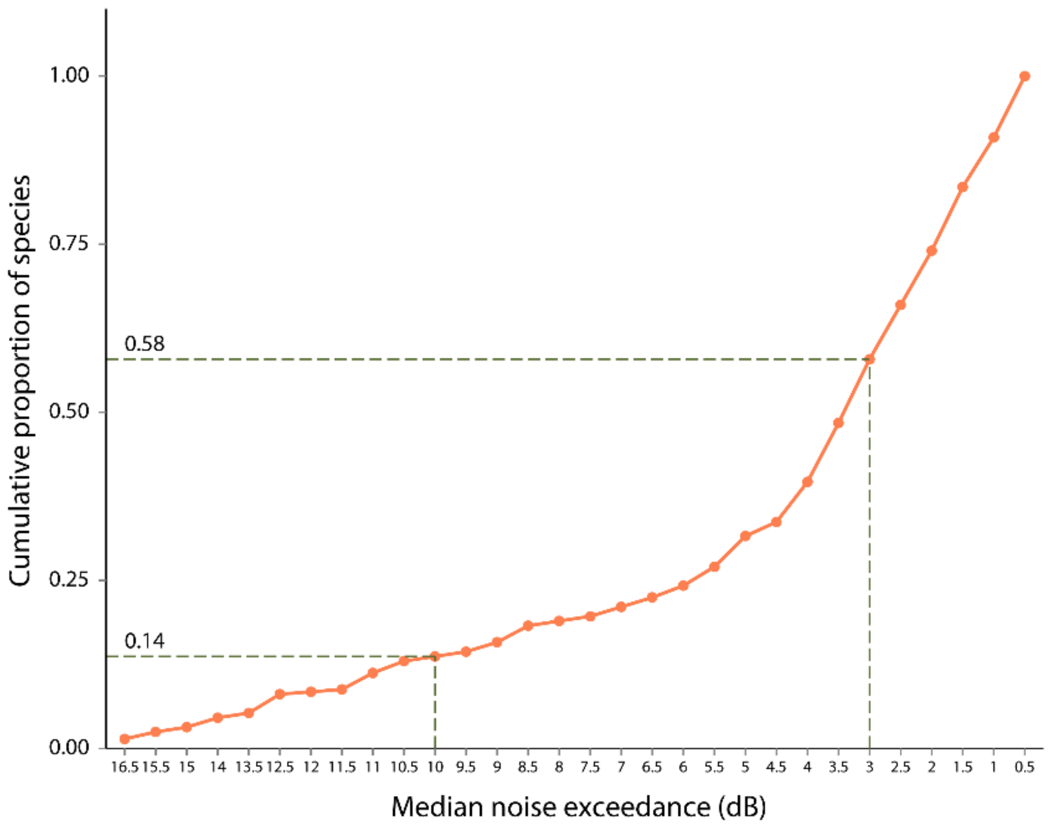

Fig. S3

Cumulative distribution function for median noise exceedance values in each species' critical habitat. Dashed lines represent the proportion of species' critical habitats with noise exceedance above 3 dB and 10 dB respectively.

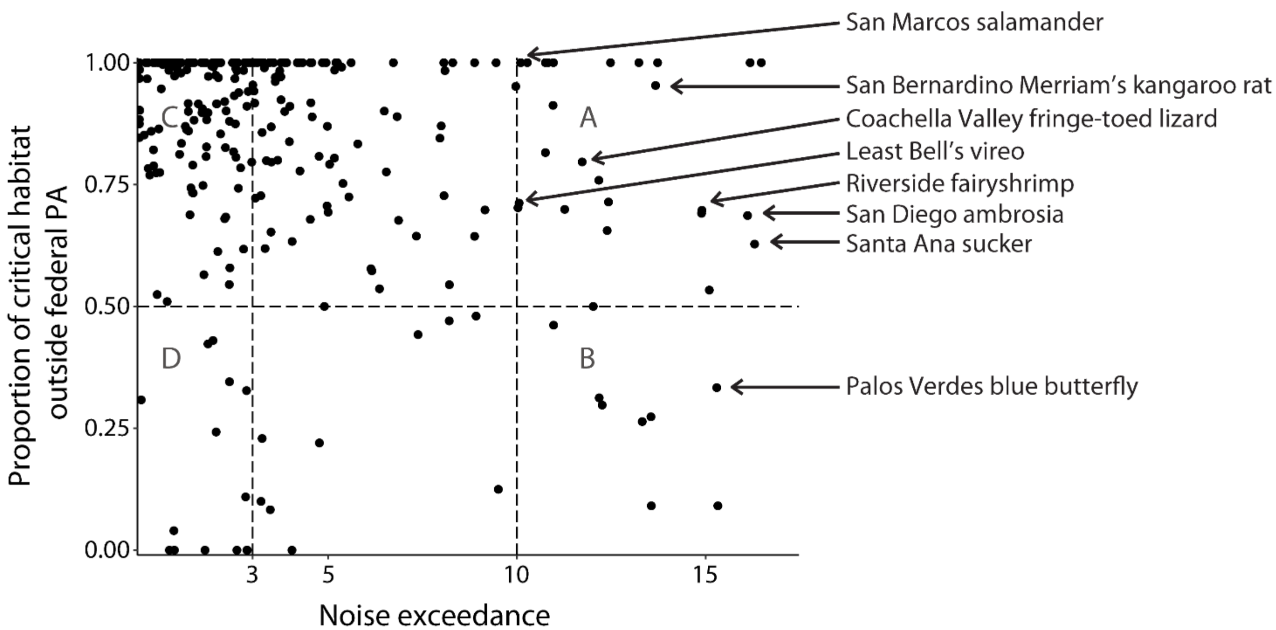

Fig. S4

For each species listed under the US Endangered Species Act, a comparison of the median noise exceedance within their critical habitat boundaries to the proportion of their critical habitat that falls outside of federally protected areas. Potential for noise management can be related to the different quadrants. Quadrant A: species whose critical habitat experiences noise pollution that may be most difficult to mitigate, because of high noise exceedance and high proportion of habitat that falls outside federal protected areas. Quadrant B: species whose critical habitat experiences high noise exceedance and has more area within federally protected land, offering more opportunity for noise management actions. Quadrant C: species whose critical habitat experiences lower noise exceedance and is still mostly outside of federally protected lands, where monitoring of human land use is important. Quadrant D: species whose critical habitat requires the least noise management and where noise monitoring is still advisable, experiencing lower noise exceedance and mostly within federally protected lands. Examples of species from each taxonomic group with loud critical habitat are presented for display. Given we used geospatial models intended for airborne noise, noise effects on aquatic animals may be dampened. Noise may have indirect effects on plants, by altering the distribution and behavior of herbivores, seed dispersers, and pollinators. Figure is modeled from Fig. 8 in (*94*).

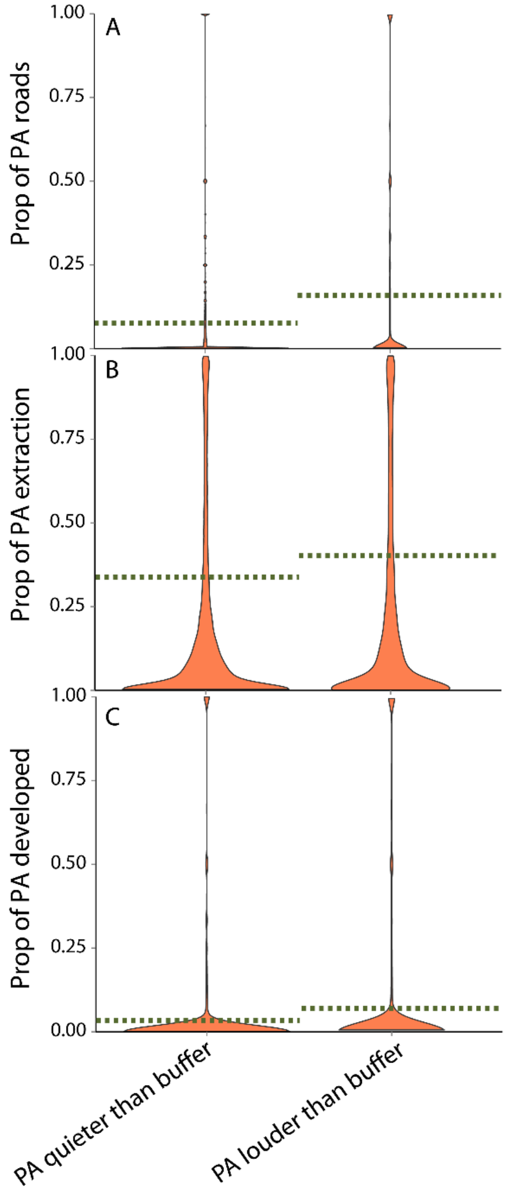

Fig. S5

In PAs where noise exceedance was higher than adjacent 5 km buffers of unprotected land (PA louder than buffer), the proportion of PA area (A) with roads, (B) used for extraction (e.g., timber, mining, oil, gas), and (C) used for development was higher. Dashed green lines indicate means and the thickness of the coral bars represents the distribution of the data, which are heavily zero-inflated (thickest near zero).

Table S1.

Mean bootstrapped parameter estimates (*b*PE) and predicted mean dBA (*b*PM) ± true standard error (tSE: standard deviation of bootstrapped parameter estimates and predicted means) from general additive models predicting noise exceedance in unprotected 5 km buffer zones around protected areas. Asterisk indicates parameter estimates where true standard error does not overlap 0.

	***b*PE ± tSE**	***b*PM ± tSE**
Protected area	n/a[†]	2.36 ± 0.08
5 km unprotected buffer*	0.36 ± 0.05	3.84 ± 0.13

[†]Protected area set as reference class

Table S2.

Mean bootstrapped parameter estimates (*b*PE) and predicted mean dBA (*b*PM) ± true standard error (tSE: standard deviation of bootstrapped parameter estimates and predicted means) from general additive models predicting noise exceedance in different protected area designations. Asterisks indicate parameter estimates where true standard error does not overlap 0.

	Abbreviation	*b*PE ± tSE	*b*PM ± tSE
IUCN designation			
Unassigned*		0.28 ± 0.1	2.58 ± 0.1
Protected landscape*	V	0.28 ± 0.15	2.37 ± 0.39
Habitat/species management*	IV	0.27 ± 0.15	2.45 ± 0.37
Natural monument	III	0.13 ± 0.48	1.97 ± 1.68
Strict nature reserve	Ia	0.12 ± 0.44	2.13 ± 1.4
National park	II	-0.05 ± 0.24	1.64 ± 0.56
Protected area with sustainable use of natural resources	VI	-0.1 ± 0.36	1.38 ± 0.92
Wilderness area*	Ib	-0.2 ± 0.12	1.37 ± 0.17
Management body			
Local government*		0.42 ± 0.33	3.87 ± 1.48
Special district		0.4 ± 0.44	4.22 ± 2.38
Native American*		0.29 ± 0.14	3.51 ± 0.28
Jointly owned		0.27 ± 0.44	3.13 ± 2.14
Private		0.07 ± 0.19	2.31 ± 0.56
State		0.06 ± 0.12	2.6 ± 0.23
NGO		-0.02 ± 0.31	2.08 ± 1.06
Unknown		-0.12 ± 0.3	1.65 ± 0.79
Federal*		-0.16 ± 0.11	2.22 ± 0.09

Table S3.

Weighted parameter estimates (wPE), unconditional standard errors (SEμ), and confidence intervals (CI) calculated from candidate models describing a binomial response variable comparing median predicted noise exceedance in protected areas and adjacent buffer zones in the contiguous U.S. (1 – noise exceedance was higher in protected area, 0 – noise exceedance was higher in buffer). Asterisks indicate parameter estimates with confidence intervals not overlapping 0 and × symbol indicates an interaction term.

	***w*PE ± SEμ**	**2.5 % CI**	**97.5 % CI**
Intercept	-0.63 ± 0.01	-0.64	-0.61
Road density*	0.34 ± 0.01	0.33	0.36
Proportion extractive land use*	0.17 ± 0.01	0.15	0.19
Unassigned IUCN*	0.12 ± 0.01	0.1	0.14
Proportion of PA developed*	0.11 ± 0.01	0.09	0.12
Proportion of PA grazed*	0.1 ± 0.01	0.09	0.12
Enplanements of nearest airport*	-0.1 ± 0.01	-0.12	-0.08
State land	0.08 ± 0.02	0.04	0.11
Distance to large water body*	0.06 ± 0.01	0.04	0.08
Proportion of PA used for crops*	0.06 ± 0.01	0.04	0.07
Railroad density*	0.04 ± 0.01	0.03	0.06
NGO land*	0.03 ± 0.01	0.01	0.05
Proportion of industrial land*	0.03 ± 0.01	0.01	0.04
Native American land*	0.02 ± 0.01	0.01	0.04
IUCN Ib	0.02 ± 0.01	0	0.03
Proportion of PA with oil & gas wells	0.02 ± 0.01	0	0.03
Federal land	-0.01 ± 0.01	-0.04	0.01
IUCN II	-0.01 ± 0.01	-0.03	0.01
IUCN VI	0.01 ± 0.01	-0.01	0.03
Local government land	0.01 ± 0.02	-0.02	0.04
Area (ha)	-0.01 ± 0.01	-0.03	0.01
Proportion of PA with oil & gas development*	-0.01 ± 0.01	-0.03	0.01
Nearby lake	0.01 ± 0.01	-0.01	0.03
Size of nearest city	0.01 ± 0.01	-0.01	0.02
Special district land	-0.01 ± 0.01	-0.03	0.01
Distance to large water body×Nearby lake	0.01 ± 0.02	-0.02	0.04
Private land*	0 ± 0.01	-0.03	0.03
IUCN Ia	0 ± 0.01	-0.01	0.02
IUCN III	0 ± 0.01	-0.01	0.02
Jointly owned land	0 ± 0.01	-0.02	0.01

Table S4.

Mean bootstrapped parameter estimates (*b*PE) and predicted means (*b*PM) ± true standard error (tSE: standard deviation of bootstrapped parameter estimates and predicted means) from general additive models predicting noise exceedance in unprotected critical habitat versus protected critical habitat. Asterisk indicates parameter estimates where true standard error does not overlap 0.

	***b*PE ± tSE**	***b*PM ± tSE**
Protected area	n/a[†]	0.96 ± 0.01
Unprotected area*	0.52 ± 0.11	1.67 ± 0.16

[†]Critical habitat within protected areas set as reference class

Table S5.
Sources and attributes of geospatial data layers used in the analysis of noise exceedance in protected areas of the contiguous U.S.

Variable	Attributes	Description	Data source
Response			
Noise exceedance (model output)	A-weighted L_{50}	Change in L_{A50} due to anthropogenic noise	(*29*)
Explanatory			
Protected area boundary	Management body	General management description‡	(*53*)
	Primary local name	Name of the protected area unit	
	Status	Official standing of the site◊	
	GAP status code	Measure of management intent (1-4*)	
	IUCN Category	IUCN management catergories (Ia - VI)**	
Critical habitat	Species common name	Animals only	(*42*)
Airport	Status	Only "operational" were used	Federal Aviation Administration (FAA) and Office of the Assistant Secretary for Research & Technology's Bureau of Transportation Statistics (OST-R/BTS)
	Enplanements	Total annual enplanements (number of passengers boarding an aircraft)	
	Distance from protected area		
Major Roads	Road classification	Only 'freeways', 'major roads', 'secondary roads', and 'important local roads' were used	ESRI Streetmap roads (2014)
	Distance from protected area		
	Density	Number of rasters with road present/total rasters	
Cities	Population size	Only those with >10,000 people in 2013 were used	ESRI 2014, U.S. Census Bureau
	Distance from protected area		
Population Density	Population size	Population census 2010	U.S. Census Bureau TIGER

			(http://www2.census.gov/geo/tiger/)
Railroad	Line status	'Abandoned' and 'out of service' were excluded	Federal Railroad Administration (FRA)
	Distance from protected area		
	Density	Number of rasters with rail line present/total rasters	
Military flights	Number of designated military flight paths	Sum within 25 mile radius area of interest from each point	(*95*)
Flight frequency	Number of weekly flight observations	Sum within 25 mile radius area of interest from each point	(John A. Volpe National Transportation Systems Center, *96*)
Body of water	Distance to large lake	Only lakes >150 ha used	National atlas water feature United States Geological Survey & ESRI v.10.1
	Distance to coastline		
Mining	Number of mines	Sum of active mines and mineral plants within a PA	(*96*)
Coalbed methane production	Proportion used for production	Oil and natural gas production by basin	(*97*)
Natural gas wells	Proportion with producing wells	Buffered polygons around producing wells	(*98*)
Land use	Proportion grazed	Areas used for livestock grazing	(*99*)
	Proportion with crops	Areas used for production of annual crops	(*99*)
	Proportion developed	Constructed materials constitute >20% of land cover	(*99*)
	Proportion extractive	Areas used for resource extraction (e.g., timber, mining, oil, and gas)	(*100, 101*)
	Proportion industrialized	Industrialized land cover	(*100, 101*)

‡ Federal, Native American, state, special district, local government, non-government organization, private, jointly owned

◊ Designated, proposed, other, unknown
*1: Managed for biodiversity - disturbance events proceed or are mimicked, 2: Managed for biodiversity - disturbance events suppressed, 3: Managed for multiple uses, 4: No known mandate for protection
** Ia: Strict nature reserves, Ib: Wilderness areas, II: National park, III: Natural monument, IV: Habitat/species management, V: Protected landscape, VI: Protected area with sustainable use of natural resources, Unassigned, and Permanently unassigned

Table S6.

Weighted parameter estimates (wPE), unconditional standard errors (SEμ), and confidence intervals (CI) calculated from candidate models describing median noise exceedance in protected areas in the contiguous U.S. Asterisks indicate parameter estimates with confidence intervals not overlapping 0 and × symbol indicates an interaction term.

	***w*PE ± SEμ**	**2.5 % CI**	**97.5 % CI**
Intercept	6.08 ± 0.01	6.06	6.11
Local government land*	1.6 ± 0.03	1.55	1.65
Developed land*	0.9 ± 0.01	0.87	0.92
Enplanements of nearest airport*	0.68 ± 0.01	0.66	0.71
Road density*	0.63 ± 0.01	0.61	0.65
Distance to nearest airport*	-0.63 ± 0.01	-0.66	-0.61
Flight frequency*	0.56 ± 0.01	0.53	0.59
Military flight path density*	-0.56 ± 0.01	-0.58	-0.54
Special district land*	0.54 ± 0.01	0.52	0.57
Distance to nearest railroad*	-0.41 ± 0.01	-0.44	-0.38
Proportion extractive land use*	-0.33 ± 0.02	-0.36	-0.3
Distance to large water body*	0.3 ± 0.01	0.27	0.33
Size of nearest city*	0.29 ± 0.01	0.26	0.31
State land*	0.26 ± 0.03	0.2	0.31
Proportion of industrial land use*	0.21 ± 0.01	0.19	0.23
Unassigned IUCN*	0.17 ± 0.01	0.14	0.19
Nearby lake*	-0.17 ± 0.02	-0.21	-0.14
Railroad density*	0.17 ± 0.01	0.15	0.19
Distance to large water body×Nearby lake*	0.17 ± 0.02	0.13	0.21
Proportion of PA grazed*	0.16 ± 0.01	0.13	0.18
IUCN Ib*	-0.14 ± 0.01	-0.16	-0.11
Federal land*	0.12 ± 0.02	0.08	0.16
Native American land*	0.12 ± 0.01	0.1	0.14
Private land*	0.11 ± 0.02	0.07	0.16
NGO land*	0.1 ± 0.01	0.07	0.13
Proportion of PA used for crops*	0.1 ± 0.01	0.07	0.12
IUCN Ia*	-0.07 ± 0.01	-0.09	-0.05
IUCN II*	-0.07 ± 0.01	-0.09	-0.05
Proportion of PA with oil & gas development*	0.07 ± 0.01	0.05	0.09
IUCN VI*	-0.04 ± 0.01	-0.06	-0.02
Jointly owned land*	0.03 ± 0.01	0.01	0.05
Number of mines	-0.02 ± 0.01	-0.04	0
IUCN III	0.01 ± 0.01	-0.01	0.03

Area (ha)	-0.01 ± 0.01	-0.03	0.01
Proportion of PA with oil & gas wells	0.01 ± 0.01	-0.02	0.03

Table S7.

Model set used to examine noise sources affecting noise exceedance in PAs vs unprotected buffers. Two types of response variables were used (40 models total): median noise exceedance in protected areas and the difference between noise exceedance in buffers and protected areas (1: median noise exceedance of PA greater than or equal to buffer, 0: median noise exceedance of PA less than buffer). The × symbol indicates an interaction term.

Model #	**Explanatory variables**
Global[‡]	Population density + Road density + Rail density + Distance to rail line[◊] + Enplanements of nearest airport + Distance to airport[◊] + Size of nearest city + Military flight path[◊] + Flight frequency[◊] + Distance to water×Water body type + Area + Oil & gas wells + Oil & gas production + Number of mines + Crops + Grazing + Extractive + Industrial + Developed + Federal[*] + Jointly owned[*] + Local government[*] + Native American[*] + NGO[*] + Private[*] + Special designation[*] + State[*] + Ia[†] + Ib[†] + II[†] + III[†] + VI[†] + Unassigned[†]
1	Area + Size of nearest city + Oil & gas wells + Oil & gas production + Road density + Rail density + Enplanements of nearest airport + Flight frequency[◊] + Extractive + Developed + Federal[*] + Jointly owned[*] + Local government[*] + Ia[†] + Ib[†] + VI[†] + Unassigned[†]
2	Area + Oil & gas production + Road density + Enplanements of nearest airport + Extractive + Local government[*] + Unassigned
3	Federal[*] + Jointly owned[*] + Local government[*] + Native American[*] + NGO[*] + Private[*] + Special designation[*] + State[*] + Ia[†] + Ib[†] + II[†] + III[†] + VI[†] + Unassigned[†]
4	NULL
5	Population density + Road density + Rail density + Distance to rail line[◊] + Enplanements of nearest airport + Distance to airport[◊] + Size of nearest city + Military flight path[◊] + Flight frequency[◊] + Distance to water×Water body type + Area + Oil & gas wells + Oil & gas production + Number of mines + Crops + Grazing + Extractive + Industrial + Developed
6	Federal[*] + Jointly owned[*] + Local government[*] + Native American[*] + NGO[*] + Private[*] + Special designation[*] + State[*]
7	Ia[†] + Ib[†] + II[†] + III[†] + VI[†] + Unassigned[†]
8	Distance to water×Water body type + Area + Size of nearest city + Grazing + Oil & gas production + Road density + Rail density + Distance to airport[◊] + Distance to rail line[◊] + Enplanements of nearest airport + Military flight path[◊] + Flight frequency[◊] + Federal[*] + Jointly owned[*] + Local government[*] + Private[*] + Ia[†] + Ib[†] + VI[†] + Unassigned[†]
9	Area + Size of nearest city + Oil & gas production + Road density + Rail density + Distance to airport[◊] + Distance to rail line[◊] + Enplanements of nearest airport + Military flight path[◊] + Developed + Federal[*] + Jointly owned[*] + Local government[*] + Ia[†] + Ib[†] + VI[†] + Unassigned[†]

10	Distance to water×Water body type + Area + Size of nearest city + Oil & gas production + Road density + Rail density + Distance to airport◊ + Distance to rail line◊ + Enplanements of nearest airport + Military flight path◊ + Developed + Federal* + Jointly owned* + Local government* + Unassigned
11	Road density + Enplanements of nearest airport + Flight frequency◊ + Local government* + Unassigned
12	Road density + Local government* + Unassigned
13	Distance to water + Road density + Rail density + Enplanements of nearest airport + Developed + Federal* + Private* + State* + Unassigned
14	Distance to water + Road density + Rail density + Enplanements of nearest airport + Oil & gas production + Number of mines + Private* + State* + Unassigned
15	Area + Size of nearest city + Oil & gas wells + Oil & gas production + Number of mines + Crops + Grazing + Rail density + Road density + Distance to airport◊ + Enplanements of nearest airport + Military flight path◊ + Flight frequency◊ + Extractive + Industrial + Developed + Federal* + Jointly owned* + Local government* + Native American* + NGO* + Private* + Special designation* + State* + Ia† + Ib† + II† + III† + VI† + Unassigned†
16	Area + Oil & gas wells + Oil & gas production + Number of mines + Crops + Grazing + Rail density + Road density + Distance to airport + Distance to rail line + Enplanements of nearest airport + Military flight path◊ + Flight frequency◊ + Extractive + Industrial + Distance to water + Lake + Federal* + Jointly owned* + Local government* + Native American* + NGO* + Private* + Special designation* + State* + Ia† + Ib† + II† + III† + VI† + Unassigned†
17	Area + Oil & gas wells + Oil & gas production + Number of mines + Crops + Grazing + Rail density + Road density + Distance to rail line◊ + Enplanements of nearest airport + Distance to airport◊ + Military flight path◊ + Flight frequency◊ + Extractive + Industrial + Distance to water + Federal* + Jointly owned* + Local government* + Native American* + NGO* + Private* + Special designation* + State* + Ia† + Ib† + II† + III† + VI† + Unassigned†
18	Area + Oil & gas wells + Oil & gas production + Number of mines + Crops + Grazing + Rail density + Road density + Distance to rail line◊ + Enplanements of nearest airport + Distance to airport◊ + Military flight path◊ + Flight frequency◊ + Extractive + Industrial + Distance to water + Federal* + Jointly owned* + Local government* + Native American* + NGO* + Private* + State* + Ib† + II† + III† + VI† + Unassigned†
19⌂	Area + Oil & gas wells + Oil & gas production + Number of mines + Crops + Grazing + Rail density + Road density + Distance to rail line◊ + Enplanements of nearest airport + Distance to airport◊ + Military flight path◊ + Flight frequency◊ + Extractive + Industrial + Distance to water + Developed + Federal* + Local government* + Native American* + NGO* + Private* + State* + Ib† + II† + VI† + Unassigned†

◊Not included in protected area vs unprotected buffer analysis

*Federal, Jointly owned, Local government, Native American, NGO, Private, Special designation, and State refer to protected area management body

†Ia, Ib, II, III, VI, and Unassigned refer to IUCN designated strict nature reserves, wilderness areas, national parks, natural monuments, protected areas with sustainable use of natural resources, and unassigned areas respectively

[‡]Received 99% of weight for models examining the median noise exceedance in each PA
[⌂]Received 99% of weight for models examining the difference between median noise exceedance in each PA versus buffer area

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