# Anthropogenic noise in US national parks – sources and spatial extent

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**In an era of unprecedented environmental change, US national parks are refuges of natural ecosystems and facilitate connections between humans and nature. However, anthropogenic noise is an increasingly pervasive threat in these parks. To diagnose noise levels and sources, we analyzed thousands of hours of acoustic recordings collected across park units and summarized results from continental-scale sound models. We found that anthropogenic noise was audible in 37% of park recordings, and that parks with high road density and those in close proximity to large airports experienced a greater number of noise events. The most common noise sources were aircraft and road vehicles, but, when present, trains and watercraft generated the loudest noise levels. Sound models show that anthropogenic noise caused a tenfold increase in median sound levels in 36% of parks, and loud areas were often localized. Our analysis identifies situations where noise management would yield the greatest benefits to park visitors and wildlife.**

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The US National Park Service (NPS) was established over a century ago to conserve natural and cultural resources. As the first system of federally protected areas in the world, US national parks have shaped a global standard for protected areas. Since NPS's inception, the US population has more than tripled, road and aircraft traffic have become widespread, and 80% of the US population now lives in urban areas (Barber *et al*. 2010). In this context, national parks represent refuges of ecological integrity and provide increasingly important opportunities for people to establish personal connections with natural environments (Miller 2005; Machlis and McNutt 2015).

This rapid increase in infrastructure, transportation networks, and human activity has resulted in the widespread distribution of anthropogenic noise (hereafter "noise"), even in the most remote protected areas of the US (Figure 1; Buxton *et al*. 2017a). At high levels of exposure, noise annoys people and contributes to health problems (Basner *et al*. 2014). At lower levels of exposure, noise reduces the benefits of experiencing natural sounds, which include increased relaxation, restored attention, improved mood, and reduced stress (Benfield *et al*. 2014; Abbott *et al*. 2016). Noise also affects wildlife, masking critical sounds (including incidental signals such as the sound of predators approaching) and increasing perceived risk, causing changes in behavior, physiology, and fitness (reviewed in Shannon *et al*. [2016]). Moreover, the responses of individual species to noise extend through ecological interactions to alter community structure and ecosystem function (Francis *et al*. 2012). Despite its known impacts on natural systems, noise is rarely considered alongside other pervasive threats to protected areas (Butchart *et al*. 2010).

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Congressional concerns about noise in national parks have been expressed through legislation since 1975, and NPS policy requires the management of noise and conservation of acoustic resources (NPS 2006). Accordingly, NPS has been identifying noise sources, measuring not only how often they are heard but also sound levels at hundreds of sites over the past two decades, resulting in a unique, spatially diverse acoustic dataset. This study is the first comprehensive analysis of all noise sources in national parks across the US. More specifically, we identify the causes of continental-scale patterns of noise exposure (Buxton *et al*. 2017a) by analyzing the identities and characteristics of noise sources audible in national park units and relating these outputs to landscape-scale summaries of acoustic conditions inside national parks. The results document (1) the loudest and most frequent sources of noise and the anthropogenic features associated with them, (2) which of these sources predict landscape levels of noise estimated using geospatial models, and (3) summaries of these noise metrics across different protection categories (ie park type, wilderness areas, and critical habitat of US endangered species). We relate this diagnosis of noise across different park contexts with emerging approaches to mitigate noise pollution, aiming to identify management strategies that preserve or restore natural soundscape experiences for park visitors and wildlife.

## Methods

### Noise sources

A team of trained acoustic technicians identified, categorized, and measured characteristics of noise by listening to and observing spectrograms of recordings from 251 sites in 66 park units (WebPanel 1). At 168 sites with

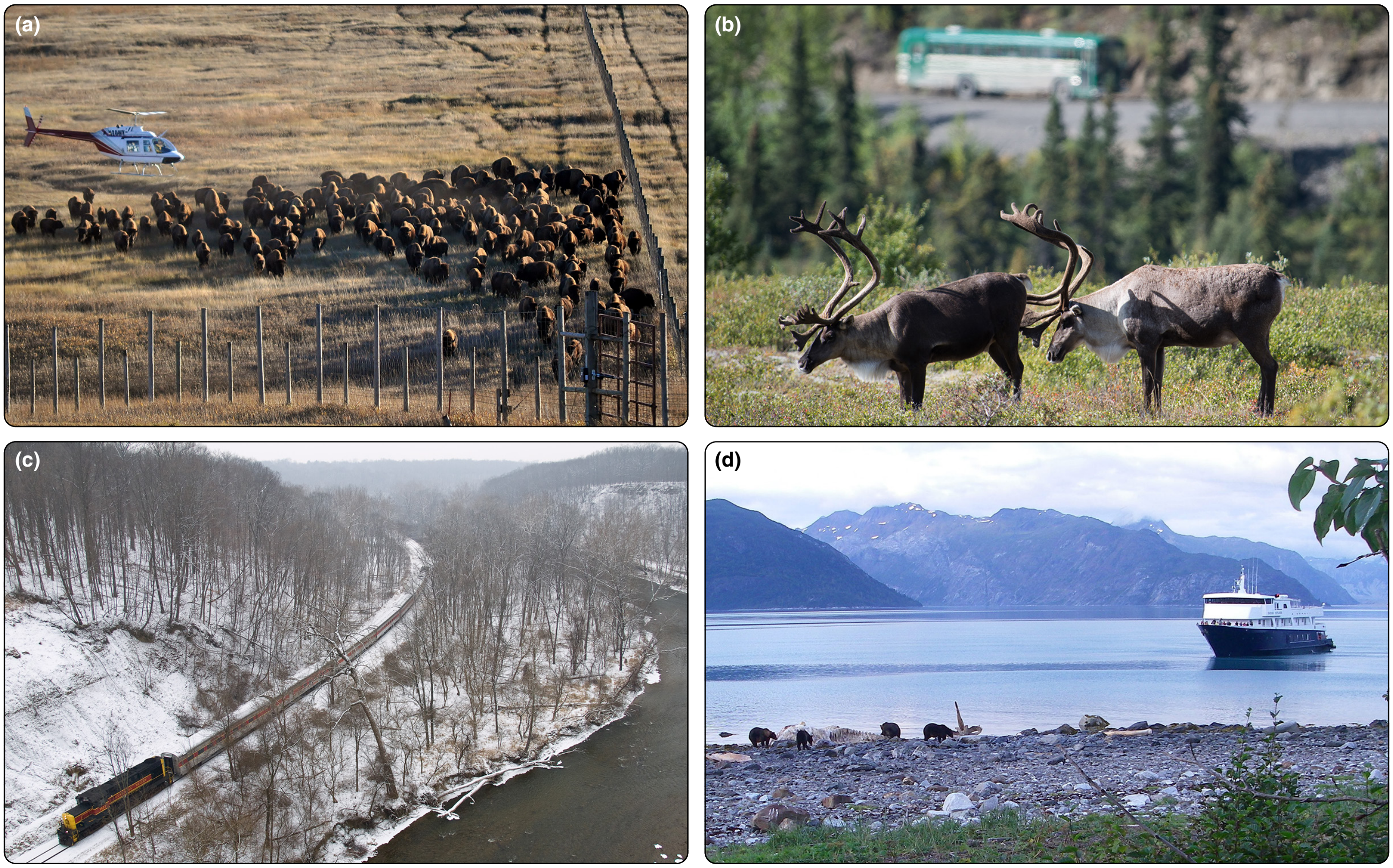

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**Figure 1.** Some examples of anthropogenic noise sources in US national parks include (a) aircraft (Theodore Roosevelt National Park, North Dakota), (b) vehicles (Denali National Park and Preserve, Alaska), (c) trains (Cuyahoga Valley National Park, Ohio), and (d) watercraft (Glacier Bay National Park, Alaska).

high rates of noise events, categories of noise (WebTable 1) were identified as present or absent in 10-second samples of audio taken every 2 minutes (except for sites in Alaska's Denali National Park; see WebPanel 1). The audibility of a noise source was calculated as the proportion of acoustic samples where the noise event was observed during an hour of sampling. At 96 sites with low rates of noise events and little overlap between events, technicians measured the following characteristics of all noise events observed throughout recordings: sound exposure level (SEL), maximum sound pressure level (max SPL), and duration (minutes) (for definitions, see WebPanel 2). We estimated audibility for these sites by calculating the probability that a noise event intersects a 10-second sample across each 2-minute interval based on the duration of the event (WebPanel 1). Note that both types of analyses were conducted at 13 sites.

To compare audibility among noise categories (WebTable 1), we fitted the most parsimonious model structure, a generalized linear mixed model (GLMM) with a quasi-Poisson error structure with the log of the total number of acoustic samples included as an offset term. Because we found substantial temporal autocorrelation in model residuals for SEL, max SPL, and duration of noise events, these were compared between categories using second-order autoregressive, integrated, moving average (ARIMA) mixed models with a Gaussian error structure. All models incorporated each category of noise, season, a variable controlling for the front- or backcountry placement of the recorder, and morning hours (0700–0900) as fixed variables, with date nested within site nested within park as a random effect.

Using data from national parks within the contiguous US, we used an information–theoretic approach to investigate which landscape-level anthropogenic features explain differences in audibility of all noise sources across sites. We constructed three global quasi-Poisson GLMMs, each of which included uncorrelated combinations of distance to, size of, or density of anthropogenic features, and variables for park designation type, wilderness areas, and critical habitats of US endangered species (covariates are described in WebTable 2). For the park designation variable we assigned each of the 21 types of national park units, based on distinctive management attributes, into one of four possible designations: (1) national parks, preserves, and reserves; (2) recreation areas; (3) cultural parks; and (4) national monuments (WebPanel 1). We included recording date nested within site nested within park as a random effect in each model. We chose the model with the lowest Akaike's information criterion (AIC) score, and considered covariates from this model with the greatest parameter estimates with 95% confidence intervals that did not overlap zero to be the most influential (Burnham and Anderson 2002). All model procedures are described in detail in WebPanel 1.

### Noise exceedance

To quantify acoustic conditions in parks within the contiguous US, we extracted national estimates of noise from a previously published geospatial model (Mennitt and Fristrup 2016). These models were generated by machine-learning algorithms to analyze the relationship between acoustic measurements at 492 sites across the contiguous US and geospatial features, including vegetation, topography, climate, hydrology, and anthropogenic activity. In addition to predicting expected sound levels, the models predicted natural sound levels by minimizing anthropogenic factors. Furthermore, the difference between these values is an estimate of the amount that anthropogenic sound energy raises existing sound levels above natural levels (Mennitt *et al*. 2014). We used this difference, termed "noise exceedance", as a metric of noise because it measures changes in sound levels due to anthropogenic noise (detailed definition in WebPanel 2; Buxton *et al*. 2017a). Noise exceedance values were predicted from A-weighted sound levels (a method of summarizing sound levels across frequencies) emphasizing sound energy at frequencies at which many vertebrates have their most sensitive hearing thresholds, and averaged over summer daytime hours, representing seasonal listening conditions (WebPanel 1). Sites in Alaska and Hawaii were included in audibility analyses, but predictions of noise exceedance were limited to sites in the contiguous US.

We summarized noise exceedance, examining median noise exceedance within each park unit and the proportion of pixels experiencing noise exceedance above 3 decibels (dB) and 10 dB within each park unit. Exceedances of 3 dB and 10 dB correspond to a doubling and tenfold increase, respectively, in acoustic energy, and to a 50% and 90% decrease, respectively, in the spatial extent of acoustic signal detection (ie "listening area"; Barber *et al*. 2010) in many vertebrates (Buxton *et al*. 2017a). In addition to masking important acoustic information, noise exceedance in this range reduces visitor enjoyment of parks through annoyance and interference with natural quiet and natural sounds (Rapoza *et al*. 2015). Moreover, the scholarly literature published over the past two decades demonstrates that noise exceedance in this range affects wildlife species richness, reproductive success, behavior, and physiology (Shannon *et al*. 2016).

### Comparison across management designations

We compared noise audibility and exceedance (1) across park types; (2) in wilderness areas within parks, non-wilderness areas within parks, and wilderness areas outside parks; and (3) in critical habitat of US endangered species within parks, non-designated areas within parks, and critical habitat outside parks. Fitting models to compare noise exceedance among park management designations was unfeasible given the dataset's large size ($n$ > 5 million) and the prohibitively large matrices needed to account for high spatial autocorrelation. Accordingly, we used a bootstrapped procedure (described in WebPanel 1). To compare audibility of noise in recordings across land designations, we used the predictions from GLMMs described above.

To examine the relationship between noise exceedance and characteristics of noise sources at each site, we built linear models predicting noise exceedance at each recorder location from mean audibility, SEL, max SPL, and duration of each category of noise. We considered noise category models with the highest $R^2$ and lowest AIC (corrected for small sample size: AICc) as the best predictors of audibility and other noise metrics.

## Results

### Audibility of the loudest and most frequent noise sources

Analysis of 1,440,999 acoustic samples from 46,789 hours of recordings in US national park units identified ten common noise sources (Figure 2). Although noise sources varied among park units, aircraft noise was heard at all sites and was the predominant source at most sites (Figure 2). The second most common noise source was ground-based vehicles (WebFigure 1). Another common category was sounds from people (eg voices, footsteps; WebFigure 1). Some noise sources were geographically limited; for example, train sounds were more common in western parks (Figure 2).

Model results, accounting for different sampling across locations and time, indicated that noise was audible in 37% of acoustic samples (WebFigure 1). Noise events were most common between the hours 0700–0900 and during the summer (July–September; WebTable 3). Aircraft and vehicle sounds were the most common noise sources, audible in 31% of samples, ranging from sites with no noise audible to 100% of samples containing aircraft or vehicle noises (WebTable 4). Aircraft noise was predominantly (73%) from jets, and 43% of ground-based vehicle noise was from automobiles (car, truck, and bus engines and tires on pavement; WebFigure 1). People sounds were mainly (89%) voices (WebFigure 1).

Among the subset (38%) of recordings for which acoustic parameters could be measured for individual noise events ($n$ = 51,754 noise events), watercraft sounds had the highest SEL (mean ± standard deviation [SD]: 64.6 ± 4.9 dB) and the longest duration (mean ± SD: 19.9 ± 1.7 seconds; WebTable 5), and train sounds had the highest max SPL (mean ± SD: 48.7 ± 13.4 dB). Anthropogenic features that were associated with higher audibility of noise sources included the density of roads within the park, and the distance to and traffic volume of nearby airports (WebTable 6).

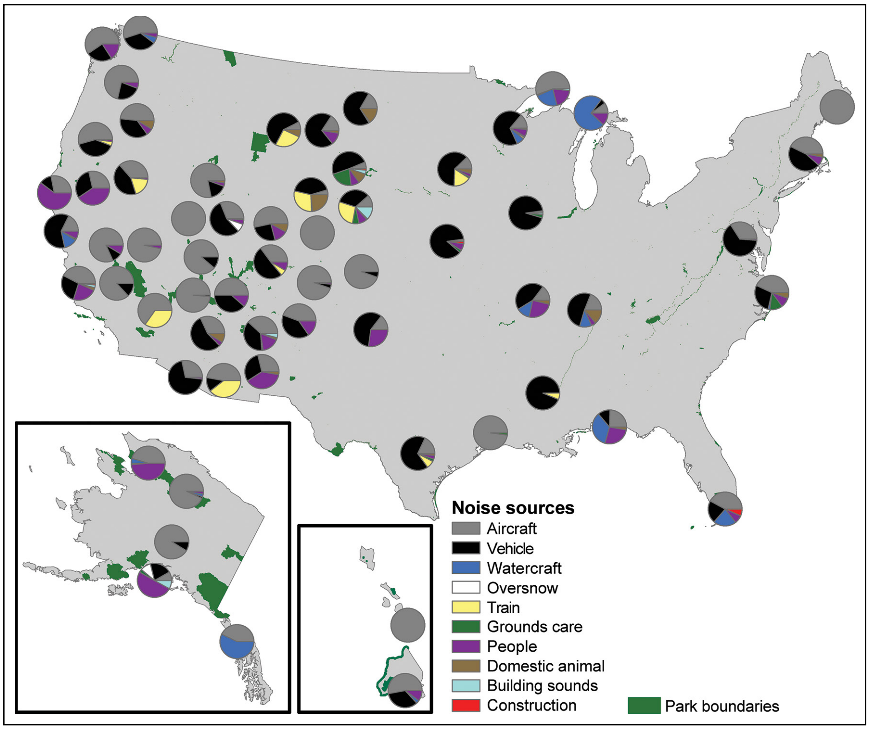


**Figure 2.** Ten common noise sources were identified through analysis of recordings made in US national park units. The proportion of each type of noise source observed in the recordings indicated the regional presence of some sources (eg trains) and the prevalence of others (eg vehicles, aircraft). The "oversnow" category includes sound from snowmobiles, snow coaches, snow groomers, and snow planes.

### Spatial extent of noise predicted from geospatial models

The median noise exceedance, measured within each park unit, ranged from 0 dB to 29.1 dB (WebTable 7). Median noise exceedance was greater than 3 dB in 77% of 364 park units (48% of total park area), representing a doubling in acoustic energy, and median noise exceedance was greater than 10 dB in 36% of park units (2% of park area; Figure 3; WebTable 7), representing a tenfold increase in acoustic energy. Park units with the highest 10% median noise exceedance had high levels of noise exceedance across the entire park area (Figure 3). Conversely, noise exceedance values were less than 3 dB across most of the park area in park units with the lowest 10% median noise exceedance. Of all noise sources detected in the acoustic recordings, audibility of ground vehicles was most strongly related to predicted noise exceedance from geospatial models (parameter estimate ± standard error: 8.64 ± 0.94, $R^2$ = 0.30; WebTable 8). In contrast, duration of audible aircraft noise events was negatively related to noise exceedance (–0.04 ± 0.01, $R^2$ = 0.34), because aircraft can be heard from greater distances at quieter sites.

### Noise across different protective categories

Examination of noise across types of park units revealed higher noise exceedance and audibility in park units designated to preserve cultural or historic resources (WebFigure 2; WebTable 9). When other landscape variables were taken into account, noise audibility was highest in parks designated for recreation (WebTable 6). Natural resource parks had the lowest noise exceedance and audibility (WebFigure 2).

Fewer noise events were audible at recording sites inside relative to outside wilderness areas (WebFigure 2), even when other landscape factors were accounted for (WebTable 6). Likewise, median noise exceedance was lower inside NPS wilderness relative to non-wilderness areas (WebFigure 2; WebTable 9). Noise exceedance in NPS wilderness was slightly elevated, but not significantly, relative to designated wilderness in other protected lands (eg Forest Service land; WebTable 9).

Audibility of noise sources was similar between designated critical habitats of US endangered species and non-designated areas within national park units. Similarly, noise exceedance did not differ significantly between critical and non-critical habitats within park boundaries (WebFigure 2; WebTable 9). Noise exceedance was slightly higher in critical habitats outside of park boundaries as compared with that inside park boundaries (WebTable 9).

## Discussion

The negative effects of noise on a range of animal species, ecological communities, and human visitors in protected areas are well documented (Rapoza *et al.* 2015; Shannon *et al.* 2016). Noise that overlaps in frequency with important natural signals compromises a primary sensory system for wildlife (Swaddle *et al.* 2015) and people. We assessed the common noise sources in US national parks, derived from 46,789 hours of recordings, and how these sources relate to noise levels predicted by geospatial models. We found that the most common sources of noise were aircraft, road vehicles, and people sounds, with vehicles accounting for much of the variation in median noise exceedance. Our large-scale assessments of the spatial distribution, common sources, and levels of noise provide insights for spatial planning to implement the numerous existing tools for reducing noise (NRC 2010).

The most common noise sources require distinct management approaches. Aircraft noise was spatially extensive and was audible for longer in areas with low noise exceedance, likely because low ambient sound levels make it easier to hear all sounds (Lynch *et al.* 2011). The vast spatial extent of air transportation networks combined with the regulatory role of the Federal Aviation Administration (FAA) means that management of aircraft noise necessitates a collaborative approach. NPS has partnered with the FAA to limit the spread of noise in parks by routing flights over road corridors (FAA 2012); collaborative mitigation approaches such

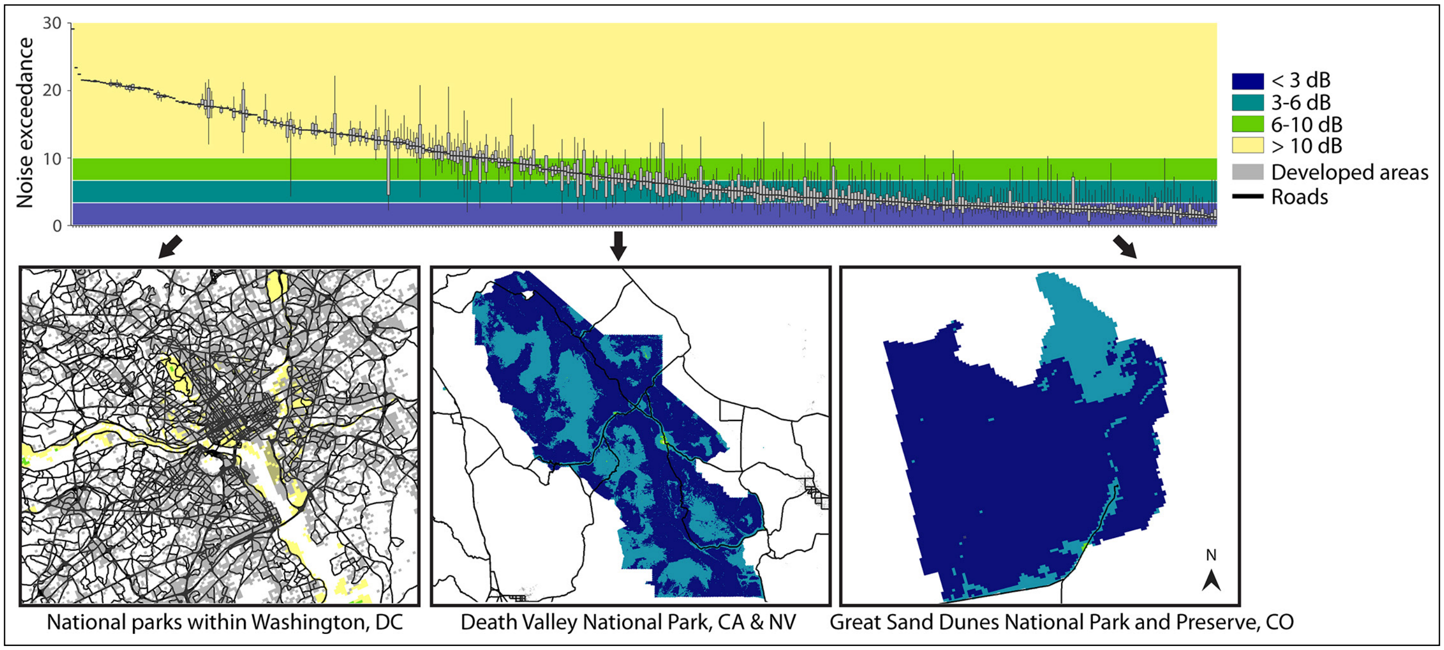


**Figure 3.** Median model-predicted noise exceedance within each national park unit in the contiguous US indicates large variability in the levels of noise across units. In the top graph, boxes (25th–75th percentile) and whiskers (2nd–98th percentile) for all park units ($n$ = 396) are overlayed on colors representing levels <3 dB (dark blue), 3–6 dB (cyan), 6–10 dB (yellow-green), and >10 dB (yellow) (representing a reduction in listening area of less than 50%, 50–75%, 75–90%, and greater than 90%, respectively). Parks were generally inundated with noise >10 dB (eg parks within the boundaries of Washington, DC), had high noise exceedance in spatially restricted areas (eg noise exceedance was >10 dB in a small area in Death Valley National Park that experiences high traffic and visitation), or experience near-natural acoustic environments (eg exceedance was <3 dB in 85% of remote areas in Great Sand Dunes National Park).

as this can be replicated in areas where our analysis identified high audibility of aircraft. Noise from road vehicles was more spatially restricted, but when present was a chronic source of noise that drove high levels of noise exceedance. Considering road vehicle noise when devising transportation plans (eg shuttle systems, speed limits) and designing park infrastructure (eg "quiet pavement") could be a key strategy for reducing its effects (Lynch *et al.* 2011). Finally, we found widespread sounds produced by people. In the context of visitor conversation and ranger interpretive sessions, voices are intrinsic to park values and visitor experience; yet even when appropriate to the setting, these sounds affect wildlife (eg Buxton *et al.* 2017b). In areas where reduced visitor sounds would further enhance natural resources (eg wildlife-viewing areas), designation of quiet zones can markedly improve conditions (Francis *et al.* 2017). Quiet zones have the additional benefit of enhancing the visitor experience in these places (Stack *et al.* 2011).

Geospatial model predictions of noise levels revealed the ubiquity of noise in national parks. Although NPS lands are among the quietest of US protected areas (Buxton *et al.* 2017a), we found high overall median noise exceedance (>10 dB) in one-third of US national park units (2% of all park area). These levels of noise have been shown to affect the body condition (Phillips *et al.* 2018), behavior (Klett-Mingo *et al.* 2016), and fitness (Schroeder *et al.* 2012) of many wildlife species. Ultimately, this level of noise exceedance can affect ecosystem services, altering processes like seed dispersal and pollination (Francis *et al.* 2012). Moreover, we found increases in sound levels of 3 dB due to noise in almost half of all park area (pooling among all parks) – levels known to alter, for example, avian song performance, with detrimental outcomes for competition and pairing success (Davidson *et al.* 2017). Often, high noise exceedance was limited to small areas within a park unit. Our assessment of the distribution and levels of noise within and among parks indicates areas where management of noise would generate substantial benefits.

Noise management strategies will depend on the management designation of the park, as well as the relationship between noise sources and visitor experience. Inside national park boundaries, noise was lower in wilderness than in areas without such protective designations. The exclusion of motorized vehicles, among the most prevalent noise sources in our analysis, is critical to maintaining near-natural conditions available in wilderness areas managed to provide "outstanding opportunities for solitude" (Watson *et al.* 2015). Noise was high in cultural parks (military, memorial, or historic sites), which are relatively small (<135 $km^2$) and usually close to large cities. Because these sites are often embedded within more developed landscapes outside park jurisdiction, collaborative approaches for noise diminution are needed in such contexts. We note that models of noise exceedance generally underestimate the highest sound levels and overestimate the lowest sound levels (Mennitt and Fristrup 2016), suggesting that parks identified as loud are likely louder than estimated and quiet parks are likely quieter than estimated. In most cases noise exceedance is underestimated, and as such represents a conservative estimate of noise levels.

Although conditions in national park units are typically quieter than conditions in their surrounding landscapes, NPS has legislative mandates to manage parks to superlative standards of resource quality and visitor experience. As park units consider accommodating higher levels of visitation, substantial challenges include designing transportation plans and park infrastructure that conserve or restore soundscapes. On large landscape scales, noise management will likely require collaboration with partners to reduce noise arriving from outside park boundaries. The variety of noise sources and their spatial distribution across park contexts emphasize the need for diverse strategies informed by local knowledge and partnerships to conserve natural soundscapes for park visitors, wildlife, and ecological processes.

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