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RESEARCH ARTICLE

An assessment of noise audibility and sound levels in U.S. National Parks

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Abstract Throughout the United States, opportunities to experience noise-free intervals are disappearing. Rapidly increasing energy development, infrastructure expansion, and urbanization continue to fragment the acoustical landscape. Within this context, the National Park Service endeavors to protect acoustical resources because they are essential to park ecology and central to the visitor experience. The Park Service monitors acoustical resources in order to determine current conditions, and forecast the effects of potential management decisions. By community noise standards, background sound levels in parks are relatively low. By wilderness criteria, levels of noise audibility are remarkably high. A large percentage of the noise sources measured in national parks (such as highways or commercial jet traffic) originates outside park boundaries and beyond the management jurisdiction of NPS. Many parks have adopted noise mitigation plans, but the regional and national scales of most noise sources call for conservation and management efforts on similar scales.

Keywords National parks · Acoustical monitoring · Noise · Acoustical resources · Natural quiet

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Introduction

Anthropogenic noise is arguably one of the least understood and most common threats to resources in national parks. Burgeoning energy development, infrastructure expansion, and urbanization create expansive noise footprints that fragment the acoustical landscape and restrict naturally quiet conditions to relatively brief intervals of the day in many protected natural areas. Acoustical resources are conserved or restored by the National Park Service (NPS) because they are crucial to ecological integrity and important for visitor experience. NPS is required by law and management policies to protect the acoustical environment.

Stewardship of acoustical resources requires systematic acoustical monitoring to determine the current status of resources, identify trends in resource conditions, and inform management decisions regarding desired future conditions. This paper summarizes the acoustical conditions in several parks in the National Park system, and identifies salient patterns in these data.

Acoustical resource management in the National Park Service

The need for resource protection in national parks was first articulated in the National Park Service Organic Act of 1916, which stated that the purpose of national parks is "… to conserve the scenery and the natural and historic objects and the wild life therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations."

The first Congressional reference to acoustical resources is in the Grand Canyon Enlargement Act of 1975, which explicitly identified "natural quiet" as a resource to be protected for future generations. In this case, Congress recognized the conflict between the demand for air tours over Grand Canyon and the resource degradation that visitors on the ground experienced. The Redwoods Act of 1978 addressed potential conflicts between visitor use and resource protection by affirming that, "the protection, management, and administration of these areas shall be conducted in light of the high value and integrity of the National Park System and shall not be exercised in derogation of the values and purposes for which these various areas have been established, except as may have been or shall be directly and specifically provided by Congress." In 1987, Congress focused specific attention on aircraft flights over park lands when it passed the National Parks Overflights Act (Public Law 100-91). This act mandated that the Park Service conduct a number of studies related to the effects of overflights on parks, and directed the NPS to report results to Congress. The Natural Sounds Program, a national NPS office, was established in 2000, with the passing of the National Parks Air Tour Management Act (NPATMA). NPATMA mandated that FAA and NPS jointly develop Air Tour Management Plans (ATMPs) for more than 106 parks where commercial air tours operate.

Effects of noise on visitor experience

The founding documents of the NPS state that parks were created for the purpose of preserving resources for the enjoyment of present and future generations. Like scenic vistas, clean air, or pristine bodies of water, natural sounds are considered a precious natural resource worthy of protection by the NPS. Any "noise," or human-caused sound that masks or degrades natural sounds is a threat to the acoustical environment (which we define as the complete set of physical sound resources intrinsic to a park). Many people visit national parks with the hope and expectation of experiencing natural sounds, and noise degrades their chance to experience the cultural, historical, and natural features that parks offer. A 1998 survey of the American public revealed that 72 percent of respondents thought that providing opportunities to experience natural quiet and the sounds of nature was a very important reason for having national parks, while another 23 percent thought that it was somewhat important (Haas and Wakefield 1998. In another survey specific to park visitors, 91 percent of respondents considered enjoyment of natural quiet and the sounds of nature to be compelling reasons for visiting national parks (McDonald et al. 1995).

The need to preserve the acoustical environment for the benefit of the visitor experience is further amplified in wilderness areas, where managers endeavor to provide opportunities for solitude. Separation from the sights and noise originating outside wilderness is one of the primary indicators used to gauge success in wilderness preservation (Dawson 2004). Noise can even affect visitors who are not actively listening to the environment, and who may not explicitly perceive the noise. For instance, a 2008 study found that noise from traffic and aircraft caused involuntary physiological responses (increased blood pressure and heart rate) in sleeping humans (Haralabidis et al. 2008). Parks are critical fora for education, and can inform visitors of all ages about the importance of natural resource protection. However, noise can elevate ambient sound levels in parks above the recommended conditions for classrooms (35 dB(A), ANSI Standard S12.60), making it difficult for park educational and interpretive presentations to reach their audience. Degraded communication can also elevate risk for park staff or visitors who are engaged in potentially hazardous activities, when shared information and coordinated actions are essential for safety (*e. g.* search and rescue, climbing, or canyoneering).

Effects of noise on wildlife

Hearing is likely more vital for wildlife than park visitors. In addition to auditory communication, animals rely on sounds to gather many kinds of important environmental information. Adventitious sounds can alert attentive listeners to the location, identity, and behavior of other animals, including predators, competitors exploiting an important resource, rivals in mating systems, and potential prey. Physical environmental features may also be revealed by the sounds they produce (changing weather, flowing water, fire).

Noise can interfere with animal acoustical awareness in several ways. Very loud sounds can temporarily deafen animals. Less dramatic noise events can distract attention or introduce clutter to the acoustical environment. Noise adds energy to existing sound levels, effectively reducing the range at which signals can be detected, identified, and localized (masking). Masking can take place even if the animals do not react to, or even perceive, the noise source. In general, sounds are more easily masked by other sounds with similar acoustical properties (e.g. center frequency, bandwidth). It should be noted that the effects of masking extend beyond intentional communication (between members of a single species). Many vertebrate species have been shown to "eavesdrop" on the communications between other species, as in the case of gray squirrels (*Sciurus caroninensis*) listening to blue jay (*Cyanocitta cristata*) calls to determine risk of cache pilfering (Schmidt and Ostfeld 2008).

Prolonged exposure to noise has been shown to cause wildlife to avoid certain areas, reducing already limited potential habitat. Sonoran pronghorn antelope, mule deer, and sage grouse have been shown to preferentially select habitat with less noise from human activity (Landon et al. 2003; Sawyer et al. 2006; Doherty et al. 2008). Studies of songbird behavior and ecology near oil and gas development found a significant reduction in pairing success, bird density, and bird species diversity caused by noise (Habib et al. 2007; Bayne et al. 2008). Development inside national parks is managed to avoid unacceptable impacts to resources, but noise can have substantial effects on habitat quality, species distribution and demographic parameters.

To adequately understand and protect acoustical resources, the park service conducts acoustical monitoring to determine the status of acoustic resources, track trends in resource conditions, and inform management decisions. This paper presents monitoring and analysis protocols, summarizes the acoustical conditions in several parks in the National Park system, identifies significant patterns in these data, and discusses ways parks have incorporated acoustical data into management actions.

Methods

Acoustical monitoring equipment is widely utilized to ensure compliance with industrial health and safety, community environmental standards, and architectural standards for indoor spaces. The Natural Sounds and Night Skies Division of the Park Service utilizes similar instruments, but high standards for resource condition and visitor experience call for different monitoring practices and objectives. Furthermore, the harsh weather conditions encountered during long deployments in national parks (ranging from summer in Death Valley National Park and Preserve to winter in Kenai Fjords National Park), and high probability of wildlife encounters demand entirely new system configurations. These monitoring systems gather long-term data about acoustical conditions in parks and provide vital metrics such as existing- and natural- ambient sound levels.

Equipment

National Park Service acoustical monitoring equipment has evolved over three distinct generations. All three types were employed in the collection of data referenced in this paper. The common denominators among the generations are ANSI Type 1 sound level meters (SLMs) using ½″ measurement microphones. Microphones were deployed with environmental housings and wind screens at approximately 1.5 m above ground (approximating the average height of the human ear). Each second, the SLMs collected 33 1/3 octave sound pressure level (SPL) measurements (in decibels, or dB) from 12.5 to 20,000 Hz, which encompasses the nominal range of human hearing.

Generation I acoustical monitoring equipment consisted of a Larson Davis 824 SLM streaming data to a laptop computer. An anemometer was collocated to record local wind speeds over the monitoring period. The generation I systems were powered by at least three 35Ah lead acid batteries and photovoltaic panels. Deployment locations for these systems were limited by weight (approximately 90 kg), solar exposure, and power requirements (approximately 12 W). The weight of these systems required at least four people for deployment and recovery. Furthermore, they experienced a high rate of data loss due to serial communication conflicts. NPS required the capacity to identify prominent noise sources and the stations were developed to make audio recordings as well as measure sound levels. The laptop software was programmed to save 10-s uncompressed audio recordings every 2 min. This sampling scheme was required due to limited storage space, but also ensured that every aircraft overflight event would span at least two recordings.

Generation II introduced several substantial improvements. In 2007, the laptop was replaced with a personal digital assistant (PDA), reducing the power consumption to approximately 2.5 W. The reduction in power consumption allowed the use of fewer batteries, resulting in a system weight of approximately 11 kg. The PDA used an optimized software interface between SLM and PDA, resulting in negligible data loss. Generation II acoustical monitoring stations included anemometers, but these data were collected by a separate data logger. Another notable improvement was the introduction of a continuous audio recorder. Audio input from the microphone was delivered to a 60 GB hard disk-based MP3 audio recorder. These audio data provided more complete and detailed records of all sounds at each site. Unfortunately, the hard disk MP3 audio recorders proved unreliable; extremes of temperature and humidity often caused them to fail.

Generation III, introduced in 2008, employed a new SLM, the Larson Davis 831. This unit possesses its own 2 GB internal memory, as well as USB storage capabilities. With these storage options, the PDA became superfluous. In addition, the introduction of solid state MP3 audio recorders, with no moving parts, proved far more reliable in inclement weather. In 2010, we configured the SLMs to accept instantaneous wind speed, wind direction, temperature, and humidity, from attached sensors. This eliminated the need for an additional data logger, and eliminated the need to resynchronize data collected by independent devices. Future acoustical monitoring systems may be much more capable. In cooperation with Colorado State University's Electrical and Computer Engineering Department, the Natural Sounds and Night Skies Division is developing small SPL meters capable of multichannel acoustic data collection, real-time beamforming to resolve direction of arrival, real-time detection for acoustical events of interest, and wireless communications to provide regular summaries of conditions and equipment status.

Study areas and site selection

This report summarizes data collected at 189 sites in 43 national parks (there are a total of 393 park units in the National Park system). The number of sites monitored in each park depended largely upon the variation in major land cover types, or the number of distinct management zones within the park. Areas with similar attributes (vegetation, topography, land cover, elevation, and climate) possess similar natural sound sources, and hence can be considered representative of a given soundscape. Additional criteria for site selection included avoidance of problematic conditions: large, reflective surfaces such as cliff walls, persistent masking sources such as rivers or waterfalls, and heavily traveled roads or trails, for security. For concision, parks are referred to in figures by 4-letter codes, but a list of full park names is listed in Table 1.

Though the variability of SPLs over time and space in national parks is not fully understood, each additional dataset provides insight into natural variability. The monitoring period used for collection of these data is based on a preliminary statistical study that evaluated long-term datasets from Bryce Canyon National Park and Arches National Park. Based on the study, 25 days was found to be adequate to account for annual variation in sound level within 3 dB (Iyer 2005). Iyer's findings are supported by the observation that this period is generally sufficient to capture a representative sample of weather conditions at a given site.

Off-site listening and visual analysis to identify sound sources

A limited amount of on-site listening and data logging was conducted at most monitoring sites. These observations, performed by experienced technicians, identify the common sound sources that can be heard at the site by an attentive listener. Monitoring equipment has made 30 days of continuous data relatively easy to gather. The resulting volumes of data demand efficient data reduction methods that yield audibility statistics comparable to what is obtained by intensive listening in the field.

Audibility denotes the capacity of a sound to be perceived by an animal with normal hearing. Audibility is influenced by the hearing ability of the animal, the masking effects of other sound sources, and by the frequency content and amplitude of the sound. Two distinct methods were developed to rapidly measure the audibility of sound sources at each site. The goal of our audibility analyses was to determine how often anthropogenic sounds were perceptible by humans at

Table 1 List of full park names, their abbreviations, and population size within 16.1 km (10 mile) of park boundary

Park code	Park name	Population
DRTO	Dry Tortugas National Park	374
SAND	Sand Creek Massacre National Historic Park	3,022
GRBA	Great Basin National Park	3,078
ORPI	Organ Pipe Cactus National Monument	3,296
BRCA	Bryce Canyon National Park	3,861
CIRO	City of Rocks National Reserve	4,040
DENA	Denali National Park & Preserve	7,523
KEFJ	Kenai Fjords National Park	8,272
GRSA	Great Sand Dunes National Park & Preserve	8,437
ELMO	El Morro National Monument	9,059
NOCA	North Cascades National Park Complex	10,710
BADL	Badlands National Park	11,600
DEPO	Devils Postpile National Monument	11,835
PEFO	Petrified Forest National Park	17,404
MORU	Mount Rushmore National Memorial	19,995
SEKI	Sequoia and Kings Canyon National Park	24,051
YOSE	Yosemite National Park	24,779
ELMA	El Malpais National Monument	25,438
MORA	Mount Rainier National Park	25,558
DEVA	Death Valley National Park	26,514
GLCA	Glen Canyon National Recreation Area	26,612
GRCA	Grand Canyon National Park	27,200
CAHA	Cape Hatteras National Seashore	29,542
ROMO	Rocky Mountain National Park	31,614
LAMR	Lake Meredith National Recreation Area	35,078
HALE	Haleakalā National Park	37,721
CALO	Cape Lookout National Seashore	42,107
ZION	Zion National Park	42,201
ACAD	Acadia National Park	42,883
HAVO	Hawai'i Volcanoes National Park	48,213
MOJA	Mojave National Preserve	54,337
OLYM	Olympic National Park	86,161
PORE	Point Reyes National Seashore	150,309
MONO	Monocacy National Battlefield	219,373
BITH	Big Thicket National Preserve	295,806
GRSM	Great Smoky Mountains National Park	311,960
MUWO	Muir Woods National Monument	403,547
LAKE	Lake Mead National Recreation Area	710,556
EVER	Everglades National Park	859,237
SAAN	San Antonio Missions National Historic Park	954, 350
MIMA	Minute Man National Historic Park	1,160,446
GOGA	Golden Gate National Recreation Area	2,487,768

Population sizes as of 2009, within 16.1 km (10 mile) of the park boundary are also reported. Anomalous population reports (such as 374 people within 16.1 km of Dry Tortugas National Park) can be attributed to the intersection of large U.S. census block borders (which in rural areas are often as large as counties) with the park boundary buffer. Any blocks which intersect park boundary buffers were included in the total population count, occasionally producing overestimates of nearby population size

each site so that we might determine what the acoustical environment would be like without noise. We call this baseline ambient sound level the "natural ambient." One of the methods for rapid calculation of audibility involves listening to a subsample of the audio data; the other involves visual inspection of spectrograms. Both of these analyses were performed in an office environment.

At sites where anthropogenic noise was rarely audible (such as remote backcountry sites) noise events were identified visually by technicians, using spectrograms generated from SPL data. Spectrograms are plots which display sound level as a function of time and frequency. By plotting daily spectrograms for each site (see Fig. 1), analyzers can quickly examine many samples within the measurement period. We've determined that most anthropogenic sounds possess recognizable sound signatures. Thus, we were able to manually identify and catalog each event, indicating its begin and end time, as well as the frequencies it spanned, maximum level, and sound exposure level (a single number representing the total equivalent energy of a sound, in dB, over a given period of time, abbreviated SEL).

In datasets with continuous audio, we confirmed identification of events with uncertain sound signatures by playing back corresponding audio files. We used the total percent time anthropogenic sounds were audible to calculate the natural ambient sound level for each hour.

For locations where many noise sources were audible at once (such as sites near roads or trails), visual detection of simultaneous events proved difficult. In these cases, technicians listened to daily samples (10 s every 2 min) from the audio data. For each 10 s sound sample, all audible sound sources were identified. This information was compiled to calculate a total percent time audible value for each sound source, which was in turn used to calculate the natural ambient sound level for each hour. To avoid limitations imposed by the office environment, such as the confounding sounds of conversation or HVAC, we used over-ear, noise canceling headphones when cataloging audible events. Results from visual analysis and auditory analysis of the same dataset were found to be comparable.

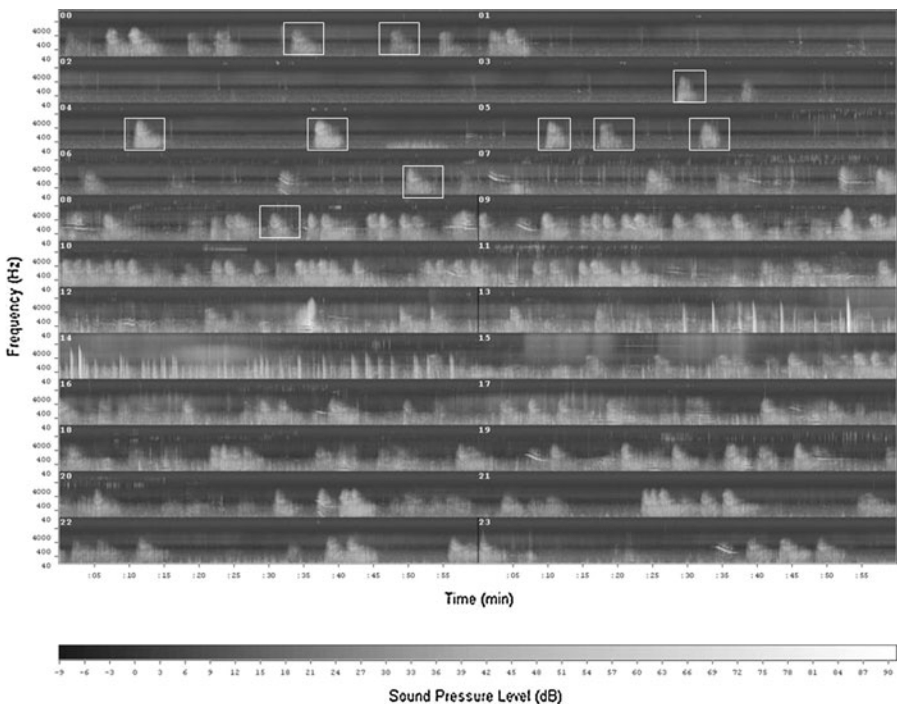

Fig. 1 24 h spectrogram, annotated with jet aircraft events This 24 h spectrogram displays 1/3 octave band SPLs for all hours of the day. The *x*-axis represents time in 5 min increments, with 2 h displayed on each line. The *y*-axis represents the logarithmic frequency scale ranging from 12.5 to 20,000 Hz. The *z*-axis (tone, ranging from *black* to *white*) describes unweighted SPLs from −9 to 90 dB. On this scale, quiet intervals appear *dark* while loud events appear *white*. The *white boxes* drawn on the plot highlight just 10 of the many jet aircraft overflights. The morning bird chorus is distinguishable as a series of subtle dots near 4,000 Hz, starting near the end of the 5th hour. Thunder claps appear as sharp, *white spikes* in the middle of the day

Calculation of metrics

No single metric is adequate to characterize acoustic resources. Furthermore, each park has unique characteristics and legislative requirements, so one set of metrics may not meet the needs of all parks. Accordingly, the Natural Sounds and Night Skies Division works with several metrics. Acoustical studies in national parks use SPL data, spectral data, audibility data, source identification data, and meteorological data.

Background sound levels are a fundamental property of the acoustical environment, because they determine the minimum amplitude of acoustical signals that can be detected, identified, and localized. The median ambient sound level (L_{50}) represents an average background level that includes all sound sources (both natural and anthropogenic); the NPS calls this quantity the existing ambient sound level. The median ambient sound level is preferred over the mean ambient sound level because it is not unduly affected by unusual events, and because the probability of exceeding this level is known (50%). The natural ambient metric (L_{nat}) estimates the desired condition for many parks. It is an estimate of what the median ambient sound levels for a site would be in the absence of all extrinsic (or anthropogenic) sources.

The NPS method of calculating L_{nat} does not simply remove all intervals in which noise is audible. While it may seem logical to do so, this method is flawed because in some cases (e.g. windy locations), quiet periods are the only time noise events are audible. Thus, removing the intervals where noise was audible would also remove the quietest moments. In some cases, this method produces nonsensical results where estimates of L_{nat} exceed L_{50}: how can adding noise result in a lower median level? Instead, NPS presently estimates L_{nat} by removing the loudest p percent of the data in each hour (where p is the percent of the time when anthropogenic noise is audible), and computing the median of the remaining SPL measurements. The calculation identifies the exceedance level, L_x, which represents the L_{50} value that would have existed in the absence of noise. Algebraically, the calculation is:

$$x = \frac{100 - p}{2} + p$$

For example, if human caused sounds are present 30% of the hour, $p = 30$, $x = 65$, and the L_{nat} for that hour is equal to the L_{65}, or the median sound level exceeded 65% of the time during the hour. This formula could underestimate natural sound levels when loud natural events, like thunder, are numerous. However, it is unlikely that this bias will persist over a 25 day measurement period (NPS 2005). This L_{nat} estimate ensures that L_{nat} levels are always lower than L_{50} levels. The audibility of both natural and anthropogenic sounds varies substantially throughout the day, so ambient values are calculated on an hourly basis. In addition, NPS measures wind speed in order to determine when sound level measurements are unreliable. Wind causes flow noise around the microphone enclosure, inflating sound level measurements above the levels that would be measured if the microphone were not present. At present, NPS does not utilize sound level measurements when the wind speed exceeds 5 m/s.

The NPS emphasizes changes in background sound levels because this effect of noise can be translated directly into lost hearing opportunities. In most environments, the energy from a sound source is distributed over the surface of hemispheres that increase in size as the sound propagates away from its origin. This effect, called spherical spreading loss, causes the sound level to decrease by 6 dB for each doubling of distance from the source. Therefore, to compensate for a 6 dB increase in background sound level, a listener would have to be half as far away from the source to detect it. A 12 dB increase in background levels causes a 75% reduction in detection distance. For animals that rely upon sounds to warn them of danger, this loss of alerting distance can have dire consequences. Other animals—and many park visitors—use hearing to search for items of interest. The search area is proportional to the square of the maximum detection distance, so each 6 dB increase in background level causes a 75% reduction in listening area. Note that these listening area effects do not necessarily correlate with measures of perceived loudness in humans. Many references state that each 10 dB increase in SPL causes a doubling of perceived loudness (Crocker 1997), but a 10 dB increase is equivalent to moving the sound source more than three times closer to the listener.

The above paragraph addresses the issue of detection, but all of its points also apply to the degradation of information content in the received signal. This information includes species and individual identity, behavioral context, and location. Numerous studies have investigated the degree to which physical environments and signal characteristics interact to limit the range at which this information can be perceived (Marten and Marler 1977; Marten et al. 1977).

Cursory inspection of the hourly metrics across sites revealed general patterns that appeared to be shared by most—but not all—sites. The existence of exceptional sites recommended a median polish procedure for analysis, rather than a linear model or ANOVA. Median polish is a computational technique for robustly decomposing a two-way table into an additive model consisting of overall, row, column, and residual effects (Tukey 1977). In our application, we focus on the column effects, which capture shared diel patterns in noise values across all sites.

Results

Measured levels of hourly noise audibility are presented for 93 sites in 22 parks in Fig. 2a, and the overall picture attests to the ubiquity of audible noise in national parks.

A median polish applied to the data in Fig. 2a estimates the median noise audibility across all sites and hours to be over 28%. Even the quietest sites in this dataset (Kenai Fjords National Park, City of Rocks National Reserve) experience audible noise more than 5% of most daytime hours (Fig. 2a). Periods of quiet can be found at most sites, during the hours between 0000 and 0600. But most sites exhibit high noise audibility from 0700 to 2200 h, even in relatively remote settings. The high levels of noise in Yosemite relative to Sequoia Kings Canyon provide an informative contrast. Many of the sites in Sequoia Kings Canyon had rushing water nearby, so it is possible that this constant sound source prevented detection of noise events. Yosemite lies beneath two high traffic aircraft routes (east–west traffic for the San Francisco Bay Area, north–south traffic between southern California and the Pacific Northwest), and it tends to have quieter natural ambient levels that enhance detection of distant noise sources.

In this figure, parks are ordered by total population size within a 16.1 km (10 mile) buffer of their boundaries, such that the parks near the least populated areas appear on the left, and parks near the most populated areas appear on the right. Though the parks in the least populated areas do display smaller time audible percentages, the vast majority of sites display a consistent pattern of audibility, independent of the size of the nearby population.

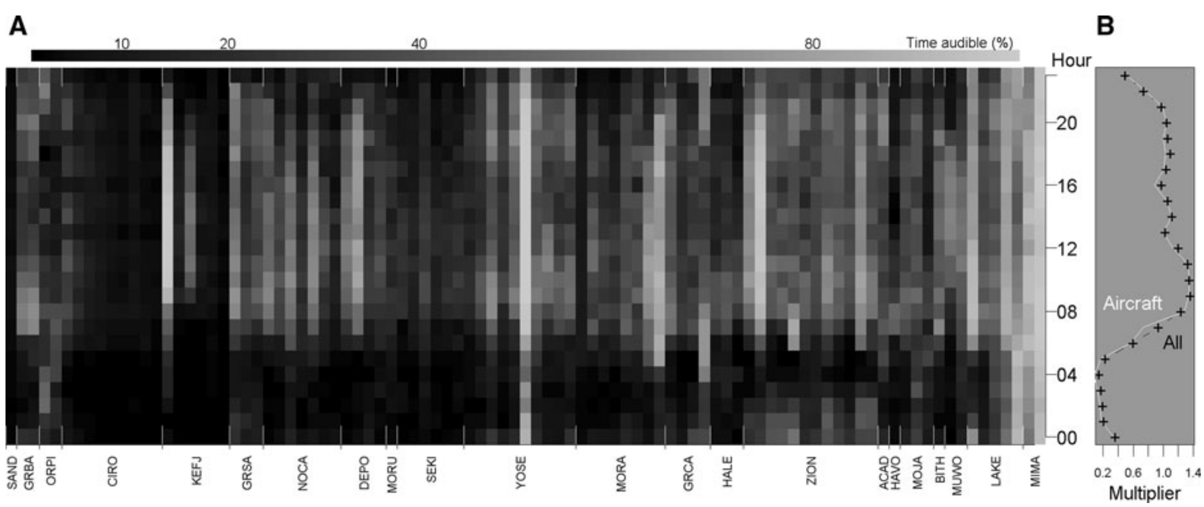

Fig. 2 Hourly percent time audible for human-caused noise sources. **a** Results of off-site noise audibility analysis for 93 sites in 22 parks. *Park names* are arranged on the *horizontal axis*, while hours of the day are shown on the *vertical axis*. The beginnings and ends of site groupings are marked by *tick marks*. *Parks* are ordered from *left to right* by total population within a 16.1 km (10 mile) buffer of park boundaries; *parks* with the smallest population nearby are on the *left*, while *parks* with the largest nearby population are placed on the *right*. Percent time audible for noise is symbolized by the tone of each *block*, with the scale displayed at the *top of the figure*. **b** Diel trend of audibility for all noise (in *black*) and aircraft noise (in *white*). These deviations were computed using a median polish procedure

This pattern suggests that the most commonly audible noise source must be something other than that caused by the surrounding communities. Figure 2b shows that the general pattern of noise audibility in parks tracks the activity cycles of humans, and that the pattern of all noise audibility is nearly identical to the pattern of aircraft noise alone. The aircraft "rush hour" is a bit later than the peak of commuter traffic in cities, with a peak between 0900 and 1000 h. A lesser peak also occurs in the early evening, which corresponds to airport departures after normal business hours. These audibility results probably understate afternoon traffic levels, because winds tend to be stronger and more prevalent in the afternoon and act to reduce the audibility of aircraft noise.

A few sites in national parks suffer from degraded noise environments comparable to urban settings. Two notable sites, one in Yosemite National Park, and one in Minute Man National Historic Park exhibited very high audibility across all hours (in Fig. 2a, these sites stand out as the brightest in their respective parks). The site in Minute Man National Historic Park, near Concord, Massachusetts, was situated close to highway Route 2A and Hanscom Field airport, while the site in Yosemite National Park was located in Yosemite Village ("The Mall"). The Mall is one of the most congested areas in the park during the day; the high nocturnal noise audibility was due to HVAC in nearby buildings. Many national parks have zones like Yosemite Village, which are designed to provide important services for large numbers of visitors (see Fig. 2, Kenai Fjords National Park, for audibility statistics from another visitor facilities zone). Future designs for such sites can plausibly provide the same services and preserve a quieter environment.

The sites which deviated from the normal pattern of audibility each have unique stories. Zion National Park, Lake Mead National Recreation Area, and Mojave National Preserve all have notable late night (0000–0400) audibility, due to train and aircraft activity near Las Vegas. The sites in Organ Pipe Cactus National Monument are near the Mexican border, and these sites experience noise from intensive border patrol activity, particularly in the evening and early morning hours.

While Fig. 2 reveals the patterns of audibility in national parks, it does not provide insight into sound levels. Audibility provides a sensitive measure of the temporal extent of noise events, but it provides no information about loudness. Figure 3 displays three measures of sound level—L_{90}, L_{50}, and L_{01}—from 189 sites in 43 parks. As in Fig. 2, sites are ordered by total population size within a 16.1 km (10 mile) buffer of their boundaries, such that the parks near the least populated areas appear on the left, and parks near the most populated areas appear on the right.

These metrics represent an estimate of background ambient sound level, the median ambient level, and the magnitude of loud events, respectively. These values are A-weighted sound levels computed from 1/3rd octave spectrum level measurements from 12.5 to 800 Hz (see ASA Specification for Sound Level Meters DF for details on these terms). The range of frequencies used in Fig. 3 spans most transportation noise energy, so these measurements provide the clearest indication of the potential impacts of noise and the capacity of the local acoustical environment to mask other transportation noise. Full spectrum dB(A) measurements are inappropriate to evaluate the potential impacts of transportation noise because they encompass all frequencies, low to high. High frequency natural sounds can substantially inflate environmental sound levels, yet these sounds cannot mask transportation noise.

While the exceedence levels in Fig. 3a vary widely among parks, panel 3B reveals that a common pattern of natural ambient sound levels does exist. A salient feature of Fig. 3 is the similarity of the three panels with the L_{90} and L_{50} patterns being nearly identical. Median polishing of the data in these three figures yielded the diel patterns displayed on the right hand side of each panel, and the following overall median sound levels across all sites and hours of the day: $L_{90} = 21.8$ dB(A), $L_{50} = 24.6$ dB(A), $L_{01} = 40.6$ dB(A). In addition to approximately 4 dB increase in level, the L_{50} panel exhibited a stronger afternoon increase in sound levels than the L_{90} panel.

As in Fig. 2, exceptional patterns in the data can be related to exceptional conditions at the sites. The highest L_{01} levels in Fig. 3 correspond to dense urban settings in Golden Gate and San Antonio Missions, unusual conditions at Rocky Mountain National Park (the "Thunder in the Rockies motorcycle rally"), and frequent aircraft activity over Lake Mead (helicopter transport of Grand Canyon air tourists over Indian Pass). The Rocky Mountain National Park data are a fairly accurate representation of acoustical conditions

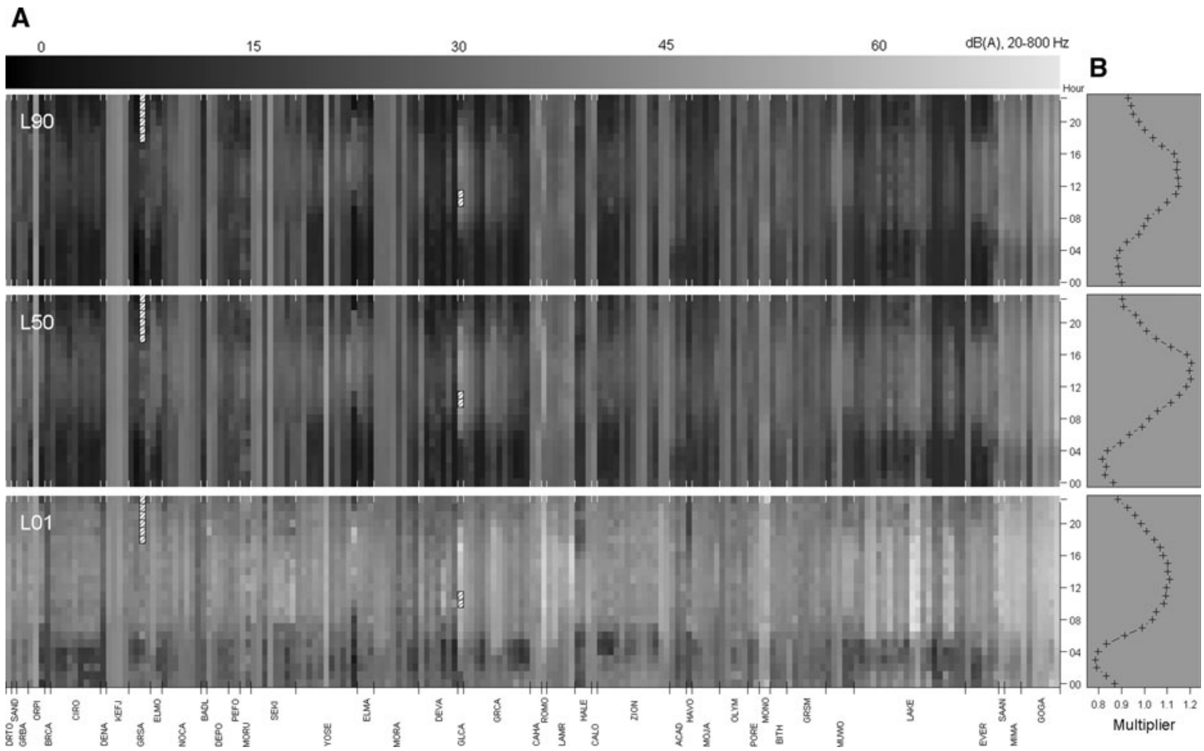

Fig. 3 Measured background, median, and peak levels of sounds between 20 and 800 Hz, in dB(A). **a** Measured hourly exceedence levels from 189 acoustical monitoring sites in 42 parks. *Parks* are displayed on the *horizontal axis*, and hours of the day are shown on the *vertical axis*. *Parks* are ordered *left to right*, from smallest population size to largest population size within 16.1 km (10 mile) of the park boundary. The *tone* of each *block* represents sound level as measured by the integral of A-weighted energy between 20 and 800 Hz. These measurements focus attention on the frequencies covering most of the transportation noise energy. *Darker tones* symbolize quieter sound levels while *brighter tones* symbolize louder sound levels. The L_{90} represents the hourly levels exceeded 90% of the time during the monitoring period, and is often used to approximate background ambient sound levels in community settings. The L_{50} represents the hourly levels exceeded 50% of the time during the monitoring period. The L_{01} represents the hourly levels exceeded 1% of the time during the monitoring period, and summarizes the sound levels for the loudest events that were measured at the site. Fields with *hash marks* indicate hours without data. **b** The overall diel trends produced by median polish of L_{01}, L_{50}, and L_{90} data in (**a**)

near any busy park road during periods of high visitation. However, not all high sound levels are attributable to noise. At sites in Olympic National Park, Cape Lookout National Seashore, and North Cascades National Park, ambient sound levels are naturally high because of the sounds of waves or cascading streams (sites such as these appear monochromatic in this figure). In this sense, the term "natural quiet" offers an incomplete image of desired conditions because the powerful sounds of water are quintessential to the character of these places.

A comparison of Figs. 2 and 3 shows that high levels of audible noise do not always coincide with high ambient sound levels. City of Rocks is noteworthy for low audibility and ambient sound levels; part of this national reserve was originally identified in legislation as "Silent City of Rocks." However, many sites in Grand Canyon, Lake Mead, Yosemite, and Zion exhibit low ambient sound levels but extensive durations of audible noise. These sites illustrate the delicate nature of exceptionally quiet locations: their pristine character is most susceptible to noise from distant sources. Several sites in Kenai Fjords and Sequoia Kings Canyon show that relatively high ambient levels due to natural sounds can be coupled with limited extents of audible noise.

Discussion

A comprehensive 1982 EPA survey assessing the noise climate in residential areas revealed that 87 percent of the urban population of the United States was exposed to a day-night sound level over 55 dB, and an additional 53% was exposed to a day-night sound level over 60 dB (day-night sound level is a standard community-noise metric, defined as 24 h average sound level, with a 10 dB penalty added for noise levels occurring between 10 p.m. and 7 a.m.) (EPA 1982). Collectively, park monitoring data show that most park sites have relatively low background sound levels, and are generally quieter than most urban or suburban communities. But despite their quiet background sound levels, extrinsic noise is audible in many parks for significant fractions of the day. High traffic locations in parks present the most degraded acoustical environments, due to the density of visitors, the mode of transporting visitors within parks, and noise from buildings and other park infrastructure. Many remote sites also have high levels of audibility, because very distant sound sources can be audible against low background sound levels. The quietest sites in parks are the most vulnerable to noise intrusions.

There are several reasons for NPS to pursue noise management. First, noise management is rooted in NPS management policies: “the natural ambient sound level—that is, the environment of sound that exists in the absence of human-caused noise—is the baseline condition and the standard against which current conditions in a soundscape will be measured and evaluated” (NPS 2006). NPS management policies (2006) also state that: “culturally appropriate sounds are important elements of the national park experience in many parks.” In NPS areas, “the Service will preserve soundscape resources and values of the parks to the greatest extent possible to protect opportunities for appropriate transmission of cultural and historic sounds that are fundamental components of the purposes and values for which the parks were established” (ibid).

Moreover, protected natural and cultural areas preserve increasingly rare sanctuaries for the public to fully experience natural sounds and solitude. Quiet settings at cultural sites or memorials enhance the contemplative or reverent atmosphere. Quiet is also an essential attribute of outstanding settings for teaching and interpretive presentations. Children are especially prone to distraction, and have more difficulty than adults in understanding speech in noisy locations. In attempting to preserve outstanding acoustical conditions, NPS confronts an accelerating historical trend. Rapid energy development, infrastructure expansion, and urbanization are fragmenting the acoustical landscape.

Degraded listening opportunities also affect innumerable aspects of ecosystem function. From the perspective of resource preservation and restoration, it is understandable if noise management pales in comparison to ensuring the survival of threatened and endangered species. Nonetheless, an emergent body of literature suggests that these concerns are often linked. For wildlife, noise pollution intensifies the ecological stress that habitat fragmentation has caused (Barber et al. 2010). Hearing is the universal alerting sense; it remains active even in sleeping animals.

Fortunately, the benefits of noise management can be measured and perceived immediately; a noise source quieted, displaced, or removed is readily apparent. However, ecosystem recovery from noise exposure and changes in visitor expectations and use patterns may progress on much longer time scales. NPS enjoys a unique obligation and opportunity to translate the principles governing architectural design for outstanding indoor acoustics into park architectures that preserve authentic conditions. Design options like noise barriers between parking areas and scenic overlooks may provide significant improvements over current conditions. In the longer term, transportation networks inside parks can be reshaped to reduce their impacts to acoustic resources and visitor listening opportunities.

Lamentably, much of the noise measured in national parks comes from sources outside park boundaries and beyond the management jurisdiction of NPS. The regional and national scales of these noise sources call for conservation and management efforts on the same scales.

As shown in Table 2, the NPS has made a number of significant achievements in the realm of soundscape management and noise mitigation. Muir Woods National Monument declared a permanent “quiet zone” in Cathedral Grove, after social science research revealed that such signage was supported by an overwhelming majority of park visitors and that the resulting reduction in sound levels was equivalent to halving the number of visitors in the park. Mass transit has become an increasingly attractive option to parks like Zion National Park and Devils Postpile National Monument, allowing them to provide access to large numbers of visitors while diminishing impacts to resources. When Zion National Park

Table 2 Noise management techniques, as applied in national parks

Park	Mitigation method(s)
Acadia National Park	Currently using baseline ambient data to fulfill legislative mandate by managing air tours over national parks
Big Thicket National Preserve	Used baseline ambient data to persuade energy development company to erect berms between park and directional drilling operations
Devils Postpile National Monument	Currently using acoustical data to determine impacts of new mass transit options (buses)
Grand Canyon National Park	Utilized baseline ambient data in completed draft Air Tour Management Plan. Currently seeking public comment
Great Sand Dunes National Park & Preserve	Cited data in an injunction of proposed oil and gas exploration in adjacent national wildlife refuge
Haleakalā National Park	Currently using baseline ambient data to fulfill legislative mandate by managing air tours over national parks
Hawai'i Volcanoes National Park	Using baseline ambient data to fulfill legislative mandate by managing air tours over national parks
Kenai Fjords National Park	Established desired future conditions and soundscape quality standards for Exit Glacier Management Plan
Lake Mead National Recreation Area	Currently using baseline ambient data to fulfill legislative mandate by managing air tours over national parks
Minute Man National Historic Park	Established desired future conditions and soundscape quality standards. Drafted Soundscape Management Plan to manage park-wide acoustical environment, currently under park review
Mojave National Preserve	Monitored areas below flight paths between to document baseline conditions prior to the construction of a nearby major airport
Mount Rainier National Park	Currently using baseline ambient data to fulfill legislative mandate by managing air tours over national parks
Mount Rushmore National Memorial	Currently using baseline ambient data to fulfill legislative mandate by managing air tours over national parks
Muir Woods National Monument	Designated permanent 'quiet zone,' based on the findings of various acoustical monitoring studies
North Cascades National Park Complex	Incorporated protection of natural sounds into wilderness management plan
Organ Pipe Cactus National Monument	Used baseline ambient conditions to determine effects of border patrol installations on the soundscape and the endangered Sonoran Pronghorn, a species which inhabits the park
Sand Creek Massacre National Historic Site	Gathered baseline ambient data in order to incorporate protection of natural sounds into the park's first general management plan. Worked with Colorado Air National Guard to assess impacts of military overflights
Sequoia and Kings Canyon National Parks	Currently using baseline ambient data to fulfill legislative mandate by managing air tours over national parks
Yosemite National Park	Incorporated developed desired conditions and standards of quality for soundscapes in Merced River Plan. Considered soundscape as a resource to be protected and incorporated into future plans
Zion National Park	Used acoustical data to quantify benefits of shuttle system in Zion Canyon. Finalized a soundscape management plan which included desired future conditions, soundscape objectives, and standards of quality

instituted a shuttle bus system to reduce summer congestion on park roads, the park received visitor comments expressing appreciation for the quieter conditions. Numerous parks have begun drafting Air Tour Management plans to mitigate noise from air tour operations. Acoustical monitoring data has even been cited in court decisions as a reason to halt oil and gas exploration near parks. These efforts to mitigate noise in parks are an encouraging trend. The NPS has a unique opportunity to educate and engage the public on issues like noise pollution, air quality, and climate change, but effective resolution will require partnerships that transcend park boundaries and institutional barriers to cooperation.

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