



Craters of the Moon National Monument and Preserve

Acoustic Monitoring Report, 2017



Acoustic monitoring in Craters of the Moon National Monument and Preserve.
NPS/ASHLEY PIPKIN

Craters of the Moon National Monument and Preserve: Acoustic monitoring report, 2017

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Abstract

This study arose from the Craters of the Moon National Monument and Preserve (CRMO) Resource Stewardship Strategy (RSS), which identified the need for baseline acoustic surveys in the park. Short-term natural soundscape RSS goals were to identify the condition of the acoustic resource, and the high priority stewardship activity associated with this goal was to collect baseline acoustic data. Therefore, from June–September 2017, the Natural Sounds and Night Skies Division (NSNSD) gathered acoustical data at six sites in CRMO to provide park managers with information about the acoustical environment, sources of noise, and the natural and existing ambient sound levels within the park. On average, noise was present from 7 to 85 percent of the time across the six sites. The most common sources of noise were vehicles, aircraft, and people. The maximum percent time audible for any detailed noise source was people at site CRMO004, audible for 81% of a 24-hr period. Aircraft was most audible at site CRMO005 (15%), and vehicles were most audible at site CRMO001 (20%). Overall, existing median ambient sound levels (L_{A50}) at sites within CRMO ranged from 17.8–31.1 dB during the day and 15.6–34.0 dB at night during the sampling period. Natural ambient sound levels (L_{Anat}) at sites within CRMO ranged from 16.4–30.0 dB during the day and 15.1–33.0 dB at night. The median impact, defined as the difference in dB between the L_{A50} and L_{Anat} , was 1.4 dB. Noise impacts ranged from 1.1 dB at CRMO006 to 8.3 dB at CRMO004, where noise was audible for 100% of the time from 07:00 to 10:00.

List of Terms

A-weighting: A-weighting is applied to sound levels in order to account for the sensitivity of the human ear (Harris, 1998). To approximate human hearing sensitivity, A-weighting discounts sounds below 1 kHz and above 6 kHz.

Acoustic Environment: A combination of all the physical sound resources within a given area. This includes natural sounds and cultural sounds, and non-natural human-caused sounds. The acoustic environment of a park can be divided into two main categories: intrinsic and extrinsic.

Acoustic Resources: Includes both natural sounds like wind, water, & wildlife and cultural and historic sounds like tribal ceremonies, quiet reverence, and battle reenactments.

Amplitude: The relative strength of a sound wave, described in decibels (dB). Amplitude is related to what we commonly call loudness or volume.

ANS Weighting: The Natural Sounds modification to A-weighting eliminates high-frequency sound (leaf rustle, equipment noise, and biologic sounds) allowing for more accurate comparisons of low-frequency ambient sound levels across different land use types (e.g., urban, protected areas; American National Standards Institute (ANSI) S3/SC1.100, 2014). This frequency weighting scheme improves ambient sound level measurements in quiet environments.

Audibility: The ability of animals with normal hearing, including humans, to hear a given sound. It can vary depending upon the frequency content and amplitude of sound and by hearing ability of individual animals.

Decibel (dB): A unit of sound energy. Sound levels are measured on a logarithmic scale relative to the reference sound pressure for atmospheric sources, 20 μ Pa. The logarithmic scale is a useful way to express the wide range of sound pressures perceived by the human ear. Sound levels are reported as decibels (dB). Every 10 dB increase represents a tenfold increase in energy. Therefore, a 20 dB increase represents a hundredfold increase in energy.

Existing ambient sound level (L_{A50}): Sound level ($L_{Aeq, 1s}$) exceeded 50% of the time (50th percentile) for a specified duration. This level is referred to as the existing ambient sound level and the preferred metric for chronic conditions, as it is insensitive to infrequent loud events.

Frequency: Related to the pitch of a sound, and defined as the number of times per second that the wave of sound repeats itself and is expressed in terms of hertz (Hz). Sound levels are often adjusted (“weighted”) to match the hearing abilities of a given animal. In other words, different species of animals and humans are capable of hearing (or not hearing) at different frequencies. Humans with normal hearing can hear sounds between 20 Hz and 20,000 Hz, and as low as 0 dB at 1,000 Hz. Bats, on the other hand, can hear sounds between 20 Hz and 200,000 Hz.

Percentile sound levels (L_{A10} , L_{A50} , L_{A90}): Metrics used to describe A-weighted sound pressure levels (L), in decibels, exceeded 10, 50, and 90 percent of the time, respectively. Put another way,

half the time the measured levels of sound are greater than the L_{A50} value, while 90 percent of the time the measured levels are higher than the L_{A90} value, and 10 percent of the time measured levels are higher than the L_{A10} value.

Day-Night average sound levels (L_{dn}): Day-Night Average Sound Level. Average equivalent sound level over a 24-hour period, with a 10-dB penalty added for sound levels between 10 p.m. and 7 a.m.

Energy Equivalent Sound Level (L_{Aeq}): The sound energy level averaged over the measurement period. Generally, refers to A-weighted 1-second time averaged sound levels measured between 12.5 Hz–20 kHz. This is a standard measurement collected using NSNSD acoustic monitoring protocol for sound level meters. Sound levels measured over 1 second intervals are used to calculate summary statistics, specifically percent of the time a sound level of interest is exceeded.

Natural Ambient Sound Level (L_{Anat}): The natural sound conditions in parks, which would exist in the absence of any human-caused noise sources. L_{Anat} is the preferred metric to represent baseline or reference conditions.

Noise Free Interval (NFI): The length of the continuous period of time during which no human-caused sounds are audible.

Time Above: Within a defined time period, the percent of the time sound levels ($L_{Aeq, 1s}$) are above a specified sound level ($L_{Aeq, 1s}$). Commonly used levels are 35, 45, 52 dB ($L_{Aeq, 1s}$).

Time Audible: The amount of time that various sound sources are audible to humans with normal hearing, commonly expressed in percent of day, or percent of daytime hours and nighttime hours. A sound may be above natural ambient sound pressure levels, but still not audible. Similarly, some sounds that are below the natural ambient can be audible. Time Audible is useful because of its simplicity. It is a measure that correlates well with visitor complaints of excessive noise and annoyance. Most noise sources are audible to humans at lower levels than virtually all wildlife species. Therefore, time audible is a protective proxy for wildlife. These data can be collected either by a trained observer (on-site listening) or by making high-quality digital recordings for later playback (off-site listening).

Sound Exposure Level (SEL): The total sound energy of the actual sound during a specific time period. SEL is usually expressed using a time period of one second.

Sound Pressure: Minute change in atmospheric pressure due to passage of sound that can be detected by microphones.

Sound vs. Noise: Sound and noise are often used interchangeably to describe an acoustic source. A common definition of noise is unwanted sound or sounds that interfere with a signal of interest (Harris 1998; Templeton 1997). However, noise is not a purely subjective designation. Any sound that serves no function is noise. Most sounds produced by human transportation and other machinery are unintended and serve no function, therefore are noise regardless of the attitudes of the listener. While there are unintended sounds in nature, like the footfalls of an animal, these sounds provide

vital cues for some receivers and are therefore considered sounds to the receiver, yet noise from the perception of the producer.

Soundscape: The human perception of physical sound resources.

Executive Summary

This report presents acoustical data gathered by the Natural Sounds and Night Skies Division (NSNSD) at Craters of the Moon National Monument and Preserve (CRMO) from June–September of 2017. Data were collected at six sites (Figure 1) to provide park managers with information about the acoustic environment, sources of noise, and the natural and existing ambient sound levels within the park. In these deployments, sound pressure level (SPL) was measured continuously every second by a calibrated sound level meter. Other equipment included an anemometer to collect wind speed and a digital audio recorder collecting continuous recordings to document sound sources. In this document, “sound pressure level” refers to broadband (12.5 Hz–20,000 Hz), A-weighted, 1-second time averaged sound level ($L_{Aeq, 1s}$ [12.5–20,000 Hz]), and hereafter referred to as “sound level.” Sound levels are measured on a logarithmic scale relative to the reference sound pressure for atmospheric sources, 20 μ Pa. The logarithmic scale is a useful way to express the wide range of sound pressures perceived by the human ear. Sound levels are reported in decibels (dB). A-weighting is applied to sound levels to account for the response of the human ear (Harris, 1998). To approximate human hearing sensitivity, A-weighting discounts sounds below 1 kHz and above 6 kHz. For reference, Table 1 provides examples of sound levels measured in parks compared to sound levels of common sources.

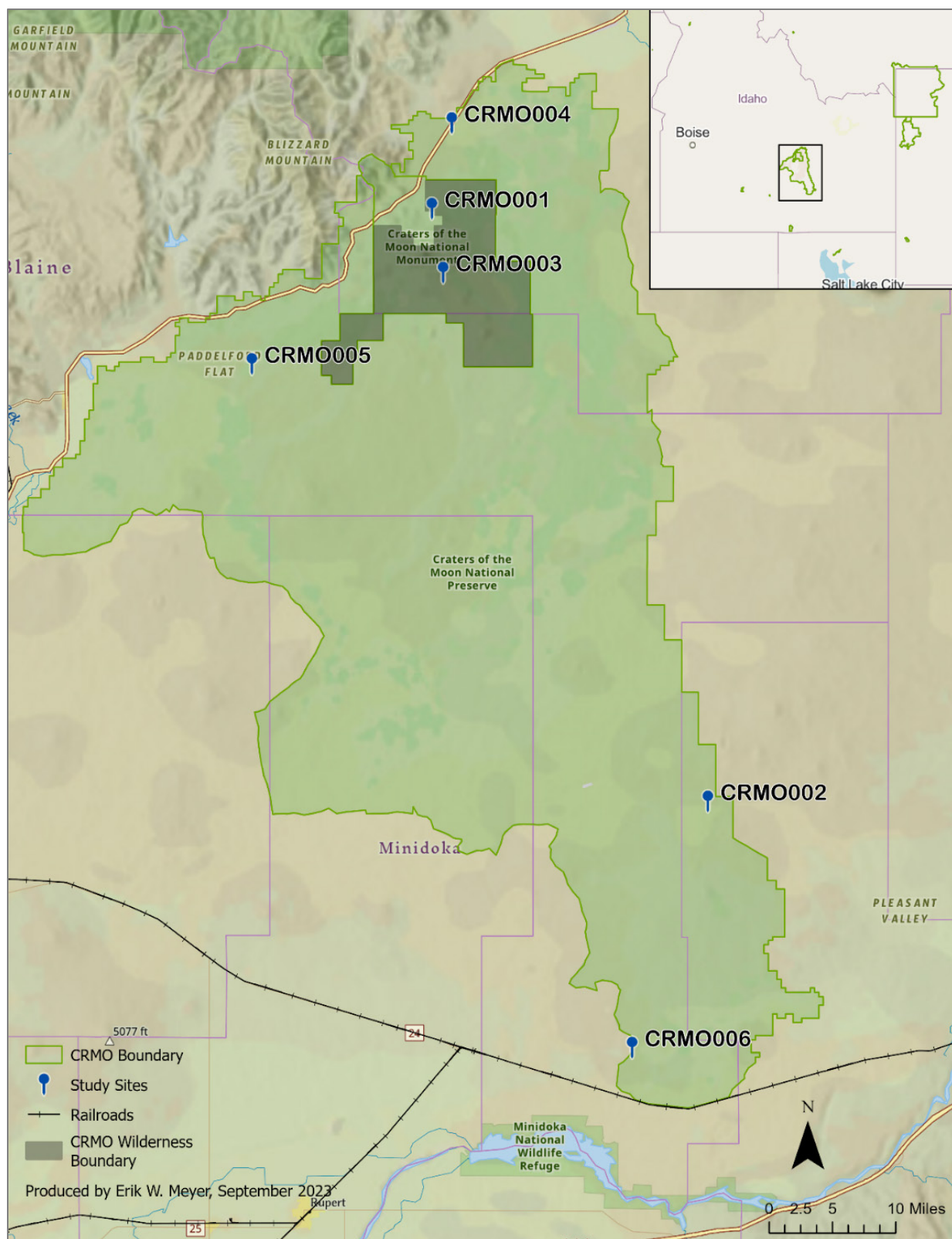


Figure 1. Study sites in Craters of the Moon National Monument and Preserve, Idaho, USA.

Table 1. Sound level examples.

Park Sound Sources	Common Sound Sources	Sound Level dB*
Volcano crater (HALE)	Human breathing at 3m	10
Leaves rustling (CANY)	Whispering	20
Crickets at 5m (ZION)	Residential area at night	40
Conversation at 5m (WHMI)	Busy restaurant	60
Cruiser motorcycle at 15m (BLRI)	Curbside of busy street	80
Thunder (ARCH)	Jackhammer at 2 m	100
Military jet at 100m AGL (YUCH)	Train horn at 1 m	120

* dB re 20 μ Pa A-weighted broadband (12.5 Hz–20 kHz), sound level measured over varied measurement durations and at the distances indicated.

Overall, existing ambient sound levels (L_{A50}) at sites within CRMO ranged from 17.8–31.1 dB during the day and 15.6–34.0 dB at night during the sampling period. Table 2 reports the percent of time that measured levels at the monitoring locations were above four key sound level values. The first value, 35 dB ($L_{Aeq, 1s}$), addresses the health effects of sleep interruption. Recent studies suggest that sound events as low as 35 dB can have adverse effects on blood pressure in sleeping humans (Haralabidis et al. 2008). This level, 35 dB, is also the desired background sound level in classrooms (ANSI S12.60-2002). The second value addresses the World Health Organization’s recommendations that noise levels inside bedrooms remain below 45 dB ($L_{Aeq, 1s}$) (Berglund et al. 1999). The third value, 52 dB ($L_{Aeq, 1s}$), is based on the EPA’s speech interference level for speaking in a raised voice to an audience at 10 meters (EPA 1974). This value addresses the effects of sound on interpretive presentations in parks. The final value, 60 dB ($L_{Aeq, 1s}$), provides a basis for estimating speech interference on normal voice communications at 1 meter. Visitors viewing scenic areas in the park would likely be conducting such conversations.

Sound levels are often measured over narrow frequency bands (typically in one-third octave bands between 12.5 Hz–20 kHz) because these smaller bands closely represent how humans distinguish between frequencies of sound. In this study, we examine how often sound levels exceeded the key values mentioned above in two frequency ranges. The top value in each split-cell of Table 2 uses the full frequency range (12.5 Hz–20 kHz) collected, whereas the bottom value focuses on frequencies affected by low frequency noise sources (20–1,250 Hz). This Natural Sounds modification to A-weighting (referred to as ANS weighting, ASA/ANSI S3/SC1.100-2014) eliminates high-frequency sound (leaf rustle, equipment noise, and biologic sounds) allowing for more accurate comparisons of low-frequency ambient sound levels across different land use types (e.g., urban, protected areas; ASA/ANSI S3/SC1.100-2014). This frequency weighting scheme improves ambient sound level measurements in quiet environments. For instance, in the full frequency range, the 35 dB ($L_{Aeq, 1s}$) level was exceeded at CRMO002 16.74% of the time during the day and 3.31% of the time at night, but in the 20–1,250 Hz range, the 35 dB functional sound level value was very rarely exceeded in daytime or nighttime. Speech interruption (between two people 1 meter apart) occurs at 60 dB ($L_{Aeq, 1s}$) and this level was rarely exceeded at any of the sites.

After data collection was complete, trained technicians calculated how often noise sources were audible. See Methods section for protocol details, equipment specifications, and metrics calculations. Sound source analysis revealed that noise was audible about 7–85% of the time during the sampling period at study sites when averaged across all hours of the day (Table 3). The most common noise sources observed during this study were aircraft and vehicles. Natural sources such as wind, rain, thunder, coyotes, songbirds, and insects were also commonly audible. Natural ambient sound levels (L_{Anat}) ranged between 16.4–30.0 dB during the day and 15.1–33.0 dB at night. Increased natural ambient sound levels during day and night varied by location and were likely caused by diurnal winds and site-specific insect and bird activity.

Table 2. Percent time above metrics for acoustic records collected in Craters of the Moon National Monument and Preserve (CRMO) from June–September 2017.

Site ID	Frequency Range	Time above sound level (% of daytime hours, 07:00 to 19:00)				Time above sound level (% of nighttime hours, 19:00 to 07:00)			
		35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
CRMO001	Full (12.5–20,000)	1.03	0.18	0.03	0.00	0.39	0.03	0.00	0.00
	ANS (20–1,250) ^B	0.95	0.18	0.04	0.00	0.38	0.02	0.00	0.00
CRMO002	Full (12.5–20,000)	16.74	1.29	0.06	0.00	3.31	0.20	0.02	0.00
	ANS (20–1,250) ^B	1.72	0.16	0.02	0.00	0.65	0.04	0.00	0.00
CRMO003	Full (12.5–20,000)	7.70	0.43	0.07	0.00	4.31	0.13	0.01	0.00
	ANS (20–1,250) ^B	3.43	0.21	0.04	0.00	0.78	0.04	0.00	0.00
CRMO004	Full (12.5–20,000)	16.88	2.09	0.46	0.02	31.54	3.99	0.45	0.00
	ANS (20–1,250) ^B	15.72	1.96	0.42	0.02	20.04	3.65	0.40	0.00
CRMO005	Full (12.5–20,000)	1.78	0.20	0.05	0.00	0.55	0.00	0.00	0.00
	ANS (20–1,250) ^B	1.57	0.18	0.04	0.00	0.35	0.00	0.00	0.00
CRMO006	Full (12.5–20,000)	25.54	2.69	0.27	0.01	47.88	4.56	0.22	0.00
	ANS (20–1,250) ^B	20.84	2.00	0.23	0.01	33.69	2.57	0.14	0.00

^A dB LAeq, 1s re 20 μ Pa

^B The percent of time ANS-weighted sound levels (20–1,250 Hz) are above functional values.

Table 3. Summary of summer noise sources and sound levels at six Craters of the Moon National Monument and Preserve (CRMO) study sites. Included for each site are a) mean percent time audible for all human-caused noise, including the top two known noise sources, and b.) existing (L_{A50}) and natural (L_{Anat}) ambient sound levels (dB re 20 μ Pa, A-weighted broadband, 12.5 Hz–20,000 Hz) during the day (0700–1900) and night (1900–0700). The difference between the natural and existing ambient sound levels indicates the deviation from the natural condition.

Site ID	a) Mean time audible for noise (% of 24-hour time period)				b) Median Existing Ambient (L_{A50}) in dB		Median Natural Ambient (L_{Anat}) in dB	
	Noise	Aircraft	Vehicles	People	Day	Night	Day	Night
CRMO001	43.4	10.6	20.2	17.2	19.0	16.4	16.9	15.7
CRMO002	13.6	10.7	0.1	0.8	27.0	19.4	25.7	18.6
CRMO003	13.9	12.3	0.0	0.0	25.9	19.7	24.5	19.2
CRMO004	85.1	8.1	0.0	80.9	28.4	25.4	20.1	16.0
CRMO005	40.1	14.8	0.0	19.8	17.8	15.6	16.4	15.1
CRMO006*	7.3	1.4	0.0	NA	31.1	34.0	30.0	33.0

* Mean time audible obtained using Sound Pressure Level Annotation Tool (SPLAT) technique over 52 days. All other sites using Listening Center software technique and were subsampled using 9–11 recording days.

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Introduction

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 & Wakefield 1998). In another survey specific to park visitors, 91 percent of respondents considered enjoyment of natural quiet and the sounds of nature as compelling reasons for visiting national parks (McDonald et al. 1995). Acoustical monitoring provides a scientific basis for assessing the status of acoustic resources, identifying trends in resource conditions, quantifying impacts from other actions, assessing consistency with park management objectives and standards, and informing management decisions regarding desired future conditions.

National Park Service Natural Sounds and Night Skies Division

The Natural Sounds and Night Skies Division (NSNSD) helps parks manage sounds in a way that protects park resources and the visitor experience. The NSNSD addresses acoustical issues raised by Congress, NPS Management Policies, and NPS Director's Orders. The NSNSD works to protect, maintain, or restore acoustical environments throughout the National Park System. Its goal is to provide coordination, guidance, and a consistent approach to soundscape protection with respect to park resources and visitor use. The program also provides technical assistance to parks in the form of acoustical monitoring, data processing, park planning support, and comparative analyses of acoustic environments.

Soundscape Planning Authorities

The National Park Service Organic Act of 1916 states 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." In addition to the NPS Organic Act, the Redwoods Act of 1978 affirmed 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."

Direction for management of natural soundscapes is represented in 2006 Management Policy 4.9: The Service will restore to the natural condition wherever possible those park soundscapes that have become degraded by unnatural sounds (noise) and will protect natural soundscapes from unacceptable impacts. Using appropriate management planning, superintendents will identify what levels and types of unnatural sound constitute acceptable impacts on park natural soundscapes. The frequencies, magnitudes, and durations of acceptable levels of unnatural sound will vary throughout a park, being generally greater in developed areas. In and adjacent to parks, the Service will monitor human activities that generate noise that adversely affects park soundscapes [acoustic resources], including noise caused by mechanical or electronic devices. The Service will take action to prevent or minimize all noise that through frequency, magnitude, or duration adversely affects the natural soundscape [acoustic resource] or other park resources or values, or that exceeds levels that have

been identified through monitoring as being acceptable to or appropriate for visitor uses at the sites being monitored (NPS 2006a).

It should be noted that “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 [acoustic resource] will be measured and evaluated” (NPS 2006b). However, the desired acoustical condition may also depend upon the resources and the values of the park. For instance, “culturally appropriate sounds are important elements of the national park experience in many parks” (NPS 2006b). In this case, “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” (NPS 2006b).

Further guidance is provided in Management Policies 2006 §4.1.4 Partnerships, §4.1.5 Restoration of Natural Systems, §8.2 Visitor Use, §8.2.2 Recreational Activities, §8.2.3 Use of Motorized Equipment, and §8.4 Overflights and Aviation Uses (NPS 2006).

Directors Order 47, Soundscape Preservation and Noise Management (2000) builds on the principles set out in Management Policies, directing park management how and when to consider acoustic resources. Through this order, parks are guided to manage noise by: identifying noise sources, minimizing noise from park operations, considering the acoustic environment in park planning documents, and promoting park sounds and noise management through communication, education, and outreach.

Focal Park Unit

Craters of the Moon National Monument and Preserve (CRMO) protects a vast “weird and scenic landscape” with remarkable and diverse volcanic features, sagebrush steppe ecosystems, and wilderness, which provides opportunities to explore, understand, and value the rugged and remote high desert landscape of the Great Rift Region (NPS 2014). The CRMO Foundation Document identifies Wilderness Character as a Fundamental Resource Value and identifies highway traffic impacts to the natural soundscape in Wilderness as an important issue for the park to strategically address (NPS 2014). Furthermore, the CRMO Resource Stewardship Strategy (RSS) identified the Natural Soundscape as a priority resource (NPS 2018). A high priority stewardship activity included collecting baseline acoustic data, which resulted in a Technical Assistance request to NSNSD in 2017 (TAR 4881). This study describes the outcome of that request.

Study Area

This report covers results from an acoustic inventory conducted in 2017 at CRMO (Table 4). Six sites were selected to represent a range of visitation, noise source, and habitat type. One site was deployed during two sampling visits (CRMO001). Two sites were deployed only during the first visit (CRMO002, CRMO003), and three sites were deployed only during the second visit (CRMO004–006). Four of the sites were deployed in the northern half of the unit, which also receives the most visitation. Two of the sites were deployed in the southern portion of the unit. The set of acoustic inventory sites spanned 130 km. (Figure 1).

Table 4. Metadata for acoustic monitoring sites at Craters of the Moon National Monument and Preserve, 2017.

Site	Site Name	Dates	Vegetation	Wilderness	Elevation(m)	Latitude	Longitude
CRMO001	Caves Trail	6/25–9/17	Lava Flow	No	1747	43.44538	–113.52893
CRMO002	King's Bowl	6/25–8/7	Montane grasslands	No	1504	42.95254	–113.21367
CRMO003	Wilderness Trail	6/27–8/12	Montane grasslands	Yes	1711	43.39246	–113.51610
CRMO004	Golden Chariot	8/8–9/27	Montane grasslands	No	1672	43.51630	–113.506252
CRMO005	SW Lava Flow	8/09–9/27	Lava Flow	No	1655	43.31663	–113.73455
CRMO006	Wapai	8/10–9/27	Montane grasslands	No	1340	42.74666	–113.30021

Methods

Automatic Monitoring

A Larson Davis sound level meter (SLM) type 831-A was deployed at each monitoring site. The SLM is a hardware-based, real-time analyzer which constantly records one-third octave band sound pressure level (SPL) data. This Larson Davis-based site met American National Standards Institute (ANSI) Type 1 standards (ANSI 1968, 1992). The sound level meter provided the information needed to calculate metrics described below in Calculation of Metrics.

Acoustical monitoring equipment is used by many practitioners to determine noise levels in different environments, both indoors and outdoors. The NPS uses equipment that is similar to the equipment used by other practitioners but has developed a unique configuration that stands up to the potentially harsh environment encountered in national parks. The microphone with environmental shroud was set up on a tripod at 1.5 m above the ground, which approximates the average height of the human ear. The digital audio recorder recorded continuous audio through the entire monitoring period. An anemometer was attached to a tripod and placed approximately 10 feet from the microphone, to capture local wind conditions without introducing acoustic artifacts from anemometer wind cup rotation.

The sampling station consisted of:

1. Type 1 sound level meter
2. Microphone with environmental shroud
3. Preamplifier
4. 12 V battery pack
5. Anemometer (wind speed)
6. Digital audio recorder

The sampling station collected:

7. Flat-weighted, time-average sound level ($L_{Zeq, 1s}$) for each one-third octave frequency band, 12.5–20,000 Hz in dB re 20 μ Pa
8. A-weighted, time-average sound level ($L_{Aeq, 1s [12.5-20000 \text{ Hz}]}$) in dB re 20 μ Pa
9. Continuous digital audio recordings (96 kbps MP3)
10. Continuous meteorological data for wind speed

Monitoring Period

It is typical to monitor a minimum of 25 days to capture daily differences within a sampling period that occur at each site within a reasonable margin of error (NPS 2005). For this study, the monitoring period ranged from 43 to 84 days (84, 43, 48, 50, 49, 48 days for CRMO001–006, respectively).

Calculation of Metrics

The status of the acoustical environment can be characterized by sound level (L_{A50} , L_{Anat} , L_{A90} , L_{A10} , L_{Aeq}) and frequency content, and event durations (through off-site listening). NPS uses descriptive figures and metrics to interpret these characteristics.

Two fundamental descriptors are existing ambient (L_{A50}) and natural ambient (L_{Anat}) sound levels. These are both examples of percentile levels, where each L_x value refers to the sound level that is exceeded $x\%$ of the time. The L_{A50} represents the median sound level and is drawn from a full dataset (removing data with wind speed $> 5\text{m/s}$ to eliminate error from microphone distortion). The L_{A50} is the preferred metric to represent prevailing acoustic conditions. The natural ambient (L_{Anat}) is an estimate of what the sound levels for a site would be if all human-caused noise sources were removed. L_{Anat} is the preferred metric to represent baseline or reference conditions.

For a given hour (or other specified time period), L_{Anat} is calculated to be the sound level exceeded x percent of the time, where x is defined by equation (1):

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

where

P_H = percentage of samples containing noise for the hour.

For example, if human-caused sounds are present 30% of the hour, $x = 65$, and the L_{Anat} is equal to the L_{65} , or the level exceeded 65% of the time. To summarize and display these data, the median of the hourly L_{Anat} values for the daytime hours (0700–1900) and the median of the hourly L_{Anat} values for the nighttime (1900–0700) are displayed in graphical format in the following sections.

Off-Site Listening and Spectrogram Analysis

Listening Center Software Analysis

Off-site analysis is completed by listening to the audio record while simultaneously viewing its spectrogram representation (for more information on Listening Center software, see Appendix A). For five sites (CRMO001-005), auditory analysis was used to calculate the audibility of sound sources at each location. Trained technicians at Colorado State University (Figure 2) listened back to 9–11 days of the audio record. Technicians considered only a subsample of each day representing the first 10 seconds of every two-minute period. Within each subsample every audible sound source was categorized. This allowed the temporal extent of audibility for each source type to be estimated. The total percent time noise was audible was then used to calculate the natural ambient sound level (L_{Anat}) for each hour (see Equation 1 above for more information). For any off-site audio playback listening techniques, Bose Quiet Comfort Noise Canceling headphones were used to minimize limitations imposed by the office acoustical environment.



Figure 2. A Colorado State University student identifies sound sources using Acoustic Monitoring Toolbox (NPS) software.

Sound Pressure Level Annotation Tool

Technical issues at site CRMO006 led to an incomplete set of audio recordings. Therefore, the Listening Center software could not be used. However, there was a complete record of sound pressure levels, so this data was annotated visually across 52 days of spectrograms using the NPS-

developed software, Sound Pressure Level Annotation Tool (SPLAT). Trained technicians used SPLAT to draw bounding boxes at the beginning and end of noise events using visual cues from the sound pressure energy, time, and frequency of a spectrogram (for more information on SPLAT software, see Appendix B). From the drawn bounding boxes, noise event counts (i.e., the number of boxes), and noise duration (i.e., the length of each box) were obtained. In addition, the noise-free interval (NFI) metric was generated. The NFI represents the length of time that passes between the end of one noise event and the beginning of the next. Over a longer sampling period, the median of NFI can describe how a typical opportunity for solitude has been fragmented by noise (Poling and Betchkal 2023). Like the Listening Center software, the total percent time noise was audible was then used to calculate the natural ambient sound level (L_{Anat}) for each hour.

On-Site Listening

In addition to sound pressure level and audio data, knowledge of the type, context, duration, and distribution of sound sources is crucial for characterizing natural and non-natural acoustic conditions. This information can be acquired during periods of observer data collection, called on-site listening. During an on-site listening session, one inconspicuously listens to the soundscape and takes note of all audible events as they occur. For this technique, an observer sits quietly at a location at least 15 m from the acoustic monitor for one hour. At the top of the hour and once the observer is acclimated to the listening area, each sound heard is entered into a handheld device. Sound type, event count, and event duration are calculated from these sessions. Three on-site listening sessions occurred at CRMO001, four at CRMO002 and CRMO003, two at CRMO004, and one at CRMO005 and CRMO006.

Results

Frequency Content

To determine the effect that noise has on the acoustic environment, it is useful to examine percentile metrics across a frequency range. High-frequency sounds (such as a cricket chirping) and low frequency sounds (such as flowing water) often occur simultaneously, so the frequency spectrum is split into 33 narrower bands, each encompassing one-third of an octave. These narrow bands closely represent how humans distinguish between frequencies of sound. The percentile sound levels for 33 one-third octave band frequencies over the day and night periods are shown in Figure 3–Figure 8.

Examining the sound energy in each one-third octave band (combined with digital audio recordings) allows acoustic technicians to determine what types of sounds are contributing to the overall sound levels at a site. The grayed areas of Figure 3–Figure 8 represent sound levels outside of the typical range of human hearing. The percentile levels (L_x) are also shown for each one-third octave band. They represent the sound levels exceeded x percent of the measurement period. For example, L_{90} is the sound level that has been exceeded 90% of the time, and only the quietest 10% of the samples can be found below this point. On the other hand, the L_{10} is the sound level that has been exceeded 10% of the time, and 90% of the measurements are quieter than the L_{10} . The bold portion of the column represents the difference between L_{50} and L_{nat} . The height of this bold portion is a measure of the contribution of anthropogenic noise to the existing sound levels at this site. The size of this portion of the column is directly related to the percent time that human-caused sounds are audible. When bold portions of the column do not appear the natural and existing sound levels were either very close to each other or were equal. The typical frequency levels for transportation, conversation, and songbirds are presented on the figure as examples for interpretation of the data. These ranges are estimates and are not vehicle-, species-, or habitat-specific.

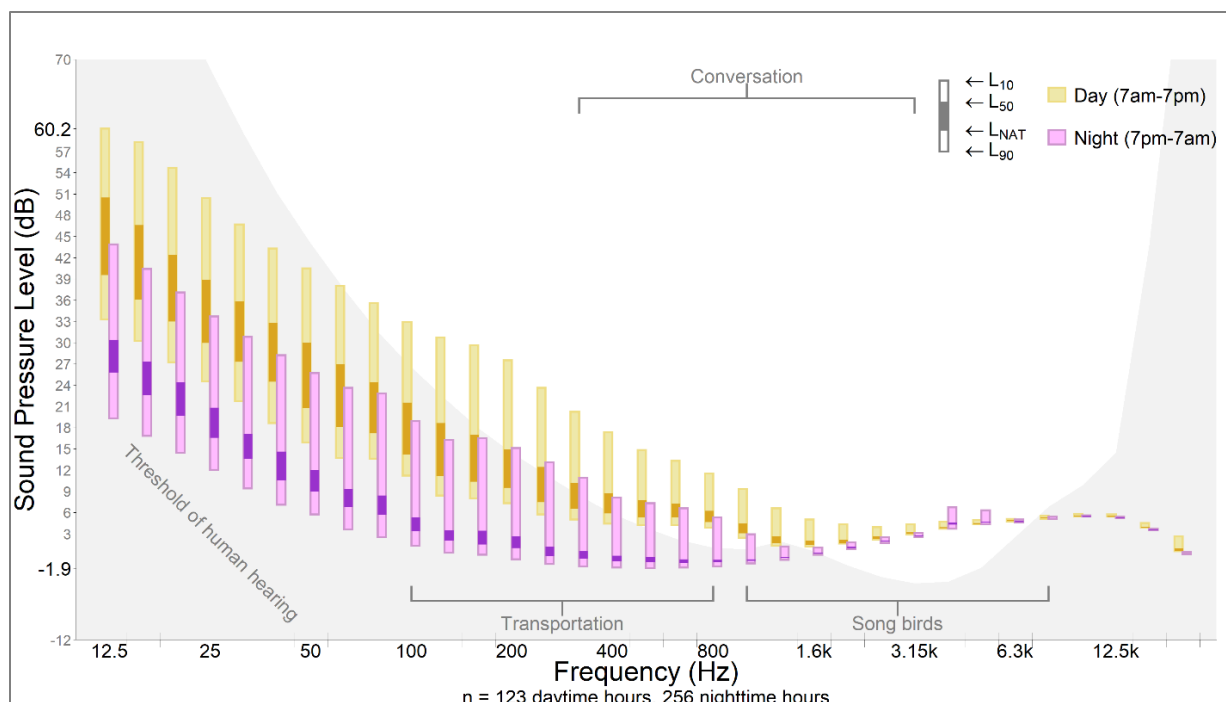


Figure 3. Day and night percentile sound pressure levels for 33 one-third octave bands at CRMO001 from June–September 2017. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted.

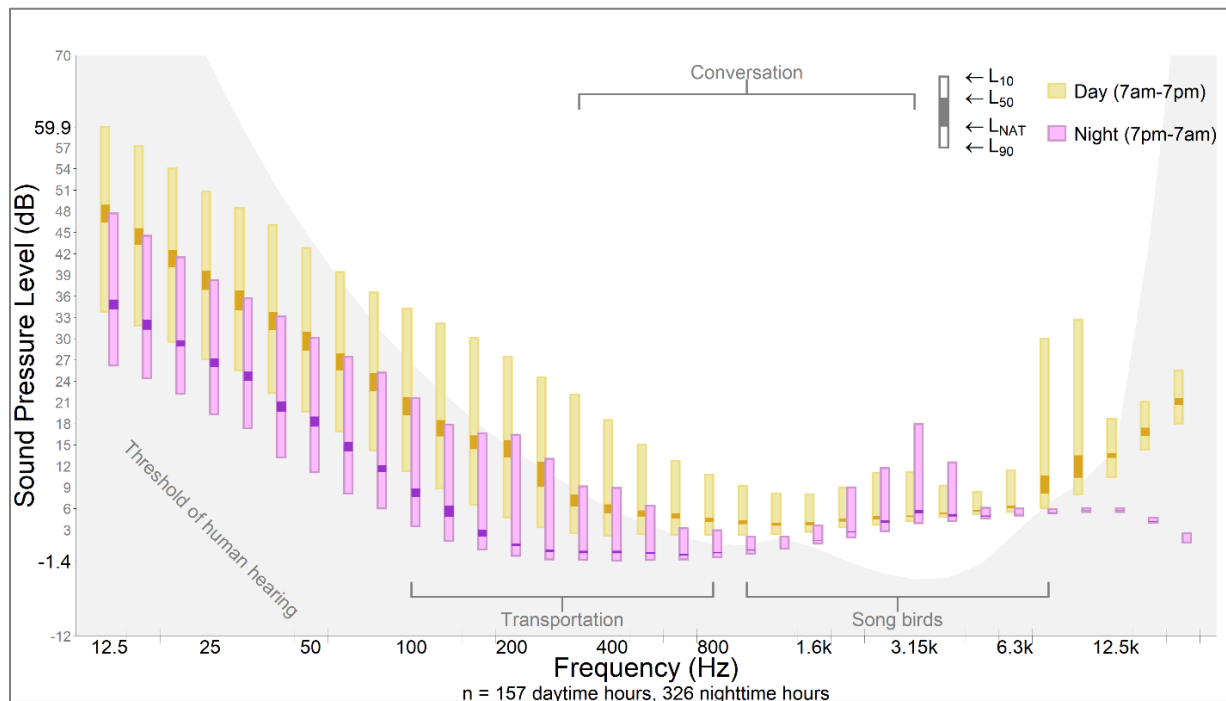


Figure 4. Day and night percentile sound pressure levels for 33 one-third octave bands at CRMO002 from June–September 2017. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted.

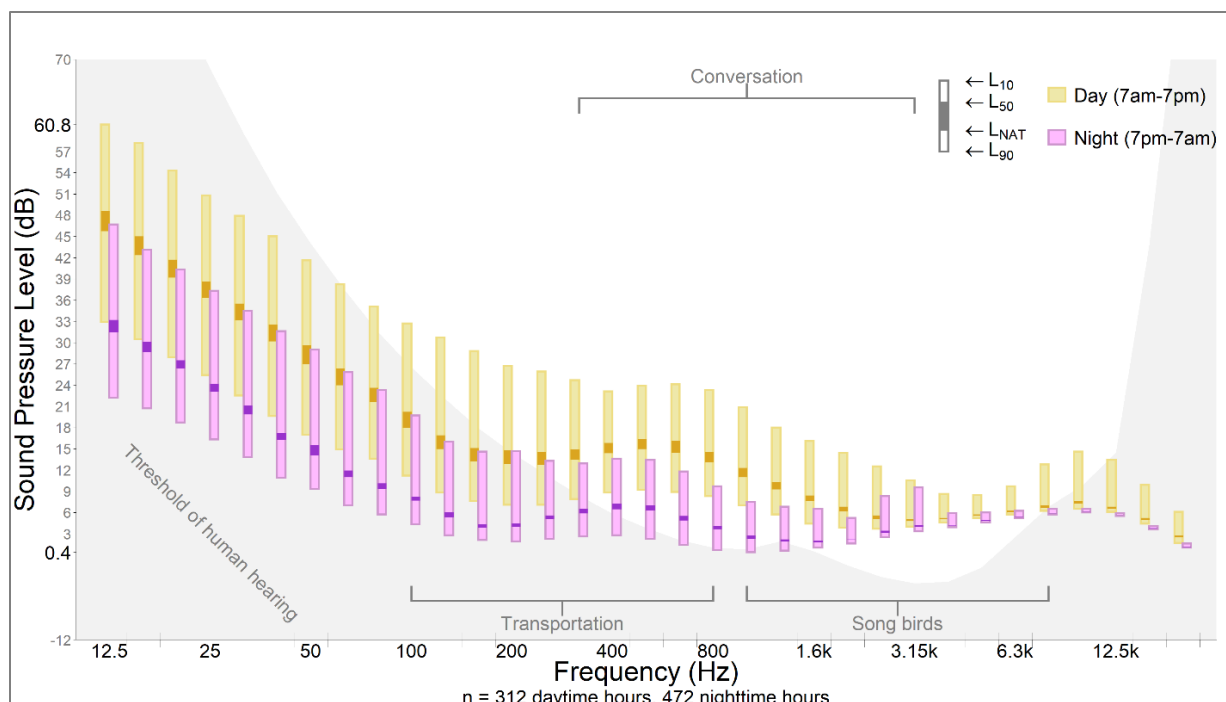


Figure 5. Day and night percentile sound pressure levels for 33 one-third octave bands at CRMO003 from June–September 2017. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted.

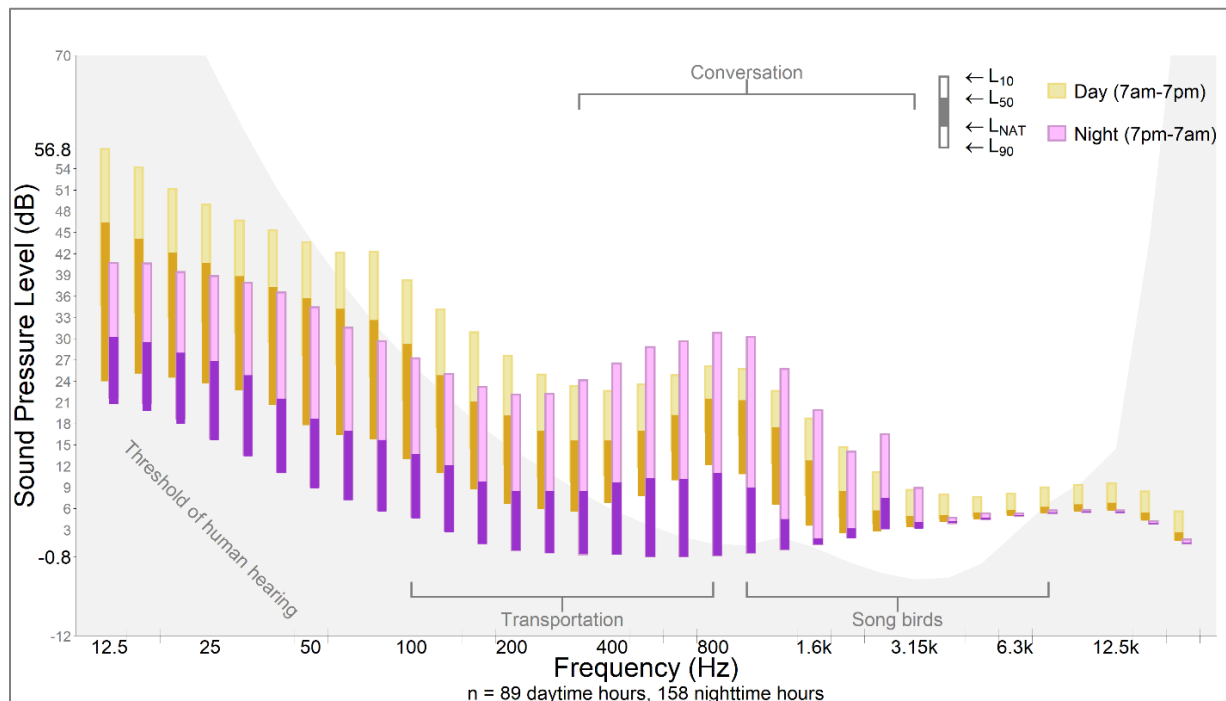


Figure 6. Day and night percentile sound pressure levels for 33 one-third octave bands at CRMO004 from June–September 2017. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted.

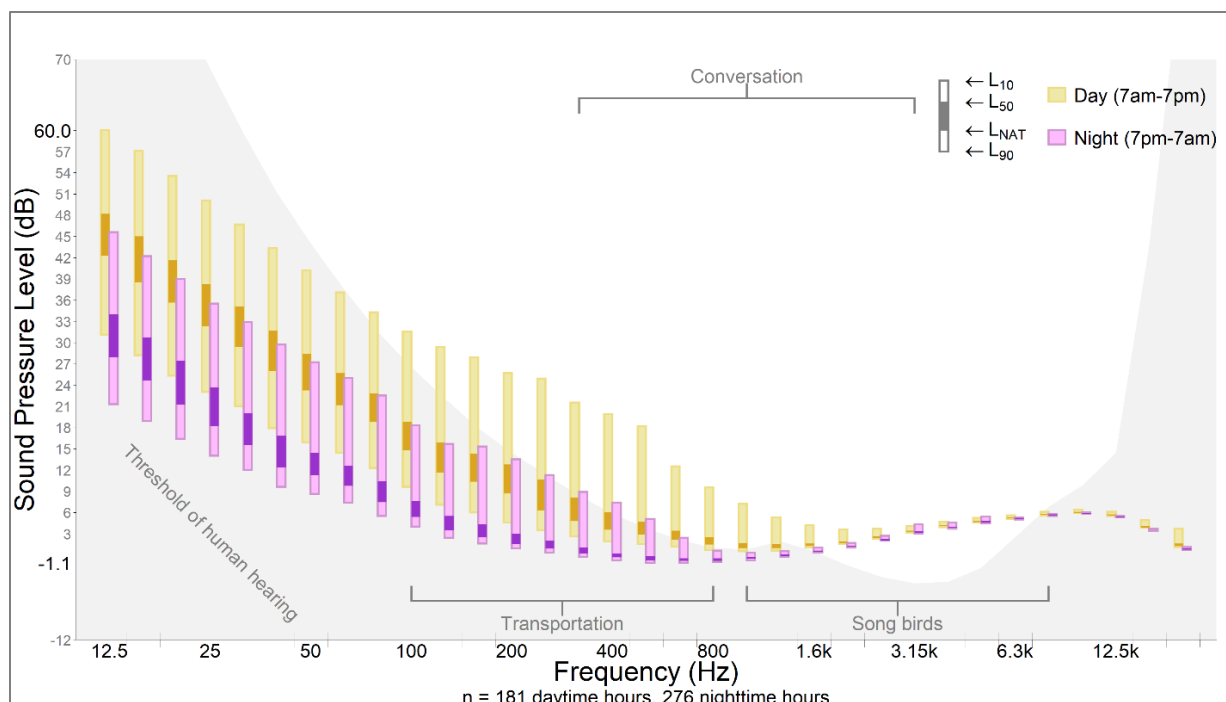


Figure 7. Day and night percentile sound pressure levels for 33 one-third octave bands at CRMO005 from June–September 2017. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted.

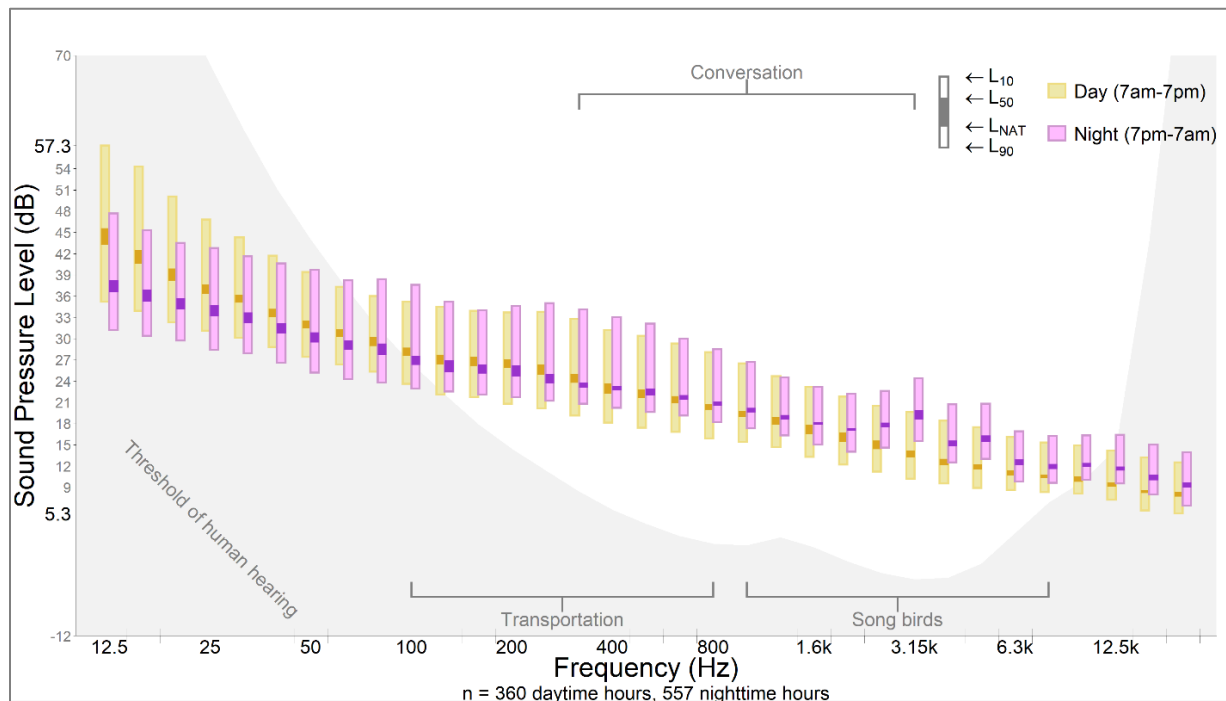


Figure 8. Day and night percentile sound pressure levels for 33 one-third octave bands at CRMO006 from June–September 2017. For each bar, the bold color indicates the range of existing (L_{50} ; upper) and natural (L_{nat} ; lower) sound pressure levels. Sound levels depicted are not A-weighted.

Sound Level: Time Above

To understand how acoustic conditions in the park might affect visitors, measured sound levels are compared to sound levels of interest. Specifically, Table 5 reports the percent of time that measured sound levels ($L_{Aeq,1s}$) were above four key functional effect levels during the monitoring periods (daytime and nighttime). The top value in each split-cell uses the full frequency range, whereas the bottom values report the percentage of the sample that ANS-weighted sound levels (20–1,250 Hz) were above functional effect thresholds. Most motorized human-caused noise is confined to the truncated, lower-frequency range, while many natural sounds, including insects and birds, are higher in pitch. ANS weighting eliminates high-frequency sound (leaf rustle, and biologic sounds) allowing for more accurate comparisons of low-frequency ambient sound levels across different land use types (e.g., urban, protected areas; ANSI S3/SC1.100, 2014). This frequency weighting scheme improves ambient sound level measurements in quiet environments.

The first functional effect in Table 5 occurs around 35 dB ($L_{Aeq,1s}$), which is designed to address the health effects of sleep interruption. Studies suggest that sound events as low as 35 dB can have adverse effects on blood pressure in sleeping humans (Haralabidis et al. 2008). This is also the desired background sound level in classrooms (ANSI S12.60-2002). For application to the present study, the 35 dB ($L_{Aeq,1s}$) effect level was exceeded at CRMO002 16.74% of the time during the day and 3.31% of the time at night in the full frequency range. In the 20–1,250 Hz range, the 35 dB functional sound level value was very rarely exceeded in daytime or nighttime. The second functional effect is expected to occur around 45 dB ($L_{Aeq,1s}$). This level addresses the World Health Organization's recommendations that noise levels inside bedrooms remain below 45 dB ($L_{Aeq,1s}$) (Berglund et al. 1999). The third functional effect is expected to occur around 52 dB ($L_{Aeq,1s}$), based on the EPA's speech interference threshold for speaking in a raised voice to an audience at 10 meters (EPA 1974). This threshold addresses the effects of sound on interpretive presentations in parks. The final functional effect at 60 dB ($L_{Aeq,1s}$), provides a basis for estimating impacts on normal voice communications at 1 meter. Visitors viewing scenic areas in the park regularly conduct such conversations.

Table 5. Percent time above metrics for acoustic records collected in Craters of the Moon National Monument and Preserve (CRMO) from June–September 2017.

Site ID	Frequency Range	Time above sound level (% of daytime hours, 07:00 to 19:00)				Time above sound level (% of nighttime hours, 19:00 to 07:00)			
		35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A	35 dB ^A	45 dB ^A	52 dB ^A	60 dB ^A
CRMO001	Full (12.5–20,000)	1.03	0.18	0.03	0.00	0.39	0.03	0.00	0.00
	ANS (20–1,250) ^B	0.95	0.18	0.04	0.00	0.38	0.02	0.00	0.00
CRMO002	Full (12.5–20,000)	16.74	1.29	0.06	0.00	3.31	0.20	0.02	0.00
	ANS (20–1,250) ^B	1.72	0.16	0.02	0.00	0.65	0.04	0.00	0.00
CRMO003	Full (12.5–20,000)	7.70	0.43	0.07	0.00	4.31	0.13	0.01	0.00
	ANS (20–1,250) ^B	3.43	0.21	0.04	0.00	0.78	0.04	0.00	0.00
CRMO004	Full (12.5–20,000)	16.88	2.09	0.46	0.02	31.54	3.99	0.45	0.00
	ANS (20–1,250) ^B	15.72	1.96	0.42	0.02	20.04	3.65	0.40	0.00
CRMO005	Full (12.5–20,000)	1.78	0.20	0.05	0.00	0.55	0.00	0.00	0.00
	ANS (20–1,250) ^B	1.57	0.18	0.04	0.00	0.35	0.00	0.00	0.00
CRMO006	Full (12.5–20,000)	25.54	2.69	0.27	0.01	47.88	4.56	0.22	0.00
	ANS (20–1,250) ^B	20.84	2.00	0.23	0.01	33.69	2.57	0.14	0.00

^A dB LAeq, 1s re 20 µPa

^B The percent of time ANS-weighted sound levels (20–1,250 Hz) are above functional values.

Sound Level: Percentile Levels

To understand the range of acoustic conditions at the park, percentile sound levels are reported. In Table 6, day and night A-weighted percentile sound levels are presented for the entire sampling period at each site, while Figures 9–14 provide hourly summaries. In Figure 9, the A-weighted percentile sound levels (L_{A90} , L_{Anat} , L_{A50} , and L_{A10}) for CRMO001 are shown. The hourly percentile sound levels are calculated from the broadband (12.5 Hz–20 kHz) A-weighted, 1-second time averaged sound levels ($L_{Aeq, 1s}$) within each hour of the day. For instance, in Figure 9, the L_{A50} (median) sound level for CRMO001 during the 8:00 hour is 19.1 dB. On the other hand, the sound level exceeded 10% of the time (L_{A10}) for the same hour at this site is 26.6 dB, meaning 90% of the measurement period is quieter. Hours where the L_{A50} and the L_{Anat} differ the most are usually hours with the most human-caused noise, as shown with site CRMO004 (Figure 12). The larger the span of the black bars, the greater the difference of the existing sound level from natural conditions. At CRMO004, existing sound levels are closest to natural conditions in the early morning hours but depart from natural conditions for most of the day (Figure 12). In general, higher natural ambient sound levels occurred in the late evening and early morning hours and are largely due to insect and bird activity (Figures 9–14).

Table 6. Summary of summer sound levels at six Craters of the Moon National Monument and Preserve (CRMO) sites. Included for each site, 90th percentile (L_{A10}), existing (L_{A50}), natural ($L_{A\text{Nat}}$) and 10th percentile (L_{A90}) ambient sound levels (dB re 20 μ Pa, A-weighted broadband, 12.5 Hz—20 kHz) during the day (0700–1900) and night (1900–0700).

Site ID	Time	L_{A10}	L_{A50}	$L_{A\text{Nat}}$	L_{A90}
CRMO001	Day	26.5	19.0	16.9	16.2
	Night	20.2	16.4	15.7	15.0
CRMO002	Day	36.6	27.0	25.7	21.0
	Night	28.2	19.4	18.6	15.6
CRMO003	Day	34.4	25.9	24.5	19.9
	Night	26.6	19.7	19.2	16.8
CRMO004	Day	34.2	28.4	20.1	24.1
	Night	37.0	25.4	16.0	16.8
CRMO005	Day	27.0	17.8	16.4	15.5
	Night	18.8	15.6	15.1	14.9
CRMO006	Day	37.4	31.1	30.0	26.3
	Night	40.0	34.0	33.0	29.8

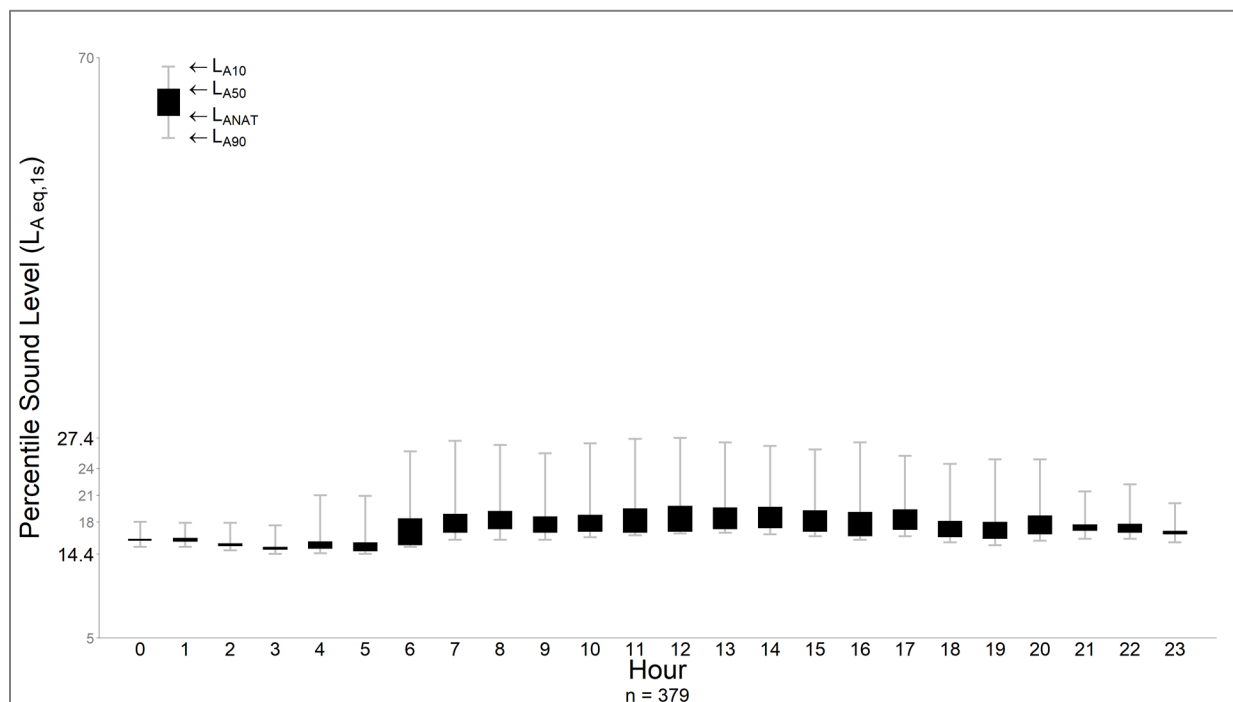


Figure 9. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at CRMO001 from June–September 2017.

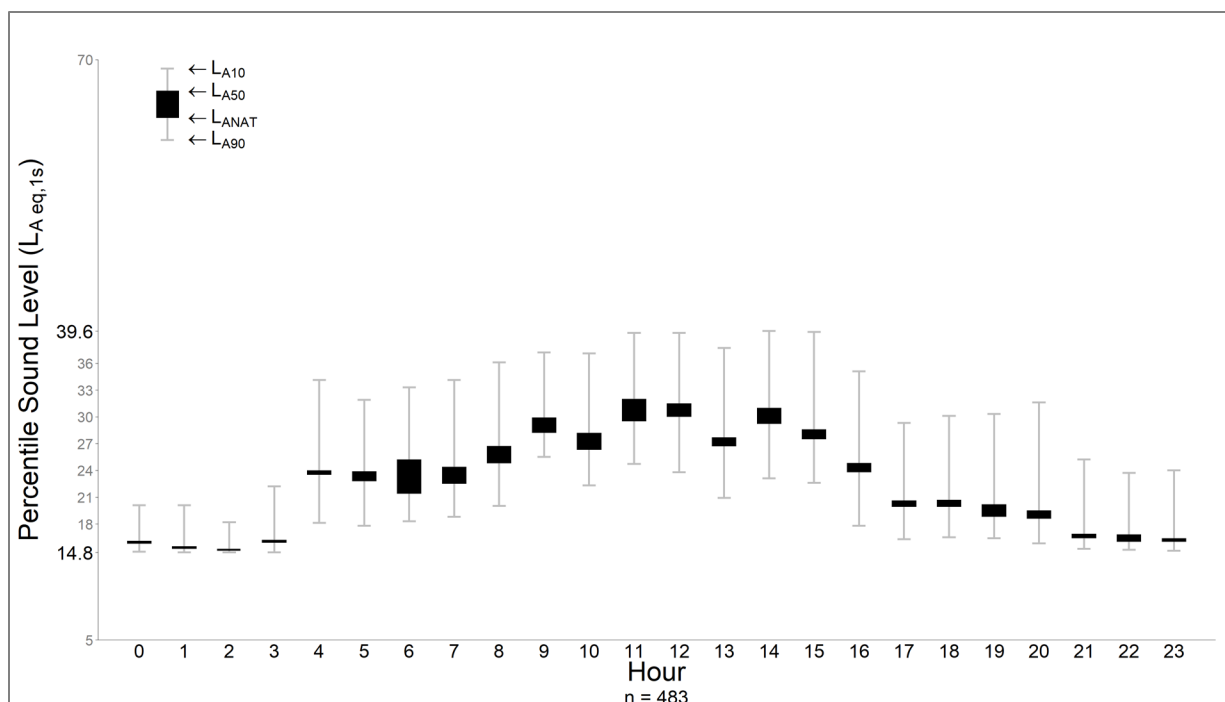


Figure 10. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at CRMO002 from June–September 2017.

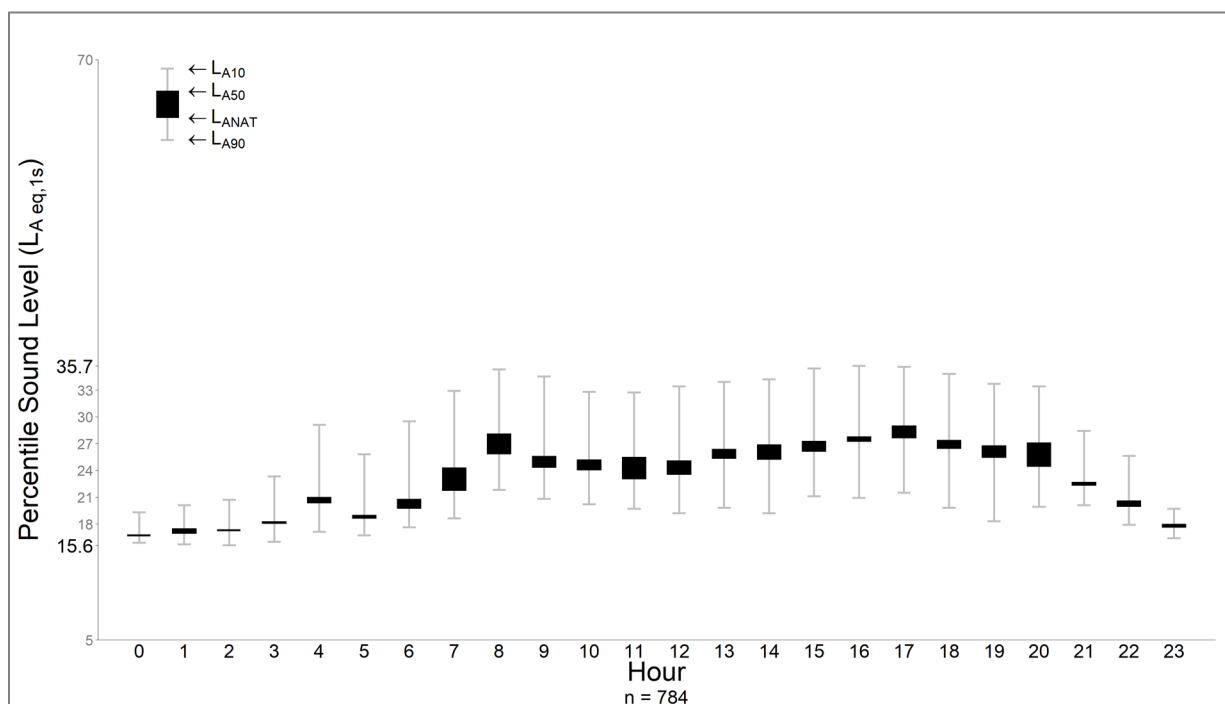


Figure 11. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at CRMO003 from June–September 2017.

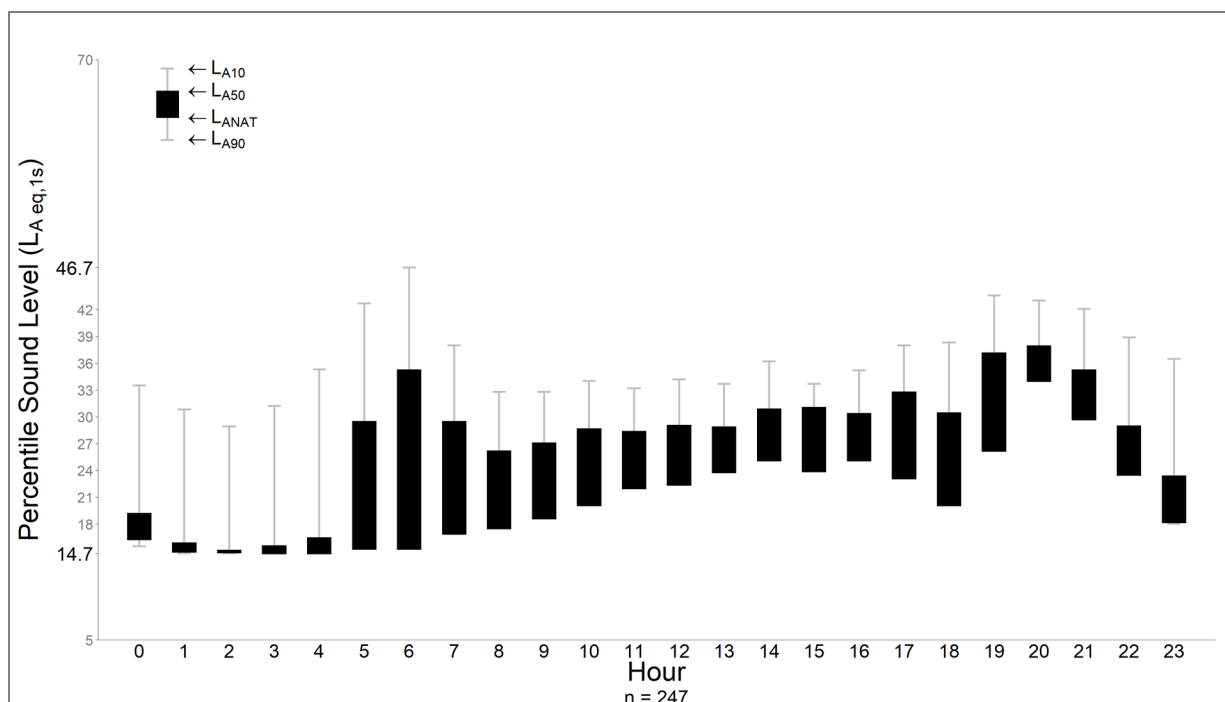


Figure 12. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at CRMO004 from June–September 2017.

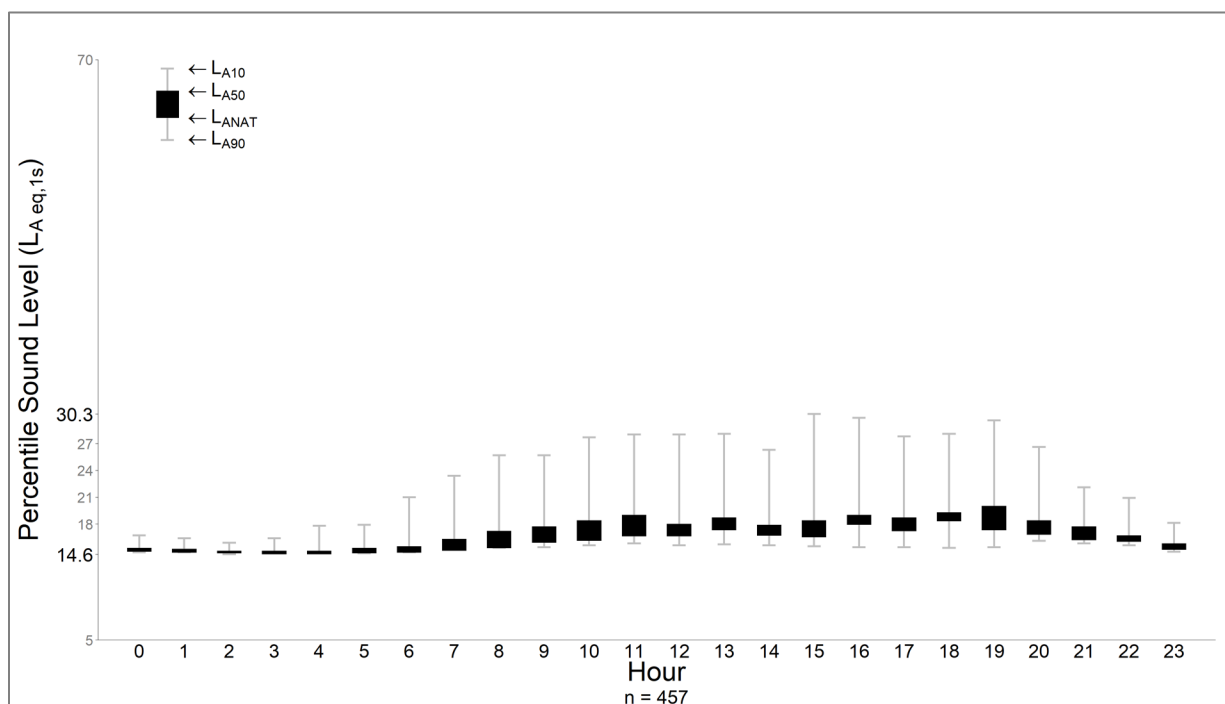


Figure 13. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at CRMO005 from June–September 2017.

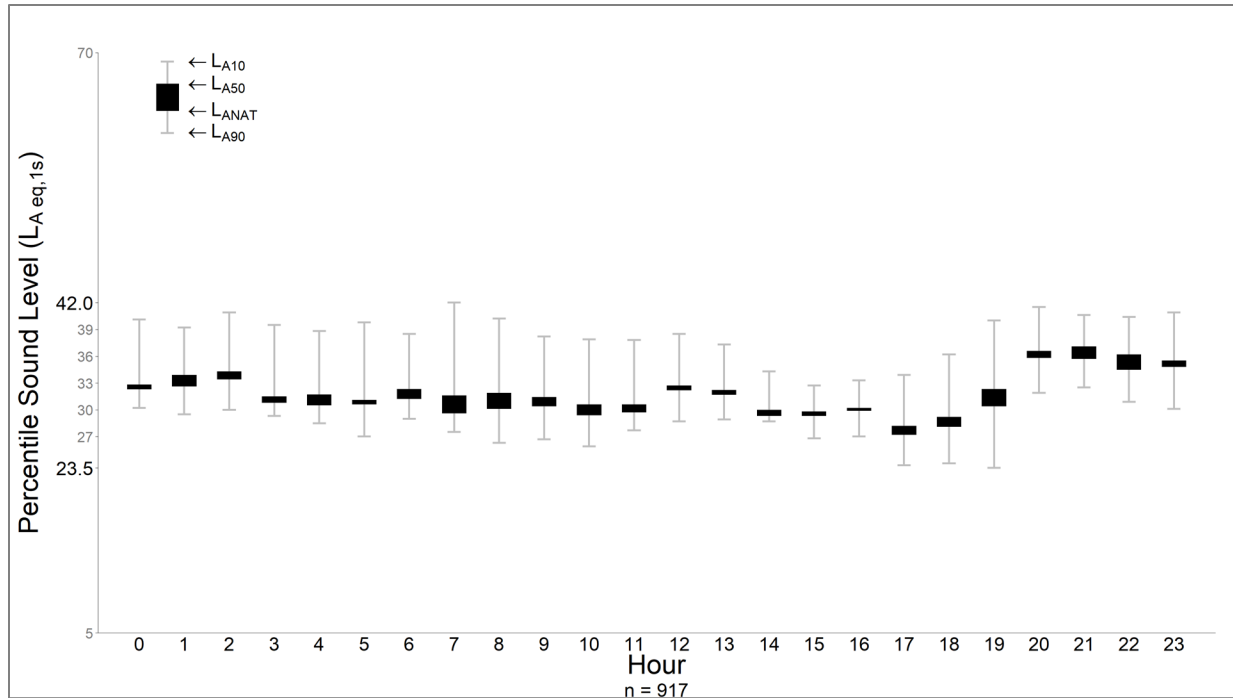


Figure 14. Median percentile sound levels ($L_{Aeq, 1s}$), in dB re 20 μ Pa, at CRMO006 from June–September 2017.

Event Duration and Noise Free Interval

Listening Center and SPLAT Software

Through off-site listening analysis, event duration for all audible sounds is calculated and averaged over the listening period. For CRMO001–005, mean hourly audibility was obtained for each hour of the day over a 9–11 day listening period (Meyer 2017). A separate dataset for these results is published to the NPS Datastore for exploration of all sound sources identified. To highlight the top salient information from that analysis, hourly audibility is displayed for all non-natural sources, while also highlighting the top sources at each site (Figure 15–Figure 19). For example, at CRMO002, noise was audible less than 35% of time across all hours of the day, and the primary contributor was aircraft (Figure 16). At CRMO004, noise was audible 100% of the time from 08:00–10:00. During that time, vehicles were audible over 90% of the time (Figure 18).

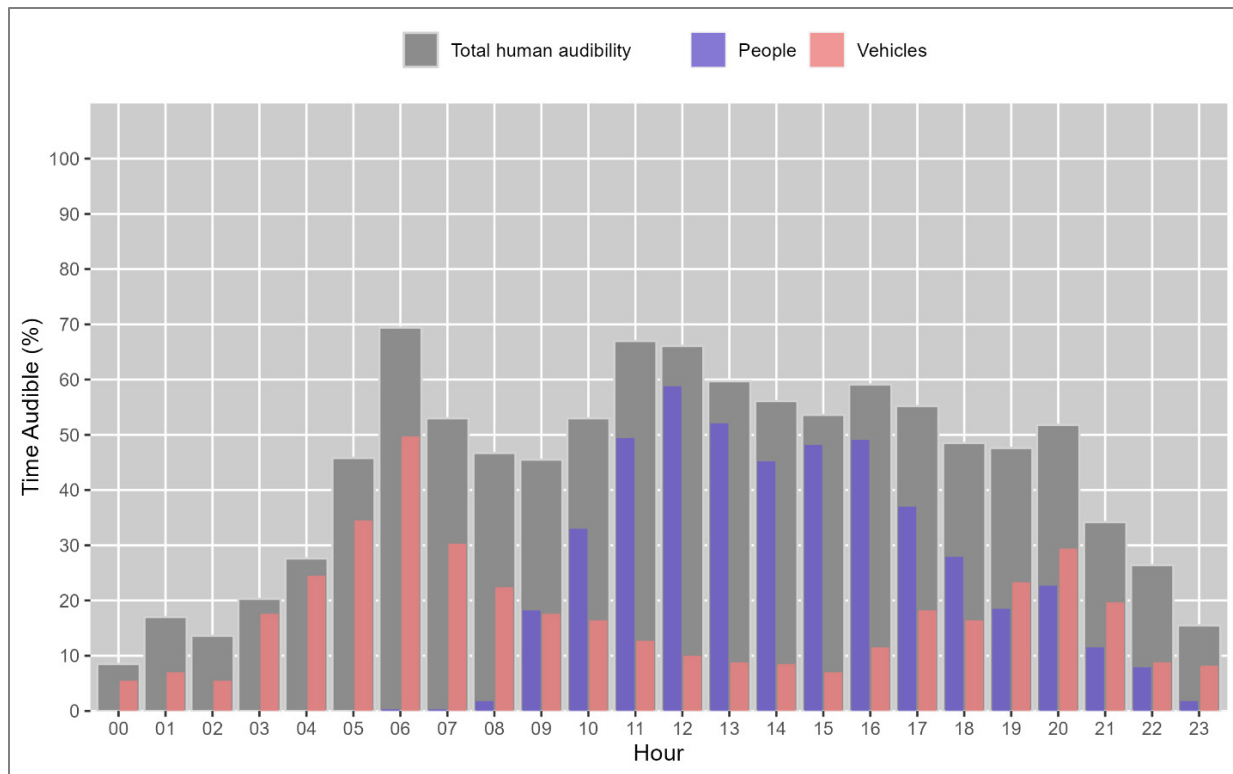


Figure 15. Hourly time audible for the top noise sources and all noise sources at CRMO001 from June–September 2017.

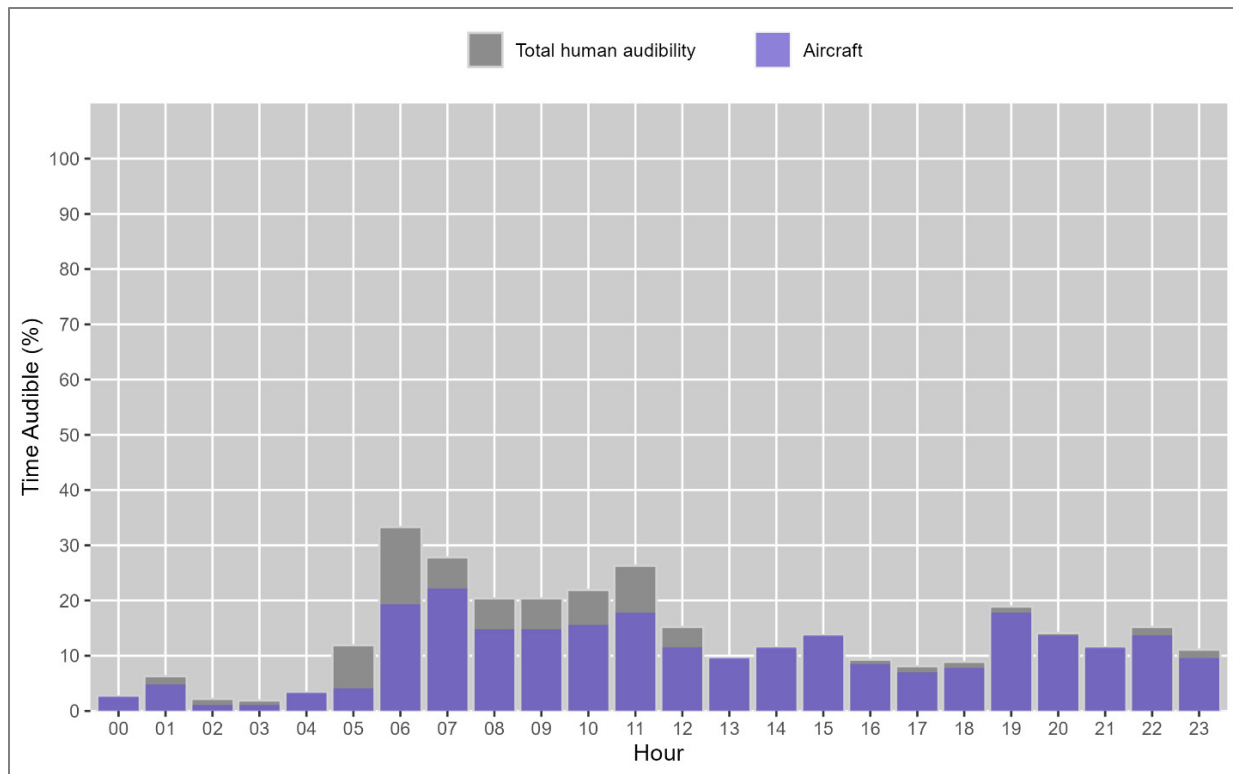


Figure 16. Hourly time audible for the top noise sources and all noise sources at CRMO002 from June–September 2017.

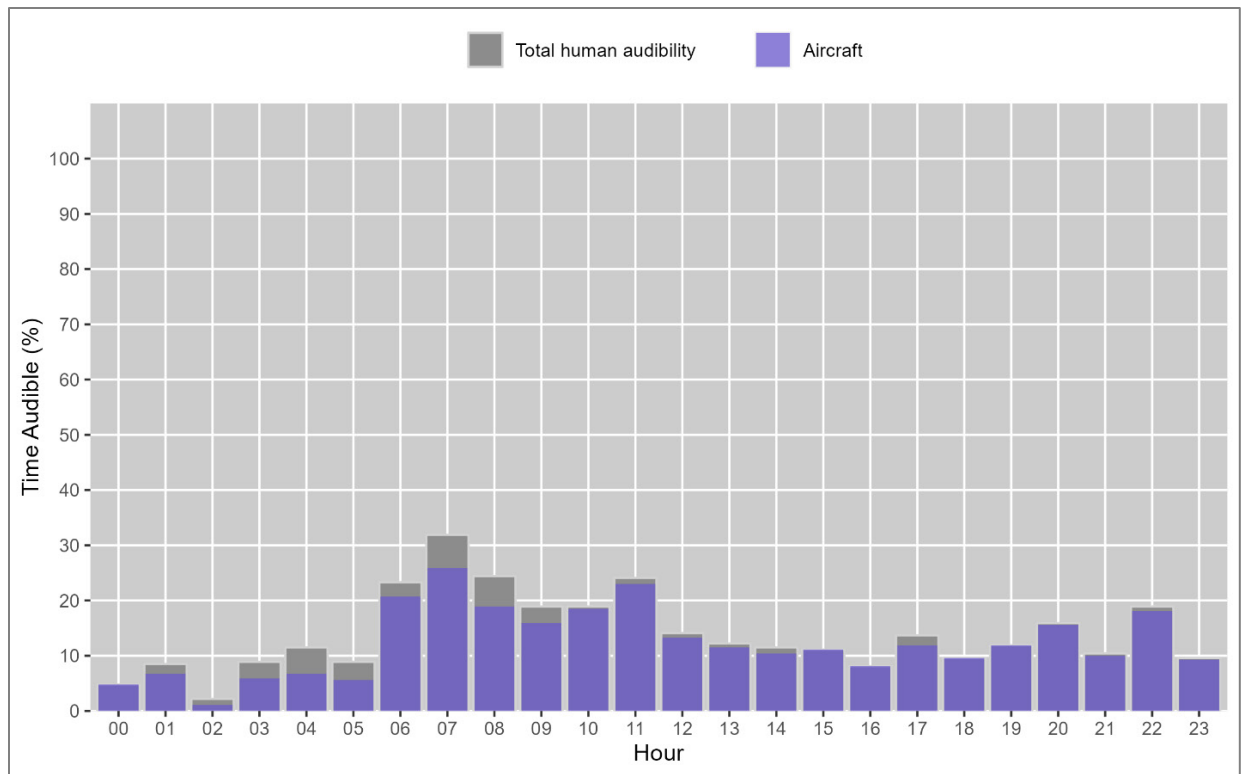


Figure 17. Hourly time audible for the top noise sources and all noise sources at CRMO003 from June–September 2017.

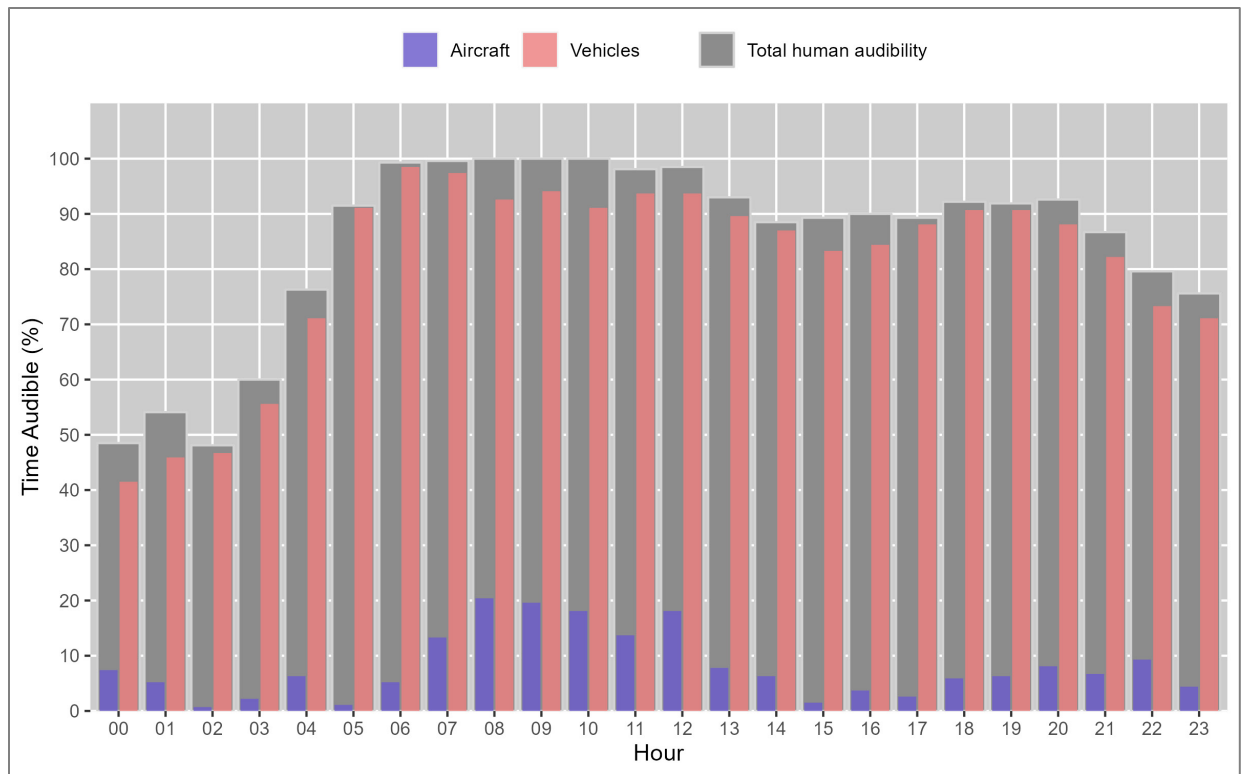


Figure 18. Hourly time audible for the top noise sources and all noise sources at CRMO004 from June–September 2017.

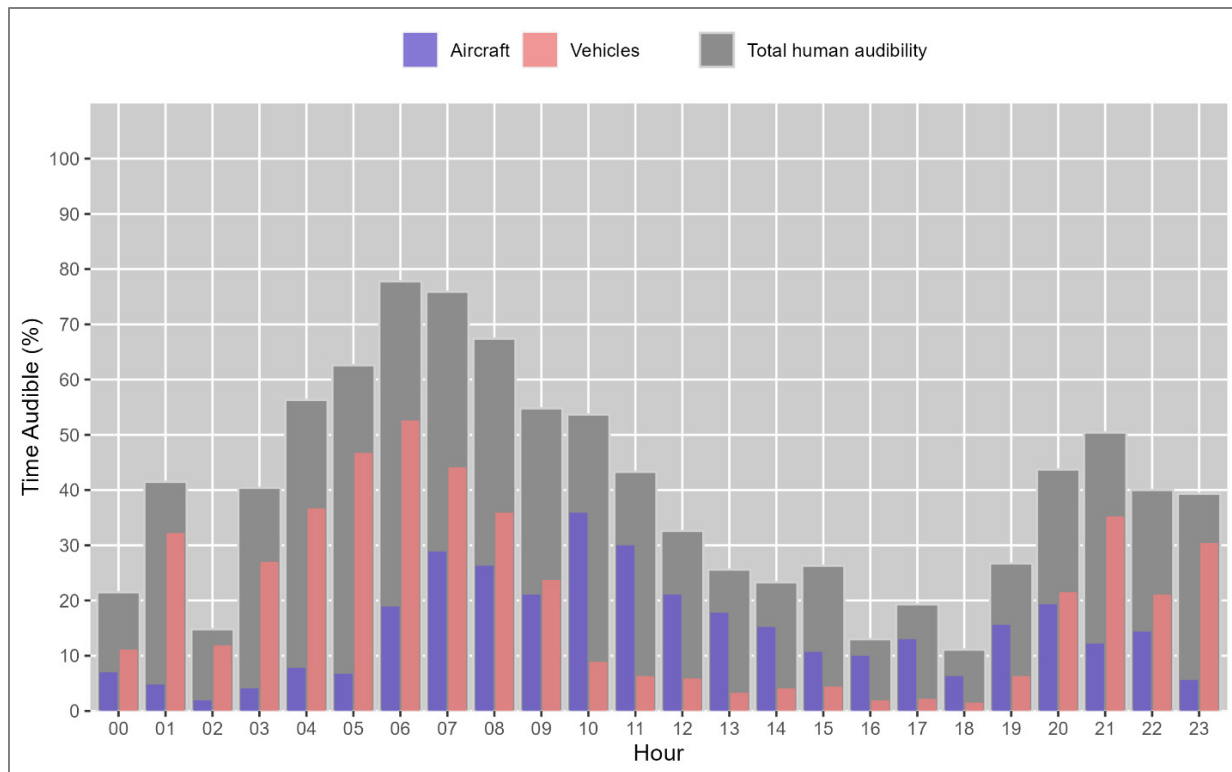


Figure 19. Hourly time audible for the top noise sources and all noise sources at CRMO005 in from June–September 2017.

Event duration metrics were also obtained from CRMO006, but only for noise sources due to an incomplete audio dataset. Using SPLAT technique, mean hourly audibility of noise events were obtained for each hour of the day over a 52-day period and published as a separate dataset (Meyer 2017). Jets and trains accounted for the highest mean number of noise events (Figure 20, Table 7). In both day and nighttime hours, trains contribute to the longest mean duration of noise, typically lasting 7:16 minutes (m in mm:ss) and 10:18 m, respectively (Table 7). The median NFI across all hours of the day was 11:06 m. The lowest hourly median NFI occurred at 08:00 h (5:09 m), and the highest hourly median NFI occurred at 00:00 h (15:07 m).

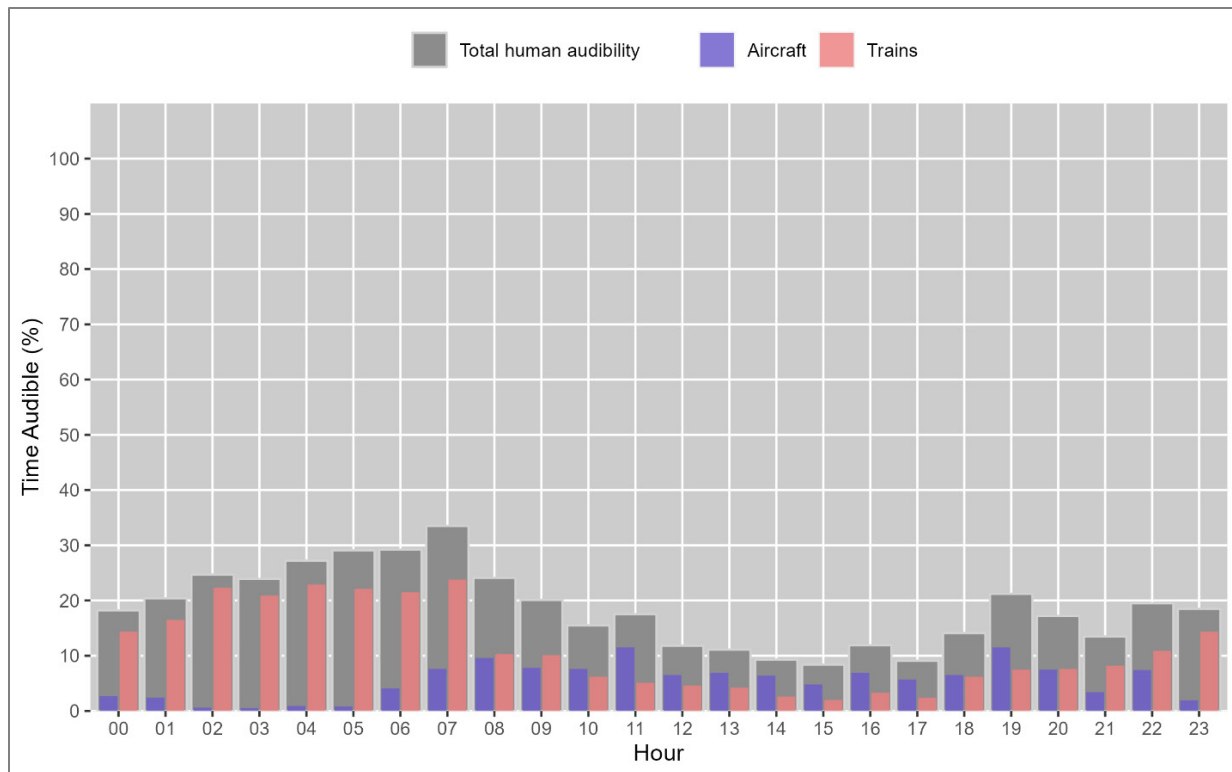


Figure 20. Hourly time audible for the top noise sources and all noise sources at CRMO006 in from June–September 2017.

Table 7. Results from SPLAT analysis for CRMO006 (n=52 days).

Sound Source	Day		Night	
	Mean Event Counts	Mean Event Length (mm:ss)	Mean Event Counts	Mean Event Length (mm:ss)
Aircraft	1.1	02:46	0.3	02:47
Jet	12.0	02:18	7.4	03:00
Prop	6.7	03:14	0.7	04:28
Helicopter	0.2	02:36	0.0	00:00
Train	6.0	07:16	10.7	10:18
Train Rumble	0.1	03:36	0.1	05:52
Train Whistle	5.6	00:48	4.1	00:42
Voices	0.0	00:00	0.0	01:15
Non-natural Unknown	3.8	03:07	4.4	04:28

On-site Listening

From on-site listening, sound source identification, event counts, and event duration are calculated over a one-hour listening period. Off-site listening sound source and event duration summaries over 1–4 listening periods per location are displayed in Table 8 to Table 13. The highest mean number of

non-natural and natural events occurred at CRMO004 (72.0 and 176.5, respectively; Table 11). Here, vehicles were audible 94.6% of the time, and the maximum time audible was 27:00 m. CRMO002 had the least mean number events and least audible non-natural noise events (Table 9).

Table 8. Results of on-site listening at CRMO001 in summer, n=3 sessions.

Sound Source Type	Source Description	Mean Number of Events	Percent Audibility (%)	Max Event Duration (mm:ss)	Mean Event Duration (mm:ss)	Minimum Event duration (mm:ss)
Non-Natural	Total	23.3	13.4	06:24	00:57	00:01
	Jet	1.7	5.7	03:05	00:51	00:01
	Prop	1.0	12.4	06:17	01:57	00:14
	Vehicle	4.3	5.2	01:01	00:32	00:01
	Truck (6+ Tires)	0.3	1.2	00:42	00:42	00:42
	People	1.7	0.2	00:05	00:02	00:01
	Voices	11.0	50.8	06:24	01:38	00:01
	Walking	2.7	9.2	00:43	00:21	00:01
	Building Sounds	0.3	0.0	00:01	00:01	00:01
	Non-natural Unknown	0.3	4.2	02:32	02:32	02:32
Natural	Total	33.7	26.6	29:57	03:30	00:01
	Wind	9.3	44.4	29:57	10:21	00:01
	Water	0.3	0.0	00:01	00:01	00:01
	Bird	5.7	8.1	03:40	00:30	00:01
	Insect	18.3	36.2	08:20	00:46	00:01

Table 9. Results of on-site listening at CRMO002 in summer, n=4 sessions.

Sound Source Type	Source Description	Mean Number of Events	Percent Audibility (%)	Max Event Duration (mm:ss)	Mean Event Duration (mm:ss)	Minimum Event duration (mm:ss)
Non-Natural	Total	5.5	3.9	02:38	00:40	00:01
	Jet	2.5	9.8	02:33	01:18	00:01
	Prop	0.3	8.8	02:38	02:38	02:38
	Vehicle	0.3	0.2	00:04	00:04	00:04
	Door	1.3	0.3	00:03	00:02	00:01
	Motor Sounds	0.5	0.5	00:14	00:09	00:04
	People	0.3	0.2	00:04	00:04	00:04
	Non-natural Unknown	0.5	0.4	00:09	00:07	00:05
Natural	Total	78.3	49.0	27:02	02:28	00:01
	Wind	21.8	39.4	09:02	00:57	00:01
	Mammal	0.3	3.4	01:02	01:02	01:02
	Bird	27.0	90.1	27:02	06:12	00:01
	Insect	27.8	64.4	16:11	02:17	00:01
	Animal	1.0	0.3	00:07	00:03	00:01
	Natural Unknown	0.5	4.7	01:23	00:42	00:02

Table 10. Results of on-site listening at CRMO003 in summer, n=4 sessions.

Sound Source Type	Source Description	Mean Number of Events	Percent Audibility (%)	Max Event Duration (mm:ss)	Mean Event Duration (mm:ss)	Minimum Event duration (mm:ss)
Non-Natural	Total	6.8	4.5	04:46	00:43	00:01
	Jet	2.5	6.3	02:25	00:54	00:09
	Prop	2.0	11.7	04:46	01:37	00:02
	Vehicle	0.3	0.1	00:01	00:01	00:01
	Motorcycle	1.3	2.4	01:31	00:22	00:01
	Motor Sounds	0.3	0.5	00:18	00:18	00:18
	People	0.3	0.2	00:08	00:08	00:08
	Non-natural Unknown	0.3	1.2	00:42	00:42	00:42
Natural	Total	45.8	34.6	29:57	03:17	00:01
	Wind	7.5	84.0	29:57	13:38	00:02
	Water	0.3	0.1	00:03	00:03	00:03
	Rain, Fog Drip	0.3	0.1	00:05	00:05	00:05
	Thunder	1.8	2.1	01:02	00:11	00:01
	Mammal	1.8	1.6	01:02	00:10	00:01
	Bird	17.0	19.7	03:11	00:23	00:01
	Insect	16.5	59.2	13:38	01:23	00:01
	Animal	0.8	0.2	00:04	00:03	00:01

Table 11. Results of on-site listening at CRMO004 in summer, n=2 sessions.

Sound Source Type	Source Description	Mean Number of Events	Percent Audibility (%)	Max Event Duration (mm:ss)	Mean Event Duration (mm:ss)	Minimum Event duration (mm:ss)
Non-Natural	Total	72.0	24.8	27:00	01:18	00:01
	Jet	6.5	10.7	02:55	00:55	00:01
	Prop	9.5	17.9	04:02	01:14	00:01
	Vehicle	12.0	94.6	27:00	04:50	00:02
	Motorcycle	15.5	12.4	03:38	00:47	00:01
	Truck (6+ Tires)	26.5	25.5	02:24	00:42	00:01
	Motor Sounds	0.5	0.0	00:01	00:01	00:01
	People	1.0	0.1	00:01	00:01	00:01
	Voices	0.5	0.0	00:01	00:01	00:01
Natural	Total	176.5	23.4	15:14	01:38	00:01
	Wind	59.0	6.7	00:38	00:10	00:01
	Bird	26.0	12.9	02:45	00:45	00:01
	Insect	91.5	50.6	15:14	03:59	00:01

Table 12. Results of on-site listening at CRMO005 in summer, n=1 session.

Sound Source Type	Source Description	Mean Number of Events	Percent Audibility (%)	Max Event Duration (mm:ss)	Mean Event Duration (mm:ss)	Minimum Event duration (mm:ss)
Non-Natural	Total	8.0	6	06:29	02:35	00:03
	Jet	2.0	10	04:01	03:04	02:07
	Prop	2.0	2	00:57	00:43	00:29
	Vehicle	1.0	11	06:29	06:29	06:29
	Non-natural Unknown	3.0	0	00:04	00:03	00:03
Natural	Total	57.0	10	03:45	00:26	00:01
	Wind	2.0	2	01:03	00:38	00:12
	Thunder	1.0	0	00:08	00:08	00:08
	Bird	19.0	24	02:31	00:45	00:01
	Insect	35.0	14	03:45	00:14	00:01

Table 13. Results of on-site listening at CRMO006 in summer, n=1 session.

Sound Source Type	Source Description	Mean Number of Events	Percent Audibility (%)	Max Event Duration (mm:ss)	Mean Event Duration (mm:ss)	Minimum Event duration (mm:ss)
Non-Natural	Total	2.0	5	01:56	01:26	00:57
	Jet	1.0	6	01:56	01:56	01:56
	Non-natural Unknown	1.0	3	00:57	00:57	00:57
Natural	Total	29.0	45	08:51	01:53	00:01
	Wind	8.0	82	07:34	03:03	00:04
	Thunder	4.0	1	00:03	00:03	00:03
	Bird	6.0	91	08:31	04:33	00:54
	Insect	9.0	52	08:51	01:44	00:06
	Animal	2.0	0	00:03	00:02	00:01

Conclusions

Acoustic measurements allow parks to gain insight into levels of extrinsic noise and biologic activity. The results can help estimate the effects of noise on park visitors and wildlife, as well as the conditions of the acoustic environment. This study arose from the CRMO RSS, which identified the need for baseline acoustic surveys in the park. Short-term natural soundscape RSS goals were to identify the condition of the acoustic resource, and the high priority stewardship activity associated with this goal was to collect baseline acoustic data. To carry out this activity, six study sites were chosen to capture acoustic conditions. Spanning 130 km, with varied vegetation and visitor use levels, this set of acoustic records successfully captured varied noise levels, sources, and patterns that exist across CRMO. Results included measures of existing ambient sound levels, calculations of sound source audibility through off-site listening, and estimates of natural ambient sound levels.

At CRMO001, functional effect thresholds were seldom exceeded. Even the most sensitive sound threshold, 35 dB ($L_{Aeq, 1s}$), was only exceeded 1% of the time for both full and ANS-weighted frequency ranges (Table 5). Sound levels at this site were lower compared to other sites, and existing median sound levels (L_{A50}) were 2.1 dB higher than natural sound levels (L_{Anat}) during the day, reducing the listening area by 38% (Table 3, Figure 4). Off-site listening in a subset of data revealed that noise was audible 43% of the day (Table 3). Noise occurred mostly from 06:00–20:00 (Figure 9), and largely due to vehicles and people (Table 8, Figure 15; Meyer 2017). The noise level data and source identification capture the visitor traffic patterns on Craters Loop Rd. and Highway 20, including the nearby trailhead parking for the popular Caves Trail. Visitors appear at 08:00 and peak at 12:00, where people are audible for nearly 60% of the hour. Of all sites, CRMO001 has the second lowest natural sound level. The energetic contributions to natural sound level at the site were wind, birds, and insects (Table 8, Meyer 2017).

At CRMO002, functional effect thresholds were mostly exceeded in the full frequency range at the most sensitive sound level, 35 dB ($L_{Aeq, 1s}$), with 17% of daytime hours in exceedance (Table 5). Sound levels at this site were the third highest among the six sites, and existing sound levels (L_{A50}) were 1.3 dB higher than natural sound levels (L_{Anat}) during the day, reducing the listening area by 26% (Table 3, Figure 4). Off-site listening in a subset of data revealed that noise was audible 14% of the day (Table 3). Noise occurred mostly from 06:00–11:00 (Figure 10), and largely due to aircraft (Table 9, Figure 16, Meyer 2017). The noise level data and source identification capture the remote nature of this site, which is in the park backcountry surrounded by 4-wheel drive roads. Here, noise is not audible for more than 33% of any hour of the day. Peak noise audibility is at 06:00, and largely from aircraft, non-natural unknown sources, and trains. Of all sites, CRMO002 has the second highest natural sound level. The main drivers of natural sound level at the site were wind, birds, and insects (Table 9, Meyer 2017). Off-site listening of 9 monitoring days revealed that bird activity was audible for 100% of the time from 04:00–06:00. Of all sites, CRMO002 shows the strongest signal for dawn bird chorus and insect activity (Figure 4).

At CRMO003, functional effect thresholds were exceeded in day and night at less than 8% of the time at both full and ANS-weighted frequency range at the most sensitive sound level threshold, 35

dB ($L_{Aeq, 1s}$; Table 5). Sound levels at this site were the fourth highest among the six sites, and existing sound levels (L_{A50}) were 1.4 dB higher than natural sound levels (L_{Anat}) during the day, reducing the listening area by 28% (Table 3, Figure 5). Off-site listening in a subset of data revealed that noise was audible 14% of the day (Table 3). Noise occurred mostly from 06:00–19:00 (Figure 11), and largely due to aircraft (Table 9, Figure 17, Meyer 2017). The noise level data and source identification are consistent with the remote nature of this site, which is in the park Wilderness boundary near the Wilderness Trail. Here, noise is not audible for more than 32% of any hour of the day. Peak noise audibility is at 07:00, and largely from aircraft. Of all sites, CRMO003 has the third highest natural sound level. The main drivers of natural sound levels at the site were wind, birds, and insects (Table 9, Meyer 2017). Off-site listening of 9 monitoring days revealed that bird activity peaked from 04:00–06:00.

At CRMO004, functional effect thresholds were exceeded in day and night at both full and ANS-weighted frequency range at the most sensitive sound level threshold, 35 dB ($L_{Aeq, 1s}$; Table 5). Nighttime exceedances occurred at this effect threshold more commonly than during daytime hours, where 31% and 20% of the time at the full and ANS-weighted frequencies, respectively. Additionally, CRMO004 exceeded the 45 dB ($L_{Aeq, 1s}$) effect threshold 2–3% of the time for both frequencies and periods of day. Sound levels at this site were the second highest among the six sites, and existing sound levels (L_{A50}) were 8.3 dB higher than natural sound levels (L_{Anat}) during the day and 9.4 dB higher at night (Table 3, Figure 6). At this impact, the listening area is reduced by 85% and 89%, respectively. Off-site listening in a subset of data revealed that noise was audible 85% of the day, which is the highest of any site that analyzed this metric with the Listening Center software (Table 3). Noise occurred mostly from 05:00–01:00 (Figure 12), and largely due to vehicles, and to a lesser extent, aircraft (Table 11, Figure 18, Meyer 2017). The noise level data and source identification are consistent with the location of this site, which is along a major traffic corridor along Hwy 20. Here, noise is audible for 100% of the time from 07:00 to 10:00. The quietest hours are from 00:00–02:00, however, noise is still audible nearly 50% of the time. Notably, the presence of persistent nighttime traffic noise is uncommon for national parks. Natural sound levels at this site are generally lower than the other sites, and driven by wind, birds, and insects (Table 11, Meyer 2017). Off-site listening of 9 monitoring days revealed that insect activity was prominent at this site, especially from 18:00–23:00.

At CRMO005, functional effect thresholds were exceeded in day and night at less than 2% of the time at both full and ANS-weighted frequency range at the most sensitive sound level, 35 dB ($L_{Aeq, 1s}$; Table 5). Sound levels at this site were the lowest among the six sites, and existing sound levels (L_{A50}) were 1.4 dB higher than natural sound levels (L_{Anat}) during the day (28% reduction in listening area) and nearly similar at night (Table 3, Figure 7). Off-site listening in a subset of data revealed that noise was audible 40% of the day (Table 3). Noise occurred mostly from 07:00–21:00 (Figure 13), and largely due to vehicles and aircraft (Table 12, Figure 19, Meyer 2017). The noise level data and source identification are consistent with the mixed-use nature of this site, which is a backcountry area but also near Laidlaw Park Road and Hwy 20. Here, audibility varies, and generally follows a diel pattern where morning and evening noise have the greatest audibility, while afternoons have the least audibility. Peak noise audibility is from 06:00 to 08:00, and largely due to vehicles.

Based upon day and night natural sound levels, CRMO005 has the lowest natural sound level of the 6 sites. Natural sound levels here are driven by wind, birds, and insects (Table 12, Meyer 2017). Off-site listening of 9 monitoring days revealed that bird activity was lowest at this site, with peak audibility occurring at 05:00, but only audible for 36% of the hour. This may be due to habitat characteristics related to lava fields such as the lack of vegetation cover.

More than any other site, functional effect thresholds were exceeded at CRMO006 in day and night at both full and ANS-weighted frequency range at the most sensitive sound level, 35 dB ($L_{Aeq, 1s}$; Table 5). Daytime exceedances occurred at this noise functional effect 26% and 12% of the time at the full and ANS-weighted frequencies, respectively. Nighttime exceedances occurred at this noise functional effect 48% and 34% of the time at the full and ANS-weighted frequencies, respectively. Additionally, CRMO006 exceeded the 45 dB ($L_{Aeq, 1s}$) functional effect 2–4% of the time for both frequencies and periods of day. Sound levels at this site were the highest among the six sites, and existing sound levels (L_{A50}) were 1.1 dB higher than natural sound levels (L_{Anat}) during the day and 1.0 dB higher at night (Table 3, Figure 8). At this impact, the listening area is reduced by 22% and 21%, respectively. Off-site listening did not occur at this site, but noise events were annotated and summarized using the SPLAT software. Over this longer, 52-day analysis, noise was audible 7% of the day (Table 3). Noise varied but occurred throughout most of the day (Figure 14) and was largely due to aircraft and trains (Table 13, Figure 20, Meyer 2017). The noise level data and source identification are consistent with the mixed-use nature of this site, which is a backcountry area but near train tracks. Here, train noise can be heard throughout the day, but prominently from 22:00 to 08:00. Train noise peaks at 07:00 and can be heard 24% of the time (Meyer 2017). There are slightly more aircraft related event counts than trains at this site, but trains account for the longest duration of noise. A visitor in this area could typically expect to encounter a noise free interval of 11:06 m, and the longest noise free moments occur around midnight. Based upon day and night natural sound levels, CRMO006 has the highest natural decibel levels of the 6 sites.

For a broader context for the acoustic conditions at CRMO, a comprehensive 1982 study of noise levels in residential areas found that nearly 87% of US residents were exposed to day-night sound levels (L_{dn}) over 55 dB, and an additional 53% were exposed to L_{dn} over 60 dB (EPA 1982). Note that noise levels have increased nationally with population growth since the EPA study (Suter 1991; Barber et al. 2010). Additionally, a nationwide study modeling daytime summer sound levels indicated that only 23% of the continental United States was predicted to have an existing ambient sound level above 40 dB ($L_{A50, 12\text{ hr}}$), and only 1% of the continental U.S. was predicted to have an existing daytime ambient sound level above 50 dB ($L_{A50, \text{existing}}$) (Mennitt et al. 2013). Consider, though, that daily sound levels reported at CRMO are influenced by both natural and non-natural sources.

Based on the results of this study, visitors to CRMO are likely to experience the least amount of noise at CRMO002 and CRMO003. In general, noise at all sites except CRMO004 was less audible during the nighttime hours. The longest duration of noise events was from human voices, aircraft, vehicles, and trains. The location of sites in relation to busy roads and train tracks influenced ambient sound levels the most. Aircraft were audible at all sites.

Noise has the potential to affect a visitor's experience in parks by causing annoyance (Rapoza et al. 2015), reducing the perceived scenic beauty (Weinzimmer et al. 2014), or simply by limiting opportunities for solitude. Increased sound levels may also have wide ranging effects on wildlife such as reduced predatory success (Mason 2015), changes in vocal communication, or increased vigilance by keystone species (Shannon et al. 2014). In a review of literature addressing the effects of noise on wildlife published between 1990 and 2013, wildlife responses to noise were observed beginning at about 40 dB ($L_{Aeq, *}$).¹ Of the papers reviewed, 20% showed impacts to terrestrial wildlife at or below noise levels of 50 dB ($L_{Aeq, 1s}$) (Shannon et al. 2016).

In addition to noise, diverse natural sounds were heard throughout the park. Strong dawn and dusk bird choruses were detected at several sites. Further acoustic analysis, such as artificial intelligence techniques like BirdNET, could generate species lists and daily call patterns from this dataset. In addition to strong bird and insect signals, coyotes were commonly identified at all sites.

The information presented in this report will be used to inform park managers and planners and it will also serve as a permanent record of what the park sounded like in the summer and early fall of 2017. Sound level data as well as continuous digital audio recordings will be archived with the Natural Sounds and Night Skies Division office in Fort Collins, Colorado. Results of a concurrent acoustic study in CRMO during the total solar eclipse are presented in Appendix D.

¹ This metric is a composite of multiple metrics with varying time averaging metrics.

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Appendix A: Site Photos



Figure 21. CRMO001, Caves Trail acoustic monitoring site.



Figure 22. CRMO002, King's Bowl acoustic monitoring site.



Figure 23. CRMO003, Wilderness Trail acoustic monitoring site.



Figure 24. CRMO004, Golden Chariot acoustic monitoring site.



Figure 25. CRMO005, SW Lava Flow acoustic monitoring site.



Figure 26. CRMO006, Wapai acoustic monitoring site.

Appendix B: Office Listening

Listening Center Software

Office listening is a way to characterize the length and type of noise events occurring at a monitored site. The NSNSD protocol calls for 8 days of analysis per monitoring period. The Acoustical Monitoring Toolbox extracts the first 10 seconds from every 2-minute period of the day (Figure 27). This results in 16 hours of audio data being analyzed per site. Each sound category is assigned a numeric source identification code, which is entered into the Listening Center software each time the listener hears a sound in that category. These numbers are eventually used to compute the L_{Anat} for the site.

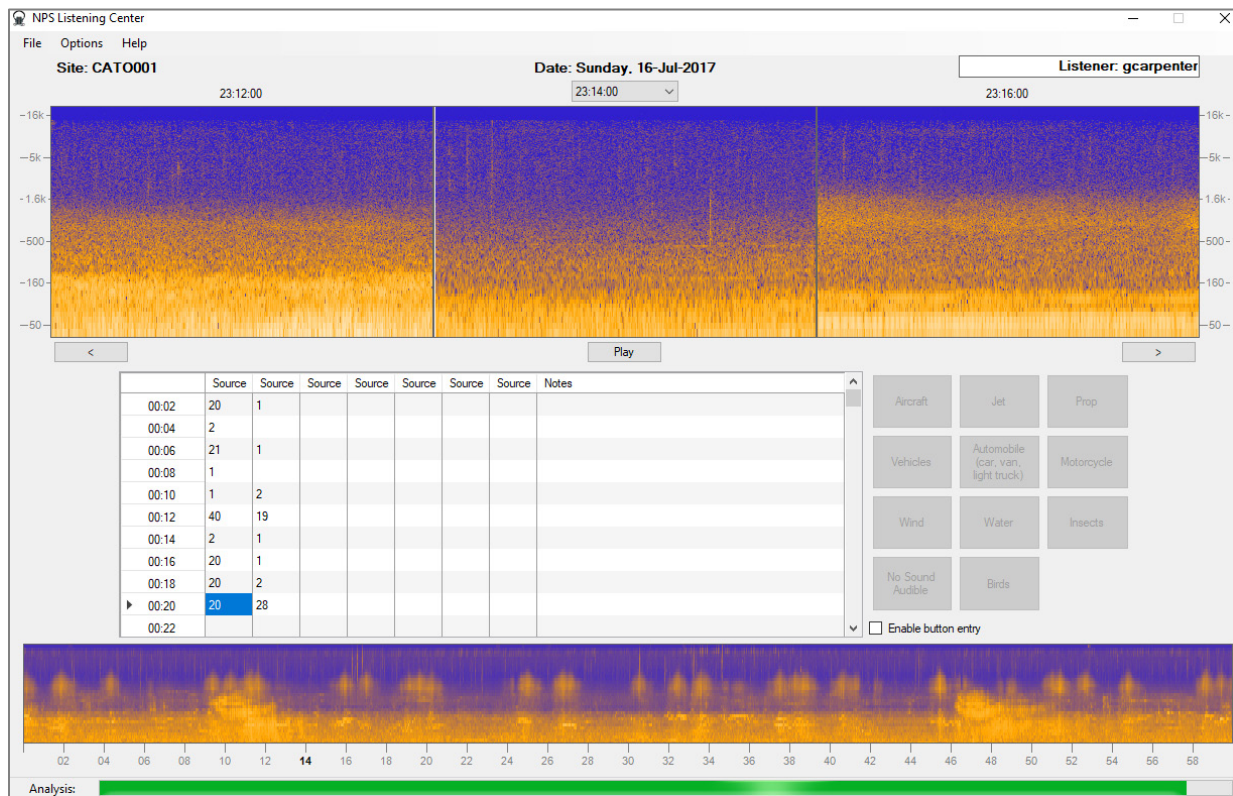


Figure 27. A screen shot of NPS Listening Center software. Three ten second samples are displayed side by side. Audible sound sources are categorized in the spreadsheet using a numeric source identification code.

Sound Pressure Annotation Tool

Figure 28, below, shows sound pressure levels (SPL) from one hour at an acoustic monitoring site at Katmai National Park. Each row shows SPL values from low frequency (12.5 Hz, bottom of line) to high frequency (20 kHz, top of line). Values are represented with a color scale, where dark blue is quiet and yellow/white is loud. This gradient helps to make individual events stand out against the blue background, appearing as yellow areas. The image is read like text, following each row from left to right and proceeding from top to bottom.

The SPL spectrogram allows us to visually identify and tag acoustic events. Source type, start time, duration, amplitude metrics, and spectral information are cataloged for each annotated event. In this example, the blue box in Figure 28 annotates a propeller overflight recorded in the Valley of Ten-Thousand Smokes.

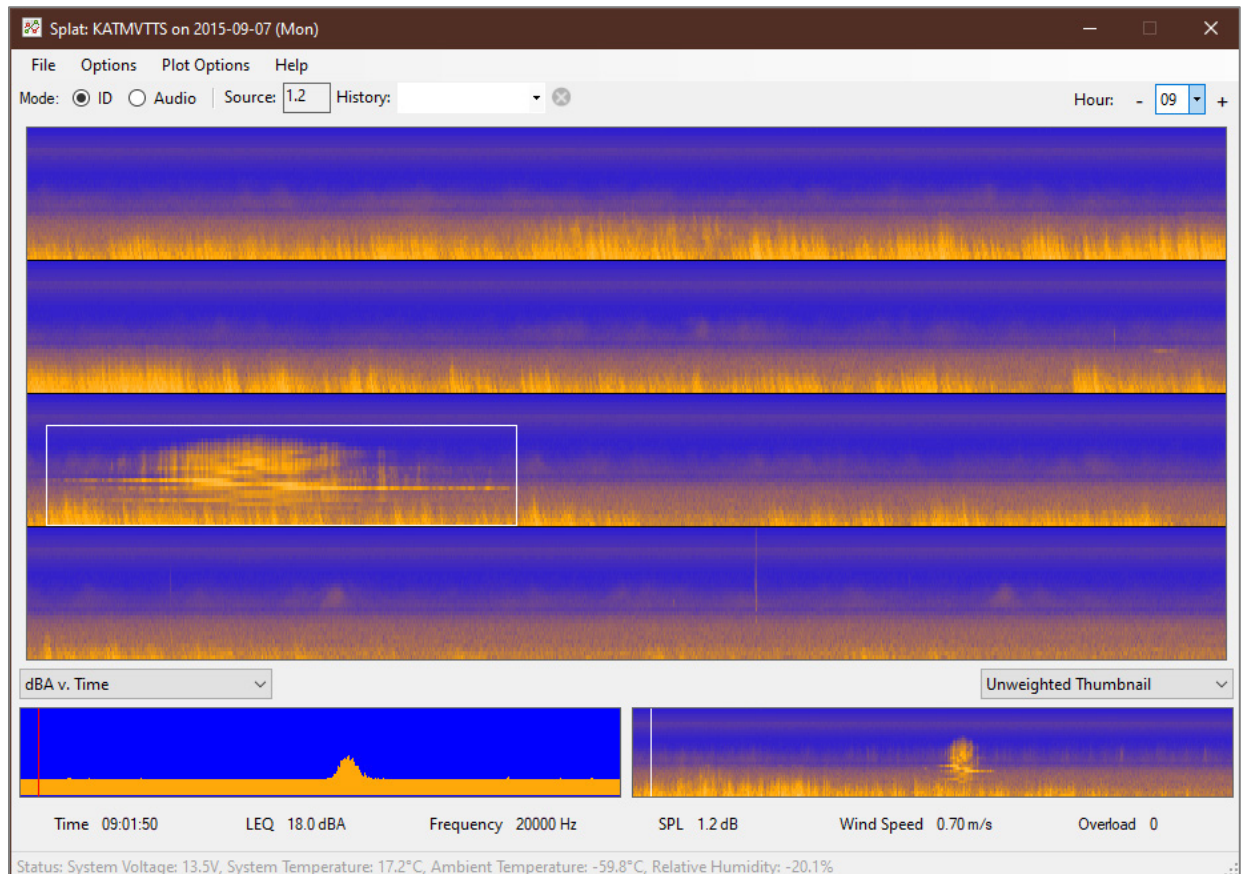


Figure 28. A screen shot of NPS Sound Pressure Level Annotation Tool (SPLAT) software. This example from Katmai National Park includes an annotated propeller aircraft noise event. The noise event annotation is delimited using a manually drawn bounding box.

Appendix C: Modeled Impact Levels

NSNSD developed a model (Mennitt et al. 2014) that predicts the median sound level using measurements made in hundreds of national park sites as well as 109 explanatory variables such as location, climate, land cover, hydrology, wind speed, and proximity to noise sources such as roads, railroads, and airports. Each pixel in the graphic shown in Figure 29 and 30 represents 270 m.

The resulting model can predict sound levels anywhere in the contiguous U. S. and estimate how much lower these sound levels would be in the absence of human activities. The modeled difference between the existing and predicted natural sound level (L_{50} impact) at CRMO is shown in Figure 29 and provides a measure of how much anthropogenic noise is increasing the existing sound level above the natural sound level on an average summer day in the park. Across CRMO, the mean modeled sound level impact is 2.9 dBA (ranging from 0 decibels (dBA) in the least impacted areas to 10.2 decibels (dBA) in the most impacted areas.) According to measured sound level data, the mean sound level impact across all 6 sites was 2.1 dBA. The range of mean acoustic impacts was 0.9 dBA (CRMO003 and CRMO005) to 8.9 dBA (CRMO004). This comparison indicates that the sound model predictions and on-the-ground measurements were closely aligned.

For translating sound level impacts into functional effects (for human visitors and resident wildlife), an increase in background sound level of 3 dB produces an approximate decrease in listening area of 50%. In other words, by raising the sound level at CRMO by just 3 dB, the ability of listeners to hear the sounds around them is effectively cut in half. Furthermore, an increase of 7 dB leads to an approximate decrease in listening area of 80%. An increase of 2.9 dBA would reduce the listening area for wildlife and visitors by 49%. For example, if a predator can hear a potential prey animal in an area of 100 square feet in a setting with natural ambient sounds, that animal's ability to hear would be reduced to 51 square feet if the sound levels were increased by the modeled average impact of 2.9 dBA.

Finally, Figure 30 provides L_{50} or median sound pressures levels for CRMO. The modeled data predicts an L_{50} of 26.0 dBA for all CRMO. The recorded data in the present study resulted in an L_{50} of 22.6 dBA. Hence, the modeled data is predicted to be higher than the measured ambient conditions collected for this report. This is likely due to fine scale conditions that existed during sampling, and the limitations of comparing a whole-park model to the representative coverage of 6 study locations.

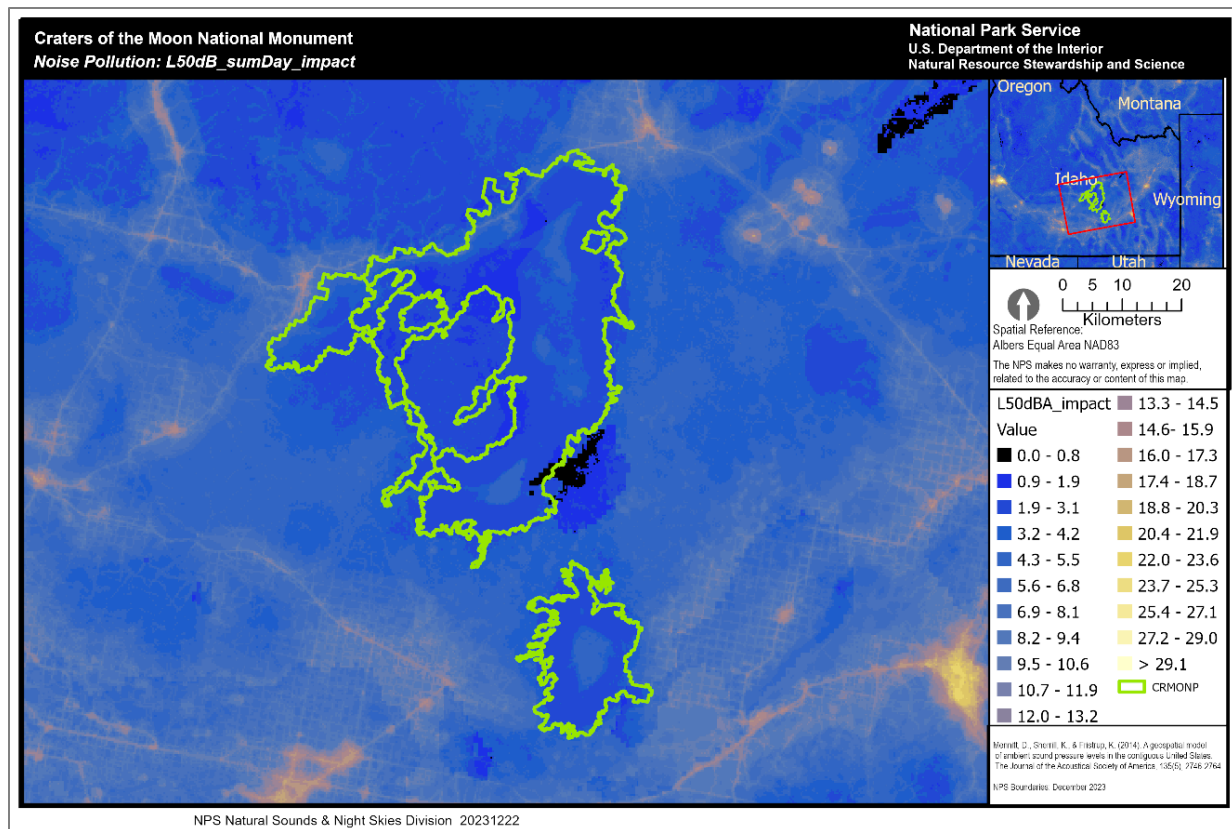


Figure 29. Map of predicted acoustic impact levels in Craters of the Moon National Monument and Preserve (CRMO) for an average summer day. The color scale indicates how much man-made noise increases the sound level (in A-weighted decibels, or dBA), with 270 meter resolution. Black or dark blue colors indicate low impacts while yellow or white colors indicate greater impacts. The mean acoustic impact level at the park is 2.9 dBA.

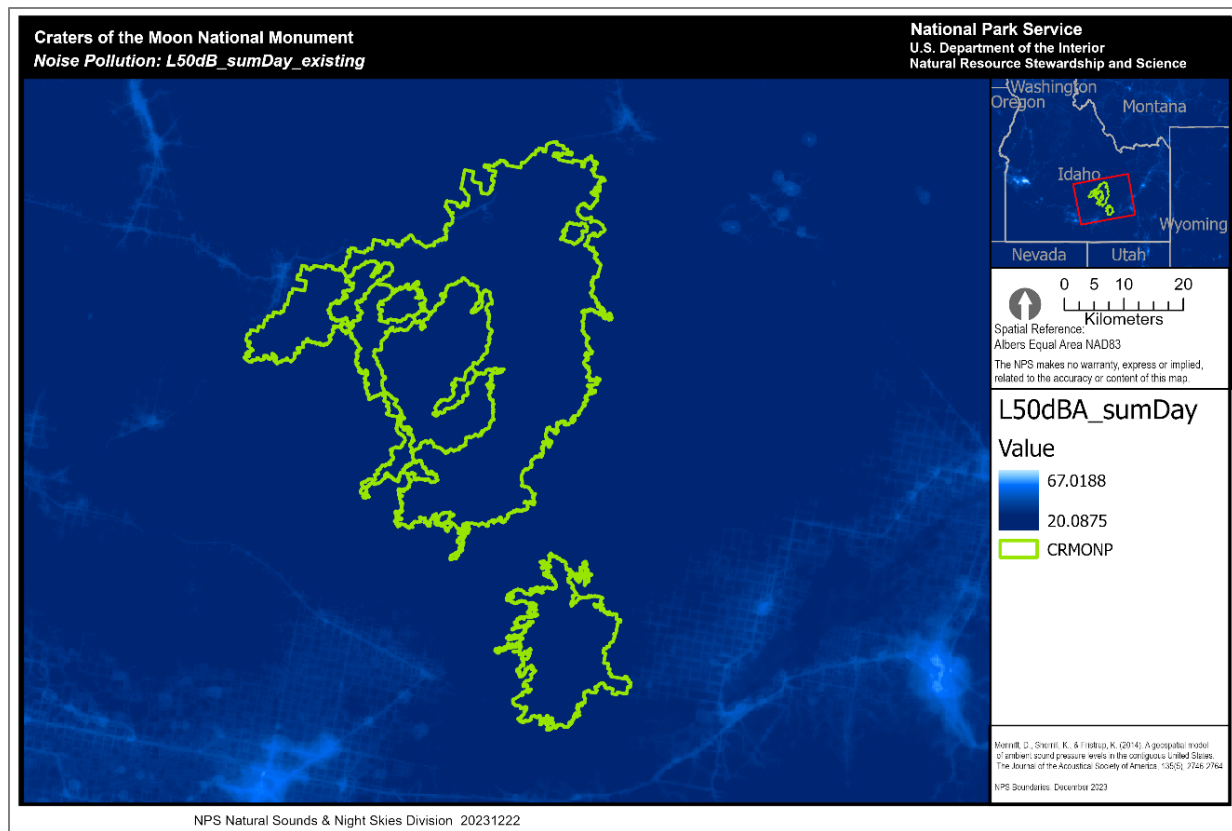


Figure 30. Map of predicted existing acoustic levels in Craters of the Moon National Monument and Preserve (CRMO) for an average summer day. The color scale indicates median (L_{50}) sound pressure level (in A-weighted decibels, or dBA), with 270 meter resolution.

Appendix D: Craters of the Moon Eclipse Report

Background

A total solar eclipse swept across the U.S. on August 21, 2017, and awed millions of viewers. The path of totality crossed 21 national park units and 7 national trails. The Natural Sounds and Night Skies Division (NSNSD) of NPS partnered with 16 park units to deploy 29 acoustic recording systems before, during, and after the total solar eclipse on August 21, 2017. This national effort captured the sounds of the eclipse and offered a unique opportunity to measure how the eclipse changed the soundscape. The 14 parks (18 sites) with data spanned the continental U.S. and included a diversity of habitats— from the plains of the Midwest to the swamps of Congaree (Figure 31). Two parks (3 sites) were not in the path of totality.

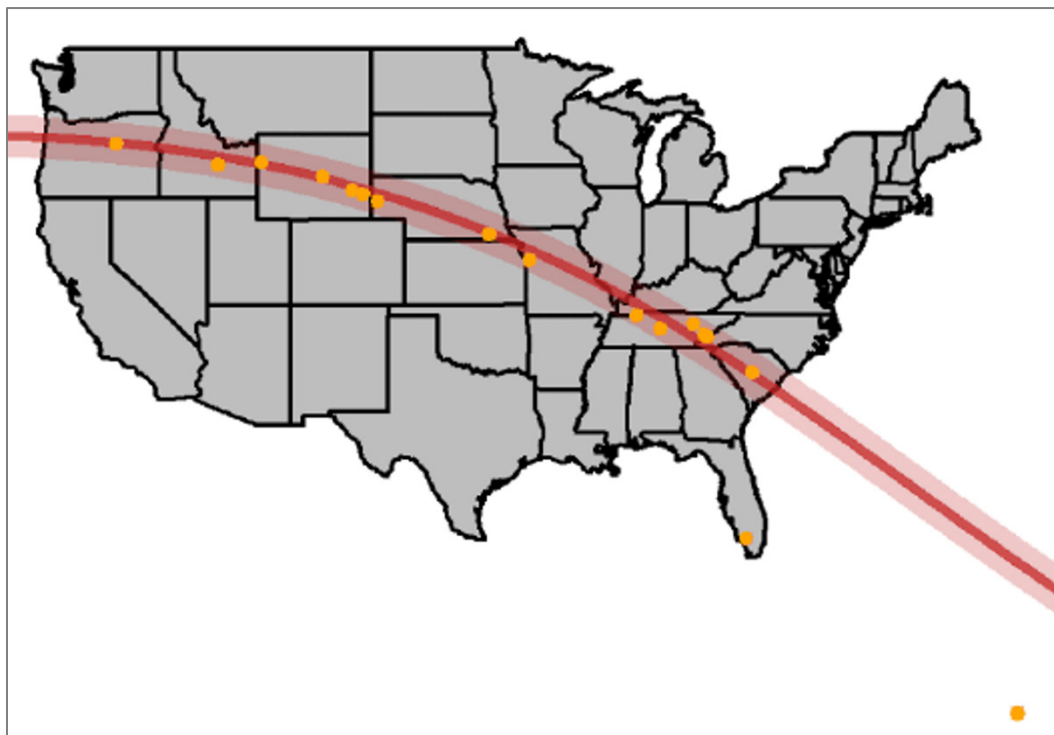


Figure 31. Locations of acoustic monitoring stations deployed during the solar eclipse.

Data Collection

At CRMO, one acoustic monitoring site was deployed (Limber Pine Stand 43.55N, -113.44W) from August 18, 2017, to August 24, 2017. This was a backcountry site in a desert habitat on rocky terrain. At this site, eclipse totality began at 17:31 GMT and lasted for 0 minutes 58 seconds.

Data Analysis

Acoustic data during the time of totality for all days was extracted using automated scripts. To see if the soundscape changed, sound levels (at different frequencies) during totality were compared to all other days at the same time. Google Form surveys were developed by NSNSD in which NPS participants listened to five different sound clips to determine what types of sounds were present or

not present during the eclipse. A total of 312 sound clips were listened to by at least two different people. The sound clip identity was unknown to remove bias. The participants marked down how often they heard different types of sounds (birds, mammals, insects, voices, human activity, weather) in each clip. Changes in the presence of the sound types were analyzed by comparing what was heard during the eclipse verses what happened on days before and after the eclipse.

Results

At the desert site in CRMO, sound levels below 500 Hz decreased below the standard deviation of non-eclipse days (Figure 32), and likely relates to a change in the weather and human activity identified in the listening exercise (Figure 33). At 1,000 Hz sound levels slightly decreased (Figure 32), possibly driven by fewer bird and insects calls during the eclipse (Figure 33).

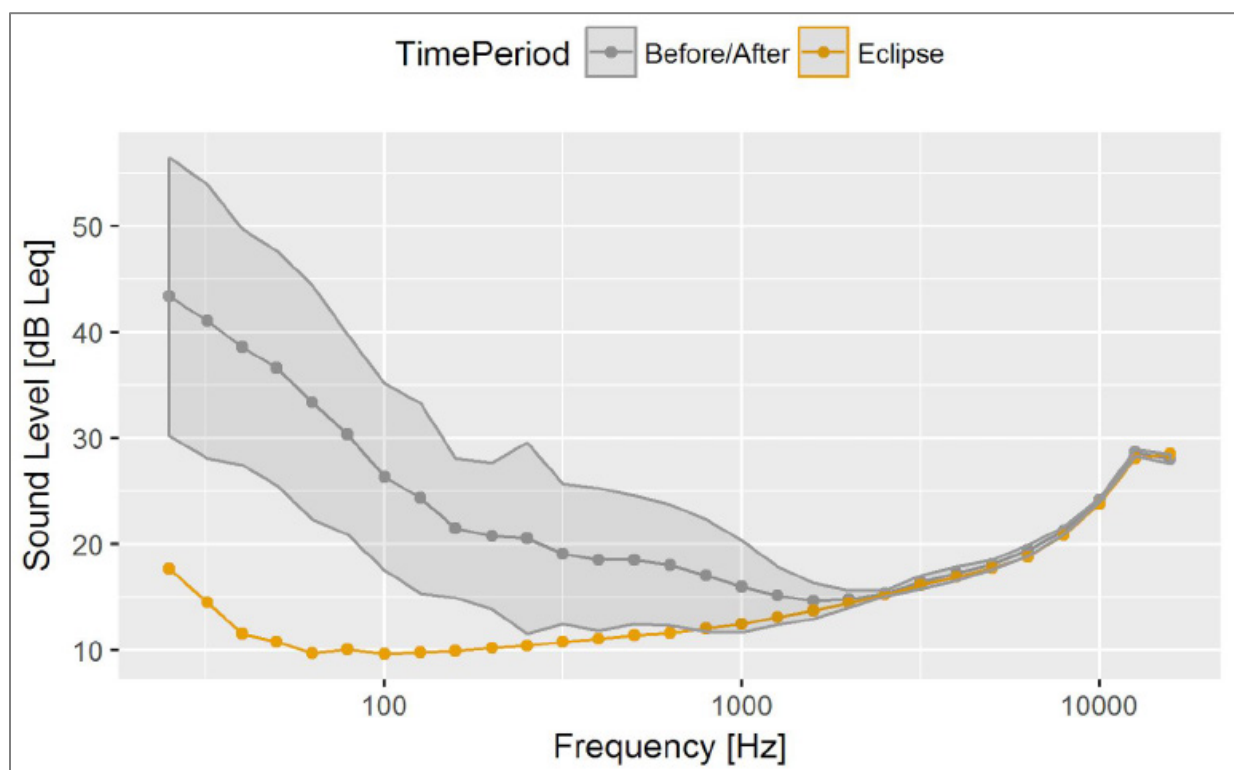


Figure 32. Sound levels at different frequencies before, during, and after the August 2017 solar eclipse.

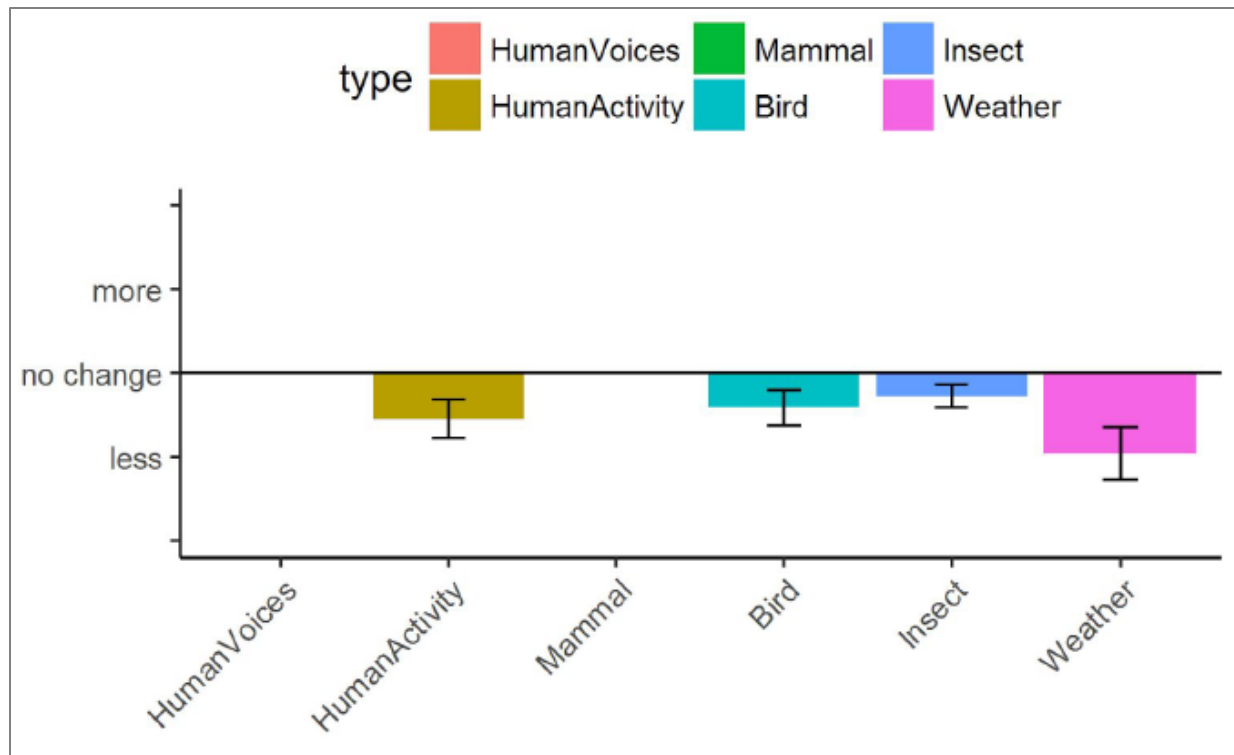


Figure 33. Sound clip identification from recordings before, during, and after the August 2017 solar eclipse.

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