

Recommendations for Improved Assessment of Noise Impacts on Wildlife

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ABSTRACT Research to determine noise impacts on animals benefits from methodology that adequately describes the acoustical stimulus as well as the resulting biological responses. We present acoustical considerations and research techniques that we have found to be useful. These include acoustical definitions and noise measurement techniques that conform to standardized acoustical practice and advice for controlled experimentation to supplement behavioral observation. Specific considerations include characteristics of noise stimulus, selection of noise metrics, use of frequency-weighting algorithms tailored to a specific animal species, selection and placement of noise measurement equipment, and methods for documenting animal responses. We also present arguments for measuring the noise stimulus at the location and time of each response observation. Our purpose is to recommend some baseline terminology, metrics, and techniques prerequisite to effective assessment of noise impacts on terrestrial wildlife whenever and wherever potential conflicts arise. (JOURNAL OF WILDLIFE MANAGEMENT 73(5):788–795; 2009)

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The potential impact of noise on wildlife is a topic of concern (Grubb and Bowerman 1997, Hayden et al. 2002, Pater and Delaney 2002, Lawler et al. 2005) because of federal mandates such as the Endangered Species Act and the National Environmental Policy Act and because the nature of anthropogenic noise is complex and pervasive (Grubb and King 1991, Grubb et al. 1992, Bowles 1995, Larkin et al. 1996, Delaney 2002). Noise impacts on terrestrial animals can take many forms, including changing habitat use and activity patterns, increasing stress response, decreasing immune response, reducing reproductive success, increasing predation risk, degrading conspecific communication, and damaging hearing if the sound is sufficiently loud (Bowles 1995, Larkin et al. 1996). Noise that can potentially impact wildlife populations include sources such as recreational (Brattstrom and Bondello 1994, Knight and Gutzwiller 1995, Swarthout and Steidl 2001) and commercial activities (Holthuijzen et al. 1990, Grubb et al. 1998), vehicle traffic (Benson 1995, Delaney and Grubb 2003), and military training operations (Guyer et al. 1995; Delaney et al. 1999, in press; Krausman et al. 2004). Valid research conclusions are important for guiding appropriate decisions regarding wildlife management and restrictions on human activities (Awbrey and Hunsaker 1997; Delaney et al. 1999, in press; Krausman et al. 2004).

We present acoustical considerations and research techniques that we have found to be useful for evaluating noise impacts on wildlife. These approaches are the result of our research experience with many species and types of noise at a variety of locations, including helicopters and chain saws on Mexican spotted owls (*Strix occidentalis lucida*) on the

Lincoln National Forest, New Mexico, USA (Delaney et al. 1999); small arms and artillery fire on red-cockaded woodpeckers (*Picoides borealis*) at Ft. Stewart, Georgia, USA (Pater and Delaney 2002, Delaney et al., in press); logging trucks on northern goshawks (*Accipiter gentilis*) on the Kaibab National Forest, Arizona, USA (Grubb et al. 1998); terrestrial, aquatic, and aerial disturbance on bald eagles (*Haliaeetus leucocephalus*) in Arizona and Michigan, USA (Grubb and King 1991, Grubb et al. 1992, Grubb and Bowerman 1997); and military blast noise on humans at a number of locations near United States military installations (Pater 1976; Pater et al. 1995, 1996; Nykaza et al. 2006; Nykaza and Pater 2006). Our recommendations are applicable to virtually all terrestrial animal species and environments in which sound is transmitted through the atmosphere. Many of the concepts also apply to sound transmitted through the ground or water, but instruments and methods may differ substantially.

CHARACTERIZING PHYSICAL PROPERTIES OF SOUND

Sound waves travel through a medium such as air or water as wave motion that exhibits pressure variations above and below the static value (Harris 1991). Noise is simply defined as unwanted sound (Crocker 1998). Acoustics is the science of sound (Pierce 1989, Harris 1991, Crocker 1998, Kinsler et al. 2000), including its production, propagation, and effects (American National Standards Institute [ANSI] S1.1 2004). Acoustic analysis should take into account salient aspects of the sound source, the receiver (e.g., an animal), and the path between them along which the sound travels. The Acoustical Society of America and the International

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Organization for Standardization (ISO) standardize acoustical terminology and methodologies.

A sound metric is a measurable parameter used to characterize and quantify a sound event. Reporting animal responses without meaningfully quantifying the stimulus events limits the utility of results and prevents their application for predicting animal responses to sound in other situations. An appropriate metric will measure sound-stimulus characteristics in a way that can be related to responses by an animal. For example, a sound metric that does not account for frequencies within the hearing range of a species cannot meaningfully characterize sound stimuli for that species. As a further example, a metric that is designed to measure continuous sound cannot adequately describe a brief transient event such as a gunshot. Animal responses to sound can depend on sound level, rate of onset, duration, number of events, spectral distribution of sound energy, presence of pure tones, and relative level of background noise. Many metrics have been defined and standardized to accomplish particular sound measurement tasks (ANSI S12.9P1 2003, ANSI S1.1 2004, ANSI S1.13 2005).

Noise metrics are quantified in terms of decibels (dB). The decibel is defined as 10 times the base-ten logarithm of the ratio of a quantity to a reference quantity of the same kind and expressed in the same units (ANSI S1.1 2004). The resulting parameter is known as a level and represents a dimensionless ratio. The decibel is not a true unit because it does not have a definable size as do units such as meters, seconds, and degrees. The decibel scale is used throughout science and engineering to quantify parameters that are of interest over a numerical range of several orders of magnitude. Addition of quantities expressed as levels in decibels is accomplished by first converting the levels to numeric values of physical parameters; a doubling of the physical quantity is a 3-dB-level increase. Temporal aspects of the sound stimulus are also critically important, as is discussed later in connection with definitions of specific metrics and recommendations regarding their use.

Sound Pressure Level

Sound pressure level (SPL) is a metric that is defined (ANSI S1.1 2004) as

$$\text{SPL(dB)} = 10 \log_{10} (P_{\text{rms}}^2 / P_{\text{ref}}^2).$$

Here P_{rms} is root-mean-square (RMS) sound pressure expressed in units such as Pascals, and P_{ref} is the reference pressure expressed in the same units. The standard reference pressure for the decibel scale used to measure sound-pressure level in air (the reference used in water is different) is 20 micro-Pascals (ANSI S1.8 2001), which was chosen originally as the lowest sound pressure that a young human with good hearing can hear. Crocker (1998) presents typical SPL levels for familiar sounds ranging from soft to loud. The decibel scale is useful because animal auditory systems generally exhibit approximately logarithmic response and function over a pressure range of >12 orders of magnitude. A 10-dB increase in sound level is a factor of 3.16 (square root of 10) increase in sound pressure, which represents a

tiny sound pressure change at very low sound levels and a large sound pressure change at high sound levels. However, a 10-dB increase in sound level is judged by humans to be about twice as loud, regardless of whether the change is at lower or higher pressure (Crocker 1998).

Exponential Time Weighting

Low-pass filters are sometimes used to smooth out transient fluctuations in sound pressure to make a meter easier to read. These filters are referred to as exponential time weighting and have been standardized and named slow, fast, and impulse (ANSI S1.4 2001, ANSI S1.1 2004). Transient sounds are sometimes characterized by a metric that is the maximum sound level measured when one of these filters is employed (e.g., max. fast level). Use of such filters should always be reported as part of the sound measurement. These filters are often encountered on older analog sound level meters; modern microprocessor-based digital instruments enable use of more suitable metrics.

Equivalent Average Sound Level

For more-or-less constant sounds, such as traffic on a busy road, office noise, some industrial noise, and most ambient noise, a measure of averaged sound level is appropriate, using the metric equivalent average sound level (LEQ), over a specified time period (e.g., 1 sec, 24 hr). The definition of LEQ is similar to the definition of SPL, except that the RMS pressure is replaced by the integrated average value of pressure squared during the measurement period. Duration of the measurement period should be representative of actual events and should be reported as part of the level measurement. Many commercially available instruments are capable of measuring LEQ for user-specified time periods.

For highly variable or transient noise events, a simple measurement of SPL or LEQ is not adequate. For transient noise events of a few to several seconds duration, such as a pass-by of a vehicle or aircraft, measuring average noise level is problematical because the choice of the measurement period duration affects the magnitude of the metric measured. A better method is to divide the event duration into short (typically 1 sec) time increments, measure LEQ during each increment, and report the maximum value that occurs in any time increment. For such a sound-stimulus measurement, total duration of the event should also be described and reported, for example the period that 1-second LEQ values were measured to be within 10 dB of the maximum value.

Sound Exposure Level and Peak Sound Pressure Level

Sound exposure level (SEL) is defined (ANSI S1.1 2004) as

$$\text{SEL(dB)} = 10 \times \log_{10} (\text{SE} / \text{SE}_0).$$

Here SE is sound exposure, which is defined as the time integral of the square of the sound pressure integrated over the entire event duration, and SE_0 is the zero reference quantity (defined as the square of P_0 multiplied by 1 sec). Sound exposure is generally indicative of the total sound energy of an event, though SE is strictly equal to sound

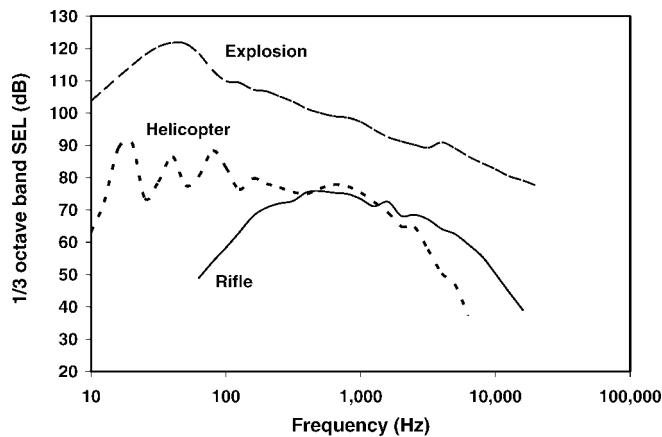


Figure 1. Acoustical spectra for sound emission from 3 different military sources (L. L. Pater, United States Army Engineer Research and Development Center, unpublished data). The explosion was produced by detonation of C4 explosive at a distance of 400 m with an overall sound exposure level (SEL) of 128 decibels (dB). The helicopter spectrum, measured during a flyby at 300 m, exhibits an overall SEL of 96 dB and is rich in low frequencies produced by the single rotor. The carbine rifle spectrum was recorded at a distance of 100 m with an overall SEL of 84 dB. Hz = hertz.

energy only under certain conditions. Sound exposure level is generally accepted as an appropriate metric for brief noise events, especially events of <1 second in duration such as impulsive noise from guns and explosions and mechanical impact noise. Peak sound pressure level, a metric that measures peak instantaneous pressure, is also often of interest for brief noise events (ANSI S12.9P1 2003). Relatively sophisticated instrumentation is required to measure these metrics accurately.

For aircraft and helicopter flyby noise events, 2 metrics are sometimes measured and reported, both the SEL and the maximum 1-second equivalent average (LEQ) level discussed previously, because both are good candidates to be related meaningfully with an animal's response. These metrics will typically be quite different in magnitude, even though they are expressed as decibels and describe the same event (see Delaney et al. 1999, in press, for examples).

Spectra

Characterizing a noise stimulus adequately often requires not only the value of ≥ 1 overall sound-level metric(s), but also a spectrum that shows how magnitude of a sound metric varies with frequency (pitch). A pure sine wave (1 frequency tone) has a spectrum consisting of emission at a particular frequency. Musical instruments typically produce a sound signal that has a fundamental frequency accompanied by overtones, or harmonics, at multiples of the fundamental frequency. Many sound sources, particularly those that produce impulsive sound, produce sound energy distributed over a range of frequencies. For animal (including human) response purposes, when dealing with sources that produce sound over a broad range of frequencies, frequency range is often divided into bands of constant-percentage width, either octave or one-third-

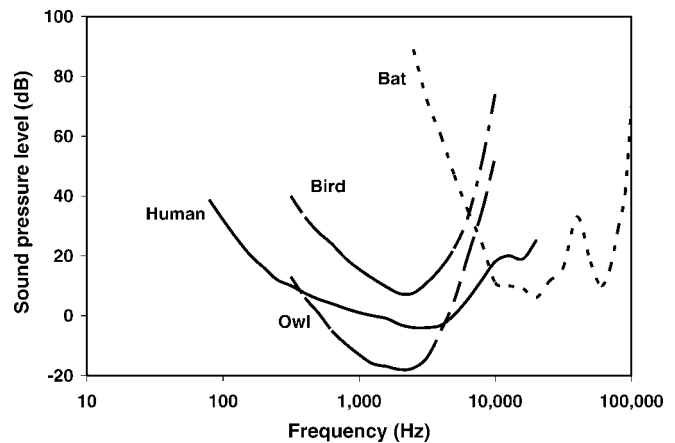


Figure 2. Audiograms for 1) a composite average developed for 7 orders of birds (Dooling 1980, Dooling et al. 2000), 2) hearing sensitivity data for the big brown bat (*Eptesicus fuscus*; Dalland 1965, Poussin and Simmons 1982), 3) a composite average for owls (Trainer 1946, Konishi 1973), and 4) a human threshold audiogram (International Organization of Standardization [ISO] 226 2003), illustrating differences in hearing range and sensitivity among species. dB = decibels; Hz = hertz.

octave (an octave being a doubling in frequency), which results in frequency bands that cover a wider range of frequencies as frequency increases (ANSI S1.6 2001). We present example spectra (Fig. 1) that we measured for a variety of sources during previous research.

Audiograms

An audiogram describes hearing range and sensitivity. A threshold audiogram provides the sound level that the animal can barely perceive as a function of frequency (pitch). An audiogram of the study species is useful to guide interpretation of noise-response data (see Delaney et al. 1999 and Delaney 2002 for examples). We present example audiograms (Fig. 2) for several species based on data from the literature, including a composite average audiogram developed for 7 orders of birds (Dooling 1980, Dooling et al. 2000), hearing sensitivity data for the big brown bat (*Eptesicus fuscus*; Dalland 1965, Poussin and Simmons 1982), a composite audiogram for owls (Trainer 1946, Konishi 1973), and a human threshold audiogram (ISO 226 2003). Differences between these audiograms are substantial; for example, human hearing range is roughly from 20 hertz to 20,000 hertz, but bats hear well at much higher frequencies, illustrating that animal perception of sounds cannot generally be inferred based on human perception. Comparing the spectrum of a sound with the audiogram of an animal can aid in response interpretation; for example, an animal is unlikely to respond to a sound that occurs at frequencies outside of its hearing range (Grubb et al. 2007).

Frequency Weighting

A sound stimulus can be more meaningfully characterized by considering how it is perceived by the animal. This characterization is facilitated by means of frequency weighting (ANSI S1.4 2001), an algorithm of frequency-dependent attenuation (a filter) that simulates the hearing

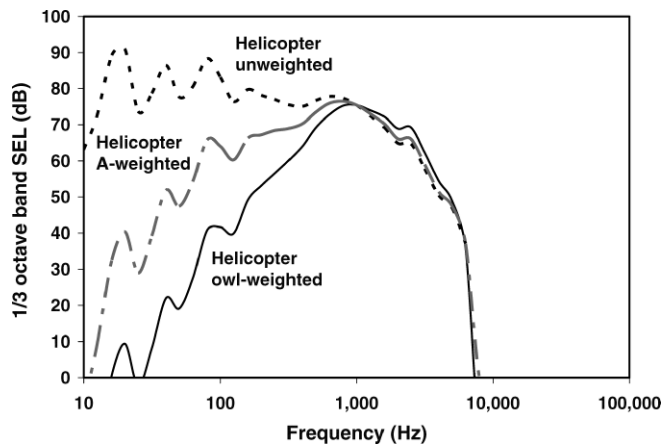


Figure 3. Effect of unweighted, human A-weighted, and owl-weighted frequency-weighting functions on the sound exposure level (SEL) spectrum of a helicopter (Delaney et al. 1999). The differences in reduced sensitivity at low frequencies are readily discernable. dB = decibels; Hz = hertz.

sensitivity and range of the study species. An example is the ubiquitous “A” weighting that filters sound energy according to human hearing range and sensitivity at moderate sound levels (ANSI S1.4 2001). Delaney et al. (1999, in press) developed weighting functions for the Mexican spotted owl and the red-cockaded woodpecker based on threshold audiograms. Applying frequency weighting for owls to a helicopter spectrum has a different effect than applying human A-weighting to the same spectrum (Fig. 3). Weighting systems developed for humans are not appropriate for animal species that have substantially different audiograms (Bowles and Pater 2000). Species-specific weighting can be implemented by measuring sound stimulus in terms of a metric such as one-third octave-band sound exposure level (determined by sound-level meters or postprocessing of recordings), applying attenuation values

to the frequency band metric values, and then calculating overall broadband weighted metric values.

TOOLS AND TECHNIQUES FOR SOUND MEASUREMENT

Because of the variety of sound measurement equipment available at a wide range of costs and technical capabilities, we have assembled a representative list of effective equipment with recommended applications and approximate costs (Table 1). Sound measurement equipment should always be selected to have sufficiently constant sensitivity over the frequency range of interest to avoid artificial accentuation or attenuation of sound energy at some frequencies. Some sound-level meters and noise monitors directly deliver sound measurements, requiring no additional equipment. Another approach is to record noise in the field for detailed analysis in the laboratory. In all cases, careful calibration of noise measurement equipment is required to ensure accurate results.

Diffraction, reflection, scattering, and absorption of sound by terrain, buildings, or vegetation, should all be considered when selecting microphone locations. A microphone should not be located within 1 m of objects such as buildings or large trees, because both reflections and shielding can influence sound measurements. Ideally, the noise stimulus should be measured at the exact location occupied by the animal. Practical considerations often dictate that recording microphones be placed at locations that minimize disturbing the animals. Microphones must be carefully located to ensure that placement yields sound measurements that accurately represent the sound stimulus to which the animal is exposed. For example, a microphone located at the base of a tree may not accurately characterize the sound in a cavity high up in the tree. One useful technique is to establish a correction, based on sound measurements at both the animal location and data microphone location, made when the

Table 1. Representative sound measurement equipment. Citation or omission of manufacturer or equipment names or models does not constitute endorsement or criticism.

Instrument	Applications	Cost (US\$)
Inexpensive sound-level meter, noise monitor, or dosimeter	Suitable for reduced-accuracy measurement of steady sound. Cannot measure spectra or metrics such as peak or sound exposure level. Check for conformance to American National Standards Institute (ANSI) standards. Avoid obsolete used instruments.	<100
Professional sound-level meter or noise monitor (ACO, Bruel & Kjaer, Larson-Davis, Norsonics, Quest, Rion)	Self-contained instruments can measure and store a variety of metrics and weightings, including spectral data, and can store many events. ANSI Standard S1.4-1971 or S1.4-1983. Cannot directly implement nonstandard species-specific weighting filters.	2,000–23,000
Microphones (ACO, Bruel & Kjaer, GRAS, Larson-Davis, PCB)	Professional microphones will have constant sensitivity within a specified tolerance (e.g., ± 1 decibel) over a specified frequency range. Inexpensive microphones typically will have large sensitivity variation with frequency.	1,000–2,000
Microphone preamplifier	Required for microphones.	1,000–2,000
Microphone power supply	Required for non-prepolarized condenser microphones.	1,000–2,000
Digital audio tape (DAT) recorder	Capacity 2 hr at 2-kilohertz bandwidth. The Sony Walkman DAT is small and light, useful for remote areas. Tape recorders are being superseded by solid state recorders.	200–800
Digital recorders	Recorders now predominantly record to electronic memory (read-only memory [RAM], hard drive, flash card). Many rapidly evolving combinations of bandwidth, capacity, and no. of channels are available, ranging from inexpensive recorders to powerful digital oscilloscopes.	600–12,000

animal is not present, which can be used to extrapolate sound measurements from the data microphone location to the animal location during response observations.

Ambient or background sound, due to insects or rustling vegetation for example, is defined as all sound other than the sound of interest. A noise event measurement will not accurately measure the event level unless the event sound is ≥ 10 dB louder than the ambient sound. A report of noise event measurements should always include a description and measurement of ambient sound before and after the noise events. Event measurements can sometimes be corrected for ambient sound contribution to the measurement when the event level is < 10 dB above ambient. A qualitative description of the event and ambient noise helps to define the noise environment. Air flow (wind) over a microphone can introduce spurious very-low-frequency noise into a measurement; use of open-cell foam wind screens and low-cut filters minimizes this problem.

As a sound wave-front expands outward from a point source, acoustical energy emitted by the source is distributed more thinly over an expanding spherical surface (similarly, sound from a line source expands on a cylindrical surface). The effect of spherical spreading from a point source is a 6-dB reduction in sound pressure level and sound exposure level for each doubling of distance from the source. Thus, the reduction in sound level due to geometrical spreading between 10 m and 20 m is the same as from 1,000 m to 2,000 m. At small distances from the source, a small change in measurement location can result in significant change in measured sound level.

Received sound level depends on many factors in addition to the distance from source to receiver, including source emission strength, source directivity, atmospheric attenuation, terrain, ground cover, and weather. Effects of many of these factors are frequency dependent. A more powerful source can of course be expected to yield a higher sound level at the receiver, all other factors being equal. Many sources exhibit directivity, that is, sound emission varies with direction; a change in orientation of the source relative to the receiver will thus yield a change in received sound level. The atmosphere attenuates low frequency sound much less than high frequency sound (ISO 9613-1 1993, ANSI S1.26 2004), which means that an acoustical spectrum changes with distance because acoustical energy decreases less rapidly at low frequencies than at higher frequencies. The spectral-energy distribution of a source affects sound propagation; sources rich in low frequency energy, such as helicopter noise and blast noise from explosions and large guns, can travel long distances efficiently. Elephants (*Loxodonta africana*) employ these phenomena to communicate over long distances by using low frequency vocalizations at times of the day when the weather favors long-distance propagation (Larom et al. 1997). Terrain, ground cover, and propagation path height above the ground also have complex frequency-dependent effects on sound attenuation during propagation through the atmosphere. Received sound level from a given source may entail other complex-

ities. For example, helicopter noise level does not depend only on the distance of closest approach, but also on aircraft speed, power settings, rotor pitch, and maneuvers.

A dominant factor for determining received sound level is weather, more precisely the vertical, horizontal, and temporal variation of temperature, wind speed, wind direction, and to a lesser extent humidity, which determine sound speed in the atmosphere and can cause sound to refract (i.e., travel along curved paths) in much the same way that a lens causes light rays to change direction. Weather can cause sound level to vary by as much as 50 dB, all factors constant except for meteorological parameters (Schomer et al. 1976a, b). Turbulence in the atmosphere can also cause significant variation in received sound, as much as 15 dB, over time spans as short as a few seconds or minutes.

ASSESSING BIOLOGICAL EFFECTS OF NOISE ON ANIMALS

We advise that researchers use the actual noise stimulus, if possible, when testing animal responses to noise. Simulated noise sources have been used in human and wildlife research (Weisenberger et al. 1996), but sound reproduction systems are limited in their ability to reproduce the full frequency spectrum and temporal aspects of a noise source, particularly low frequency sound and rapid-onset transient sound events. Without the full array of audio stimulus characteristics, experimental animals are unlikely to respond as they would when presented with the actual stimulus in its full natural context. Also, playing a recorded sound stimulus over a sound reproduction system may not reproduce the effect of a moving sound source and also does not include visual cues; for example, playing aircraft noise recordings over a loudspeaker does not include the visual stimulus of a shape in the sky.

For humans, the typical noise response criterion is annoyance (ANSI S12.9P4 2005). For domesticated animals, the relevant response might be damage to individual animals or impacts on profits. For endangered species, an important response might be reproductive success that can influence species persistence. Immediate responses, such as alert and flushing behavior at nests or roosts and changes in activity patterns, are of special interest when associated with foraging and rearing offspring (Delaney et al. 1999, in press; Pater and Delaney 2002). Researchers have also used physiological response measurements such as heart rate, brain waves, blood chemistry, and endocrine levels to investigate potential disturbance impacts that may be applicable for assessing responses to noise (O'Connor et al. 1994, Wingfield et al. 1997, Wikelski et al. 1999, Romero and Wikelski 2002). Sound, both anthropogenic and natural, can also affect nest-site selection (Benson 1995) and can mask biologically important sounds, including mating call behavior and predator and prey sounds (Awbrey and Bowles 1990, Bowles et al. 1990, Awbrey and Hunsaker 1997).

Observational validity can be enhanced by careful observation of an animal's behavior for a period of time

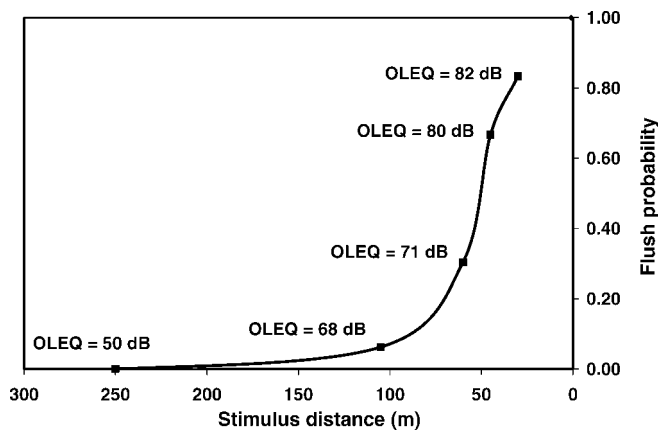


Figure 4. Flush response of Mexican spotted owls as a function of distance from an operating chain saw, obtained during research in the Sacramento Mountains, New Mexico, USA, 1995–1996 (Delaney et al. 1999). Noise levels are mean values of measured, 10-second equivalent average sound level (LEQ) noise at each distance, with an owl frequency-weighting function applied (hence, OLEQ). dB = decibels.

before and after the stimulus was presented to the animal to provide context for evaluating a response. Conclusions regarding effects of noise on reproductive success and other population-level responses can be improved by monitoring reference sites where noise levels differ from subject sites. Although research results are often obtained by observing behavioral responses to noise events that the researcher does not control, efficiency of gathering data and statistical power of results can be enhanced by using experimentation where the researcher controls type, location, and timing of noise stimuli.

Temporal scales of both stimulus and response are important considerations. Stimuli duration can vary from abrupt and brief point sources such as gunshots or sonic booms to continuous, extended sources such as the drone of transportation noise. Response durations may also range from brief, immediate behavioral responses, such as alerting or flushing, to long-term responses that affect reproductive success of individual and populations.

Researchers should also consider whether an animal is responding to noise or to some other aspect of a potentially disturbing activity, because many potential disturbances include both auditory and visual stimuli. Segregating responses to auditory and visual aspects of a stimulus event may be difficult; therefore, it may be useful to thoroughly characterize the stimulus, including the degree to which the noise source was visible to the animal.

One way to express the observed responses of an animal to noise is by means of a dose-response model, an equation or graph that describes how probability of a specific response measure varies with noise stimulus level. Response probability is expected to be negligible at low stimulus levels and approach 100% at high stimulus levels. The entire dose-response curve may not be feasible to obtain because of concern for the welfare of study animals at high noise levels. The portion of the curve that defines a rapid increase in probability of a response will often suffice for impact

assessment and wildlife management purposes. In the event that no significant responses or impacts are observed, a useful result may be a lower limit for the response threshold. A classic dose-response model was presented by Schultz (1978) for human response to noise from aircraft and road traffic, but few dose-response models have been developed for animals (Bowles et al. 1990). Animals may rapidly habituate to noises that they learn do not pose a threat (Grubb et al. 1992, Brown et al. 1999, Krausman et al. 2004), which can complicate gathering and interpreting dose-response data.

An alternate response format is response probability as a function of distance from the noise source (Fig. 4). However, presenting average noise levels measured at each distance used during dose-response measurements provides less information regarding subject receivers' responses to noise. This format may also incorporate larger variance in noise stimulus implications because noise level almost always varies substantially due to changing sound-propagation conditions, even at comparable distances. Nonetheless, response probability as a function of distance is a straight forward approach for management purposes.

Delaney et al. (1999, in press) obtained dose-response functional relationships for Mexican spotted owls and red-cockaded woodpeckers for several noise types and found that dose-response models were different for each combination of species and type of noise. Experience with humans has also shown that the dose-response relationship generally is different for distinctly different types of noise, such as aircraft noise and blast noise (ANSI 12.9P4 2005). Thus researchers should expect dose-response models to likely differ for each combination of noise type and animal species.

Sound-level changes of only a few decibels can result in substantial changes in animal responses (Grubb et al. 1998; Delaney et al. 1999, in press). Some environmental phenomena, particularly weather, can cause variations of as much as 50 dB in received sound level as we discussed previously. Because of large potential variation in received sound level, we strongly suggest that every sound event be measured at the time of observation and at the animal's location when collecting noise dose-response data or carrying out behavioral observation of response to noise, to avoid large unknown variance in stimulus dose data. Natural variability in propagation conditions cause received sound levels to vary so widely that one measurement or calculation, even at a given observation location and for a given sound source, will not be sufficiently accurate at all times for purposes of rigorous research.

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LITERATURE CITED

- ANSI S1.4. 2001. American national standard specification for sound level meters. American National Standards Institute, Washington, D.C., USA.
- ANSI S1.6. 2001. American national standard preferred frequencies, frequency levels, and band numbers for acoustical measurements. American National Standards Institute, Washington, D.C., USA.
- ANSI S1.8. 2001. American national standard reference quantities for acoustical levels. American National Standards Institute, Washington, D.C., USA.
- ANSI S12.9P1. 2003. American national standard quantities and procedures for description and measurement of environmental sound, Part 1. American National Standards Institute, Washington, D.C., USA.
- ANSI S1.1. 2004. American national standard acoustical terminology. American National Standards Institute, Washington, D.C., USA.
- ANSI S1.26. 2004. American national standard method for calculation of the absorption of sound by the atmosphere. American National Standards Institute, Washington, D.C., USA.
- ANSI S1.13. 2005. American national standard measurement of sound pressure levels in air. American National Standards Institute, Washington, D.C., USA.
- ANSI S12.9P4. 2005. American national standard quantities and procedures for description and measurement of environmental sound, Part 4: noise assessment and prediction of long-term community response. American National Standards Institute, Washington, D.C., USA.
- Awbrey, F. T., and A. E. Bowles. 1990. The effects of aircraft noise and sonic booms on raptors: a preliminary model and a synthesis of the literature on disturbance. Noise and Sonic Boom Impact Technology, Technical Operating Report 12. Wright-Patterson Air Force Base, Ohio, USA.
- Awbrey, F. T., and D. Hunsaker, II. 1997. Effects of fixed-wing military aircraft noise on California gnatcatcher reproduction. Journal of the Acoustical Society of America 102:3177.
- Benson, R. 1995. The effect of roadway traffic noise on territory selection by golden-cheeked warblers. Bulletin of the Texas Ornithological Society 28:42–51.
- Bowles, A., F. Awbrey, and R. Kull. 1990. A model for the effects of aircraft over-flight noise on the reproductive success of raptorial birds. Pages 1129–1132 in H. G. Jonasson, editor. INTERNOISE 90 proceedings: noise and sonic boom impact technology. Acoustical Society of Sweden, Gothenburg, Sweden.
- Bowles, A. E. 1995. Responses of wildlife to noise. Pages 109–156 in R. L. Knight and K. J. Gutzwiller, editors. Wildlife recreationists: coexistence through management and research. Island Press, Washington, D.C., USA.
- Bowles, A. E., and L. L. Pater. 2000. Developing noise-dosage weighting functions for animals. Journal of the Acoustical Society of America 107: 2784.
- Brattstrom, B. H., and M. C. Bondello. 1994. Effects of off-road vehicle noise on desert vertebrates. Pages 167–206 in R. B. Ruby and D. J. Germano, editors. Biology of North American tortoises. National Biological Survey, Fish and Wildlife Research 13, Washington, D.C., USA.
- Brown, B. T., G. S. Mills, W. A. Russell, G. D. Therres, and J. J. Pottier. 1999. The influence of weapons-testing noise on bald eagle behavior. Journal of Raptor Research 33:227–232.
- Crocker, M. J., editor. 1998. Handbook of acoustics. John Wiley and Sons, New York, New York, USA.
- Dalland, J. 1965. Hearing sensitivity in bats. Science 150:1185–1186.
- Delaney, D. K. 2002. Prioritization of threatened and endangered species sound research on army installations. United States Army Engineer Research and Development Center/Construction Engineering Research Laboratory Technical Report TR-02-30, Champaign, Illinois, USA.
- Delaney, D. K., and T. G. Grubb. 2003. Effects of off-highway vehicles on northern spotted owls: 2002 results. Report to California Department of Parks and Recreation, Off-Highway Vehicle Recreation Division, Contract No. 4391Z9-0-0055. United States Army Engineer Research and Development Center/Construction Engineering Research Laboratory, Champaign, Illinois, USA.
- Delaney, D. K., T. G. Grubb, P. Beier, L. L. Pater, and M. H. Reiser. 1999. Effects of helicopter noise on Mexican spotted owls. Journal of Wildlife Management 63:60–76.
- Delaney, D. K., L. L. Pater, L. D. Carlile, E. W. Spadgenske, T. A. Beaty, and R. H. Melton. In press. Response of red-cockaded woodpeckers to military training operations. Wildlife Monographs.
- Dooling, R. J. 1980. Behavior and psychophysics of hearing in birds. Pages 261–288 in A. Popper and R. Fay, editors. Comparative studies of hearing in vertebrates. Springer-Verlag, New York, New York, USA.
- Dooling, R. J., B. Lohr, and M. L. Dent. 2000. Hearing in birds and reptiles. Pages 308–359 in R. J. Dooling, R. R. Fay, and A. N. Popper, editors. Comparative hearing: birds and reptiles. Springer-Verlag, New York, New York, USA.
- Grubb, T. G., and W. W. Bowerman. 1997. Variations in breeding bald eagle response to jets, light planes, and helicopters. Journal of Raptor Research 31:213–222.
- Grubb, T. G., W. W. Bowerman, J. P. Giesy, and G. A. Dawson. 1992. Responses of bald eagles, *Haliaeetus leucocephalus*, to human activities in north-central Michigan. Canadian Field Naturalist 106:443–453.
- Grubb, T. G., D. K. Delaney, and W. W. Bowerman. 2007. Investigating potential effects of heli-skiing on golden eagles in the Wasatch Mountains, Utah. Final report to Wasatch-Cache National Forest, Agreement No. 05-JV-11221607-237. U.S. Department of Agriculture Forest Service, Rocky Mountain Research Station, Fort Collins, Colorado, USA.
- Grubb, T. G., and R. M. King. 1991. Assessing human disturbance of breeding bald eagles with classification tree models. Journal of Wildlife Management 55:501–512.
- Grubb, T. G., L. L. Pater, and D. K. Delaney. 1998. Logging truck noise near nesting northern goshawks. U.S. Department of Agriculture Forest Service Research Note RM-RMRS-RN-3, Rocky Mountain Research Station, Fort Collins, Colorado, USA.
- Guyer, C., K. E. Nicholson, and S. Baucom. 1995. Effects of tracked vehicles on gopher tortoises (*Gopherus polyphemus*) at Fort Benning military installation, Georgia. Georgia Journal of Science 54:195–203.
- Harris, C. M. 1991. Handbook of acoustical measurements and noise control. Third edition. McGraw-Hill, New York, New York, USA.
- Hayden, T. J., R. H. Melton, B. Willis, L. B. Martin, III, and T. Beaty. 2002. Assessment of effects of maneuver training activities on red-cockaded woodpecker populations on Fort Stewart, Georgia. Engineer Research and Development Center/Construction Engineering Research Laboratory Technical Report 02-17, Champaign, Illinois, USA.
- Holthuijzen, A. M. A., W. G. Eastland, A. R. Ansell, M. N. Kochert, R. D. Williams, and L. S. Young. 1990. Effects of blasting on behavior and productivity of nesting prairie falcons. Wildlife Society Bulletin 18:270–281.
- ISO 9613-1. 1993. Attenuation of sound during propagation outdoors, Part 1: calculation of the absorption of sound by the atmosphere. International Organization for Standardization, Geneva, Switzerland.
- ISO 226. 2003. Acoustics—normal equal-loudness-level contours. International Organization for Standardization, Geneva, Switzerland.
- Kinsler, L. E., A. R. Frey, A. B. Coppens, and J. V. Sanders. 2000. Fundamentals of acoustics. Fourth edition. John Wiley and Sons, New York, New York, USA.
- Knight, R. L., and K. J. Gutzwiller. 1995. Wildlife and recreationists. Island Press, Washington, D.C., USA.
- Konishi, M. 1973. How the owl tracks its prey. American Scientist 61:414–424.
- Krausman, P. R., L. K. Harris, C. L. Blasch, K. K. G. Koenen, and J. Francine. 2004. Effects of military operations on behavior and hearing of endangered Sonoran pronghorn. Wildlife Monographs 157.
- Larkin, R., L. L. Pater, and D. Tazik. 1996. Effects of military noise on wildlife: a literature review. U.S. Army Construction Engineering Research Laboratory Technical Report 96/21, Champaign, Illinois, USA.
- Larom, D., M. Garstang, M. Lindeque, R. Raspet, M. Zuncel, Y. Hong, K. Brassel, S. O'Beirne, and F. Sokolic. 1997. Meteorology and elephant infrasound at Etosha National Park, Namibia. Journal of the Acoustical Society of America 101:1710–1717.
- Lawler, J. P., A. J. Magoun, C. T. Seaton, C. L. Gardner, R. D. Boertje, J.

- M. Ver Hoef, and P. A. Del Vecchio. 2005. Short-term impacts of military overflights on caribou during calving season. *Journal of Wildlife Management* 69:1133–1146.
- Nykaza, E. T., and L. L. Pater. 2006. The experimental methods to obtain correlation between peak sound pressure level and noise complaints for blasts and preliminary observations. International Institute of Noise Control Engineering, Inter-Noise 2006 Proceedings, 3–6 December, Honolulu, Hawaii, USA.
- Nykaza, E. T., L. L. Pater, and R. H. Melton. 2006. Sleep impacts of nighttime training noise from large weapons on residents living near a military installation. U.S. Army Engineer Research and Development Center Technical Report 06–21, Champaign, Illinois, USA.
- O'Connor, M. P., J. S. Grumbles, R. H. George, L. C. Zimmerman, and J. R. Spotila. 1994. Potential hematological and biochemical indicators of stress in free-ranging desert tortoises and captive tortoises exposed to a hydric stress gradient. *Herpetological Monographs* 8:5–26.
- Pater, L. L. 1976. Noise abatement program for explosive operations at Naval Service Warfare Center/Dahlgren Laboratory. Proceedings Department of Defense Explosive Safety Board, 17th Explosives Safety Seminar, 27 January, Washington, D.C., USA.
- Pater, L. L., and D. K. Delaney. 2002. Assessment of training noise impacts on the red-cockaded woodpecker. *Journal of the Acoustical Society of America* 112:2431.
- Pater, L. L., M. J. White, N. Lewis, G. Luz, and W. A. Russell. 1996. Considerations in developing a model for assessing the annoyance of small arms ranges. Institute of Noise Control Engineering, NoiseCon 1996 Proceedings, 21–25 October, Montreal, Quebec, Canada.
- Pater, L. L., R. Yousefi, and J. Burnett. 1995. Measurements of the effect of helicopter landing approach on community noise level. International Institute of Noise Control Engineering, Inter-Noise 1995 Proceedings, 10–12 July, Newport Beach, California, USA.
- Pierce, A. D. 1989. *Acoustics: an introduction to its physical principles and applications*. Acoustical Society of America, Woodbury, New York, USA.
- Poussin, C., and J. A. Simmons. 1982. Low-frequency hearing sensitivity in the echolocating bat *Eptesicus fuscus*. *Journal of the Acoustical Society of America* 72:340–342.
- Romero, L. M., and M. Wilkelski. 2002. Exposure to tourism reduces stress-induced corticosterone levels in Galapagos marine iguanas. *Biological Conservation* 108:371–374.
- Schomer, P. D., R. J. Goff, and L. M. Little. 1976a. The statistics of amplitude and spectrum of blasts propagated in the atmosphere. Volume I. Construction Engineering Research Laboratory Technical Report (TR) N-13, Champaign, Illinois, USA.
- Schomer, P. D., R. J. Goff, and L. M. Little. 1976b. The statistics of amplitude and spectrum of blasts propagated in the atmosphere. Volume 2. Appendices C through E, CERL Technical Report (TR) N-13, Champaign, Illinois, USA.
- Schultz, T. 1978. Syntheses of social surveys on noise annoyance. *Journal of the Acoustical Society of America* 62:377–405.
- Swarthout, E. C. H., and R. J. Steidl. 2001. Flush responses of Mexican spotted owls to recreationists. *Journal of Wildlife Management* 65:312–317.
- Trainer, J. E. 1946. The auditory acuity of certain birds. Dissertation, Cornell University, Ithaca, New York, USA.
- Weisenberger, M. E., P. R. Krausman, M. C. Wallace, D. W. DeYoung, and E. O. Maughan. 1996. The effects of simulated jet aircraft noise on heart rate and behavior of desert ungulates. *Journal of Wildlife Management* 60:52–61.
- Wilkelski, M., S. Lynn, C. Breuner, J. C. Wingfield, and G. J. Kenagy. 1999. Energy metabolism, testosterone and corticosterone in white-crowned sparrows. *Journal of Comparative Physiology A* 185:463–470.
- Wingfield, J. C., K. Hunt, C. Breuner, K. Dunlap, G. S. Fowler, L. Freed, and J. Lepson. 1997. Environmental stress, field endocrinology, and conservation biology. Pages 95–131 in J. R. Clemmons and R. Buchholz, editors. *Behavioral approaches to conservation in the wild*. Cambridge University Press, Cambridge, United Kingdom.

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