Noise monitoring recommendations for greater sage-grouse habitat in Wyoming

Prepared for:
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Summary of noise-monitoring recommendations

- Noise measurements can be used to establish baseline ambient values, determine compliance with noise regulations, profile noise sources, and ground-truth noise prediction models.
- Due to the difficulty of measuring ambient noise levels in quiet conditions, we recommend the use of both empirical sampling and ambient noise modeling to establish baseline ambient values.
- Measurements should be made by qualified personnel experienced in acoustical monitoring.
- Measurements should be made with a high quality, calibrated Type I (noise floor < 25 dB) sound level meter (SLM) with a microphone windscreen and (where applicable) environmental housing.
- Measurements should be collected during times when noise exposure is most likely to affect greater sage-grouse— nights and mornings (i.e. 6 pm – 9 am) and should be taken for ≥1 hour at each site, ideally over multiple days with suitable climactic conditions. To capture typical variability in noise level at the site of interest, deployment of SLM units for multiple days is preferred.
- Environmental conditions should be measured throughout noise measurement periods so that measurements made during unsuitable conditions can be excluded.
- Measurements should be made at multiple (3-4) locations between each noise source and the edge of the protected area. On-lek measurements should exclude time periods when birds are lekking.
- Accurate location data should be collected for each measurement location. Surveyors also should catalog the type and location of all nearby sources of anthropogenic noise.
- Critical metrics should be collected: L_{50}, L_{90}, L_{10}, L_{eq}, and L_{max}. All measurements should be collected in A-weighted decibels (dBA) and, if possible, also collected in unweighted (dBF) and C-weighted (dBC) decibels. If possible, SLM should log 1/3-octave band levels throughout the measurement period. Additional metrics may be collected, depending on the goals of the study.
- To determine baseline ambient levels, we recommend the use of A-weighted L_{90} metric. As a measure of median noise exposure, we recommend the use of A-weighted L_{50} metric.

The purpose of noise measurements

Noise is associated with most phases of human development activity, from early construction to the daily operation of a completed project. Studies have demonstrated that anthropogenic noise can have a range of impacts on wildlife, including temporary or permanent hearing damage, increased stress levels, disruption of natural behaviors, changes in breeding success and avoidance otherwise suitable habitat (Barber et al. 2010; Kight & Swaddle 2011). Even though the rapid spread of human development and the associated anthropogenic noise has impacts on wildlife, it is not always logistically, politically, or economically feasible to eliminate or even minimize noise (Blickley & Patricelli 2010). The more common policy approach is to establish noise standards that set an upper limit on the level of noise that can be produced in the habitat of species of concern. Policy makers may also mandate or recommend particular noise mitigation measures to comply with these standards or require prediction of the potential impacts from noise in the planning phase. Effective implementation and enforcement of compliance with noise management strategies requires information about pre-development ambient levels and the actual or predicted changes in noise levels that result from anthropogenic development. This information is often obtained through empirical measurements made in the geographic area of interest. Such noise measurements may inform noise management strategies in the following ways:

- *Establish baseline ambient values*. Measurement of ambient noise levels may be necessary to establish baseline values in an area prior to development or for comparison to noise levels in nearby developed areas. Such ambient values may be established on a site-specific or region-wide basis, depending on the availability of funding and manpower, existing data availability, and habitat homogeneity across the landscape. Current noise regulations for sage-grouse habitat, for example, use an ambient-based noise standard, which allows measured amplitudes to increase a pre-determined amount relative to the undisturbed ambient level (e.g. Wyoming Executive Order 2011-5). Such standards require knowledge about the ambient conditions in an area prior to development or in similar but undisturbed areas. Due to the difficulty of obtaining accurate measurements of quiet ambient levels, we recommend that baseline ambient values be established using a combination of empirical sampling of ambient noise (using the methods described here) and ambient noise modeling (see section below "*A statement about the difficulty of measuring ambient noise and quiet sounds"*).

- *Measure compliance with noise regulations.* Noise measurements may be used to measure noise production by noise sources or noise exposure at critical sites to gauge compliance with noise-exposure management strategies and evaluate the effectiveness of noise abatement measures.

- *Profile noise produced by different noise source types.* Noise measurements can be used to determine the noise output of individual pieces of equipment or noise sources to develop noise profiles of these sources for inclusion in a database of noise sources. These data can be used in predictive models to estimate the likely impact of new development on the noise levels in areas of pre-existing or no development.

- *Calibrate and ground-truth noise prediction models.* Noise prediction models, such as Soundplan or NMSimNord can be used to estimate the likely impact of development on ambient noise levels in an area. Output from such models is best when validated using on-the-ground measurements.

The following recommendations are intended to serve as a general protocol for collection of noise measurements in areas of existing and proposed development. This protocol includes equipment recommendations, recommendations for timing and duration of measurements, as well as a recommendation of which metrics should be incorporated. Our goal is to develop a protocol that is efficient, effective and produces consistent results. The protocol was written to facilitate the gathering of noise measurements relevant to stipulations for greater sage-grouse protection; however, noise impacts are not restricted to sage-grouse and we attempted to make this protocol useful for noise monitoring more generally. Use of a standard protocol for noise monitoring will ensure that future measurements are comparable across locations, times, and surveyors. The following recommendations are based upon our experience, discussions with other experts, and existing noise monitoring protocols developed for other noise types and species. This protocol should be considered a work in progress and should be updated, as data needs and availability change.

A statement about the difficulty of measuring ambient noise and quiet sounds

As likely will become clear when reading this document, the measurement of noise requires expensive, complicated equipment and the interpretation of resulting data requires specialized knowledge and experience. The measurement of quiet noise levels (approximately 40 dB or less)—such as ambient values, quiet sources or even loud sources at a large distance—is especially difficult, since this requires extremely-sensitive, finely-calibrated equipment and excellent environmental conditions. Any flaws in the equipment, conditions and measurement protocol will likely lead to over-estimation of noise levels. For example, many noise meters (Type 2 meters) are unable to measure sounds quieter than 35 dBA, so measurements of any sources near or below this limit are meaningless and potentially misleading. Similarly, collecting measurements on a windy day or while moving the meter (or moving near the meter) can lead to over-estimates of ambient values. Even professional measurements on Type-1 sound level meters will typically overestimate ambient levels in quiet areas (<27 dBA). This is because A-weighting (defined below) boosts the amplitudes of the mid-frequencies, which in very quiet areas includes noise from the pre-amplifier on the sound-level meter. This is not a problem when measuring louder sounds (i.e. many noise sources associated with energy development) which overwhelm any contribution of the noise from the SLM (as well as noise from a slight breeze or other incidental sounds). Since many noise stipulations are relative to ambient values, over-estimation of ambient measures can have enormous repercussions, increasing allowable noise levels at that site.

Given the ease with which poor measurements can be made, and the large consequences of these measurements, noise measurements should be collected by experienced personnel. It is simply not true that any person (or consulting firm) can rent a noise meter and make adequate measurements of noise—especially of ambient and relatively quiet sources. Therefore, we want to emphasize that this protocol is not meant to replace specialized training on noise measurement. The intent is to provide guidelines to experienced personnel so that measurements

are made in a more consistent and accurate manner and to highlight areas where specialized training and care is required. To be blunt, we encourage agencies interested in gathering noise measurements to ensure that consultants offering to make them have the relevant expertise as, in this case, bad data are worse than no data at all. Overestimation of baseline ambient values can have serious repercussions for sage-grouse and other noise-sensitive species.

Due to the difficulty of measuring quiet ambient levels—as well as experimental evidence indicating that ambient values used in noise management strategies should represent the pre-development ambient levels, such that new developments do not further impact already impacted soundscapes (Blickley et al. 2012; Patricelli et al. 2012)—we recommend that baseline ambient values ultimately be established using a hybrid approach, combining empirical sampling of noise levels with modeling to create a map of pre-development ambient noise. This would lead to broader coverage, since collecting empirical measurements at each key site would be time consuming and interpolating levels between these sites would be inaccurate without a model. For example, the National Parks Service (NPS) Natural Sounds and Night Skies Division is currently developing a model to predict ambient noise levels with and without existing developments at the landscape level. The model uses a machine-learning algorithm to improve predictions using publically-available input variables related to location, climate, land cover, hydrology, and degree of human development. The algorithm improves its accuracy (i.e. learns to improve its estimates) with each new empirical measurement. Therefore, collection of ambient noise levels in areas with little disturbance, using the protocol described here, will help to improve the accuracy of the model. Data from such an approach would be useful for multiple public and private agencies interested in tracking noise exposure over larger areas for a variety of species.

The process described above, however, will take time. In the interim, we have recommended to the BLM and Wyoming Game and Fish Department that noise management strategies for sage-grouse habitat should *not* set baseline for each lek by measuring ambient noise at lek edge. Rather, measurements of pre-development ambient values should be used in lieu of measurements made at lek edge. Based on our survey of the literature and data from recent noise-monitoring efforts, we recommend using an ambient value of 20-22 dBA as a baseline in noise management strategies for sage-grouse habitat. For a justification of these values and a broader discussion of noise stipulations related to sage-grouse, please see Patricelli et al., 2012.

A statement about the difficulty of measuring traffic noise

There is evidence that noise from traffic is has a significant impact on sage-grouse (Blickley et al. 2012; Patricelli et al. 2012). However, measuring traffic noise can be quite challenging, since intermittent traffic, such as the traffic in most sage-grouse habitat, causes short periods of loud noise interspersed with longer periods of quiet. With a variable noise source such as this, is it difficult to choose which metric to use to characterize noise. This is especially true since we do not know whether it is the total noise exposure through the day (or in a critical time period, such as nights and/or mornings) or the maximum noise level as a vehicle passes that best predicts impacts on grouse. A measure of "average" amplitude (e.g. L_{eq}) would be problematic, since the occasional noise events would be averaged with much longer quiet periods, having little effect on measured values. A great deal of traffic would be needed to raise average noise levels (L_{eq}) by 10 dBA. In general, a ten-fold increase in traffic is associated with a 10 dB increase in average noise levels, so an increase from 2 to 200 vehicles or from 200 to 2,000 vehicles over a given

time interval. A ten-fold increase in traffic would likely have a major impact on sage-grouse, yet may not exceed current noise management objectives inside and outside of core areas in Wyoming. Similarly, the sounds of vehicles passing would have little to no influence on median noise level (L_{50}), unless traffic noise is detectable 50% of the time or more. Even measures of maximum noise levels (such as the L_{max}) can be problematic, since other sound sources besides vehicles can affect these measures. This is especially problematic during long-term deployment of meters for monitoring, since a single meadowlark perched near (or on) the meter could lead to extremely high L_{max} measurements. Excluding these events would require that they be identified in synchronized audio recordings; alternatively, the 1/3-octave band frequency profile of the noise (at 1-second intervals) may be useful for these exclusions (these methods are discussed below).

These difficulties in choosing the appropriate measure to characterize noise suggest that approaches for the management of more continuous noise sources (e.g. compressors stations, drilling rigs and other infrastructure) may not be suitable for the management of traffic noise. Patricelli et al. (2012) discuss this issue in more detail and provide recommendations for management strategies focused on traffic noise. The recommendations for long-term monitoring of noise made into his protocol should provide useful measurements of traffic noise. It may also be useful to complement these measurements with data from axle counters.

Recommendations

Noise measurement surveyors:

As discussed above, all noise monitoring should be carried out by qualified personnel in order to ensure the accuracy of measurements. Qualified personnel should have:

- A familiarity with and experience in applying relevant acoustical standards, (e.g. ISO and ANSI).
- A familiarity with acoustical monitoring equipment and protocols.
- Practical knowledge of spectrum analysis (octave band and 1/3 octave band) and a range of noise metrics (L_{10}, L_{50}, L_{90}, L_{max}, L_{eq}, etc.)
- An ability to perform necessary acoustic calculations as well as analyze, interpret, and explain results.

These qualifications can most easily be met by having noise monitoring carried out by experienced acoustic consultants or researchers.

Equipment recommendations:

- *Sound level meter:* A sound level meter (SLM) is used to measure the amplitude of a noise source in decibels (dB). Measurements should be made with a self-contained, professional-quality meter to ensure accurate measurements. Due to the low level of ambient noise levels, accurate measurements will require use of Type 1 meters (as defined by standards ANSI S1.4-1983), which have higher quality microphones than Type 2 meters. Professional-quality sound level meters allow users a wide range of measurement options and are capable of logging data over multiple days at a variety of time intervals. Professional-quality meters, such as those made by Larson Davis, Brüel & Kjær and Quest, among others, also have the capability to identify individual noise events and are typically capable of processing data onboard to calculate a variety of metrics (see *Metrics* below). Octave and 1/3- octave band analyzers should meet specifications set by ANSI (ANSI S1.11- 2004). Such meters are typically expensive to purchase, but may be available for rental for short time periods. Meters should be regularly recalibrated professionally as recommended by the manufacturer and calibrated before each use with a field calibrator (meeting standard ANSI S1.40-2006). Since all meters differ, it is not possible to include detailed instructions on the use of meters here. Rather, the surveyor should consult the (often voluminous) instructions for their SLM to ensure that the desired metrics are being collected and that calibration has been performed correctly.

  As discussed above, most Type-1 precision sound level meters (SLM) have a "noise floor" of ~17 dB, meaning that they cannot measure sounds quieter than this level, since these sounds will be masked by the noise from the SLM itself. Some SLM noise is typically detected up to 10 dB above the noise floor (i.e. 27 dB), especially when using A-weighting, since A-weighting boosts the amplitudes of the mid-frequencies, which in very quiet areas includes noise from the pre-amplifier on the sound-level meter. This is not a problem when measuring louder sounds (i.e. many noise sources associated with

energy development) which overwhelm any contribution of the noise from the SLM (as well as noise from a slight breeze or other incidental sounds). Type-2 SLMs are more affordable (often ~$400 rather than ~$9,000 for Type-1) but can have noise floors of ~35 dB and should therefore never be used to measure ambient noise or quiet sound sources (expected to be <35-40 dBA); some more expensive Type-2 meters have noise floors approaching 22 dBA and would therefore be more useful for measuring quiet sounds, but not ambient levels. Within a few decibels above the noise floor, the accuracy of Type-2 meters is typically only slightly lower than Type-1 meters. Type-3 SLMs have higher noise floors and lower accuracy and should not be used for measuring ambient or assessing compliance.

- *Additional SLM equipment:* Weather-proof case and external battery will allow sound level meters to be deployed over multiple days. A microphone windscreen (typically purchased or rented with the SLM) should be used for all outdoor measurements to reduce effects of wind-generated noise.

- *GPS receiver:* Accurate location data should be collected for each measurement location and all nearby noise sources. Location data will allow subsequent measurements to be taken from the same location, which is important for long-term data sets. Such data will also be important for validation of spatially-explicit models.

- *Rangefinder:* When making measurements of a noise source, such as a generator or compressor station, it is useful to know how far away from the source the measurement is taken. This information is necessary in order to estimate the noise level at the source, or to estimate the noise levels at other distances. This information is also needed to use the measurement as a source file for use in a noise propagation model (e.g. NMSimNORD or SoundPLAN).

- *Weather station* Proper documentation of meteorological conditions is critical to determine the accuracy and comparability of measurements. An anemometer, thermometer and hygrometer will provide the important wind speed/direction, temperature and humidity data, since all these measurements can influence noise levels. A portable weather station placed near the noise monitoring equipment will allow accurate, local data to be collected continuously; such data can be logged on some meters or by the weather station. Alternatively, weather data from a nearby weather station may be adequate for assessing the weather at a noise-monitoring site.

- *Recording equipment (optional):* Audio recordings of noise may be useful for monitoring intermittent noise sources or determining the identity of different noise sources at different time periods. Due to the difficulty of processing and analyzing what are often lengthy recordings, audio recording may not always by desirable; however, it may be useful in some cases when combined with more traditional noise monitoring methods. For example, if one was interested in measuring loud sound events during construction (e.g. using L_{max} or L_{10}), then it may be critical to exclude events cause by songbirds using the SLM microphone as a signing perch; by listening to an audio recording of the monitored period, one could identify and exclude these events from the SLM log. Alternatively, one could analyze the audio files to determine the relative contribution of

different noise sources to the overall noise levels in an area measured by an SLM (e.g. using L_{eq})(Lynch et al. 2011). To collect audio data, Automatic Recording Units (ARUs), such as the commercially available SongMeter or ARUs developed by the Cornell Lab of Ornithology, may be deployed to a location to record over a designated time interval synchronous with the SLM recording periods. Some SLMs have splitters available (Larson Davis ADP015) so that noise from the SLM microphone can be recorded both by the SLM and an external audio recorder; alternatively, sounds can be recorded from the SLM output port (Lynch et al. 2011; Blickley & Patricelli 2012).

- *Traffic counters (optional)* Traffic on most roads varies with the day of the week and time of day. Axle counters (particularly if vehicle passes are time-stamped) allow noise measurements to be associated with traffic levels.

Placement of noise monitoring equipment:

Location

- *Leks*: Many current noise management strategies define maximum allowable noise level at lek edge (Patricelli et al. 2012). Implementation of such standards requires that ambient levels be measured on or near the lek. If measurements are made on or near a lek, measurements made while birds are present on the lek period (for approximately four hours after sunrise) should be excluded from ambient or noise level calculations as sage-grouse vocalizations are likely to be louder than all but the loudest and closest anthropogenic noise sources. If measurements were made during the lekking time, one can imagine a scenario where increasing development noise causes declines in lek attendance, which causes amplitude readings to decrease over time as fewer birds contribute to the sounds of the lek. Clearly, these data would tell us little about the actual noise levels of anthropogenic sources and could be very misleading. For this reason, it would be preferable to collect measurements prior to bird arrival (sunrise), prior to the lekking season and when temperature and wind profiles are generally similar as estimates of noise at lek edge during the lekking period. If measurements are made off-lek to avoid measuring the sound produced by grouse, they should be at an equivalent location with similar topography and relative distance to noise sources in the area. Recordings of the ambient noise may be useful for excluding periods when sage grouse or other species are vocalizing, which may substantially increase the measured ambient levels. Representative ambient baseline measurements made in undisturbed areas should be made at sites with vegetation and topography similar to the area of interest.

- *Noise sources*- The placement of microphones relative to a noise source will be determined by both acoustic properties of the noise and measurement goals. Typically one would want to be as close as possible to the source being measured, without being in the near field. Measurement errors that can result from hydrodynamic fluctuations very close to the source (within the hydrodynamic near field) and interference from sound waves that emanate from various parts of the noise source (in the geometric near field)(Bies & Hansen 2009). To avoid measurement errors associated with the near field, microphones should be placed at least one wavelength or two source widths away from the source (Mueller 2002). For example, if one were measuring noise from a compressor station that measured 50 meters wide, one would need to be a minimum of 100 meters from the station (here a rangefinder is very useful to choose a measurement location in the field). For most large infrastructure sources, a minimum distance of 100 meters will be adequate. Some stipulations or recommendations may also be relevant in determining the location of noise measurement. For example, noise management strategies may stipulate a maximum level of noise at the edge of a protected area, or at a particular distance from the noise source. If the goal is to develop a noise source file for a noise modeling program, such as NMSimNORD, then the program will specify the distance at which source measurements are to be made (for NMSimNORD, this is 1000 feet from the source). Ideally, measurements would be made at various points along a transect extending from the source. Transect measurements will allow propagation of the noise through the local environment to be estimated.

- For all noise and ambient measurements, surveyors should catalog the type and location of all nearby sources of anthropogenic noise.

Meter height

Noise levels can differ when measured near the ground or at the height of the human ear due to ground waves and propagation effects caused by vegetation. Therefore, most SLM instruction manuals suggest mounting meters or holding hand-held meters at approximately breast height to reduce ground effects. Average human ear height (1.2-1.5 meters) is also commonly used so that measurements approximate the noise heard by a human. When measuring noise levels for greater sage-grouse, we recommend placing meters at 12 inches above the ground, to approximate the height of a sage-grouse. However, if the goal of noise monitoring is to compare measurement to prior measurements collected at another height, then it would be preferable to match the height at which the previous measurements were made. Noise measurements made by meters with higher placement may be more relevant to many other species, so measurements taken at human ear or breast height may be more general. We have observed very small (<<1 dB) differences in measurements at different heights in the same locations, so meter height is unlikely to substantially affect the measured amplitudes at a given location.

Timing of measurements:

Noise levels can vary substantially depending on the time of day and season. Ambient levels can vary 10-15 dB between day and night due to differences in temperature, humidity, and activity of other species. Noise levels should be measured across a range of times and environmental conditions, and should a focus on times of day and seasons when the focal species may be particularly sensitive. For sage-grouse, the most relevant measurements would be those collected during times when noise exposure is most likely to affect them— nights and mornings (i.e. 6 pm – 9 am). If noise output by anthropogenic sources is variable, noise measurements also should seek to characterize the range of noise produced and typical emissions throughout the day and night. For example, the noise produced by wind turbines may vary with wind speed and the vehicular traffic on a highway may vary with time of day or day of week. Measurements should be compared with measurements made at similar times of day, so meters should be deployed for a similar range of time for pre and post development measurements. Measurements should be taken for at least one hour at each site, ideally over multiple days with suitable climactic conditions.

Deployment

To characterize noise levels over the entire day and night, SLMs should be deployed to sites of interest for a minimum of 24 hours, and, preferably, 48-72 hours. For noise sources that are intermittent or irregular, longer deployments may be necessary in order to capture the full range of noise conditions. In order to ensure accurate measurements, individual locations should be measured on three separate occasions at least 1 week apart. Measurements should be made on days with good weather conditions (see *Weather*). Inclement weather over the measurement period may require further deployment.

Manual spot measurements

Manual measurements or short-term deployments of noise monitoring equipment of individual locations or noise sources may be may be used as part of long-term noise monitoring efforts, such as to ensure continued compliance with regulations. All relevant time, location, and weather data should be collected for such measurements. Timing of measurements should be coordinated to maximize the comparability with previously made measurements.

Weather:

The propagation of sound is heavily influenced by local environmental conditions and noise measurements in a single location can very greatly due to differences in temperature, wind levels, snow cover, and other environmental factors. Environmental conditions should be measured throughout noise measurement periods so that measurements made during unsuitable (windy) conditions can be excluded.

Wind

Wind can affect noise measurements in several ways. Wind creates noise (e.g. rustling vegetation) and alters the propagation of noise from pre-existing sources in the local environment. In addition, wind can also create 'pseudonoise' by affecting the movement of wind and air across the microphone of the SLM; this pseudonoise is not a measure of audible noise caused by wind, it is only an artifact of wind shear across the microphone. This pseudonoise can be reduced at low wind levels with use of a microphone windscreen, which should always be used for outdoor measurements. Even with a wind screen, the accuracy of measurements is reduced in windy conditions. Therefore, when measuring loud sources, measurements made in wind greater than 11 mph should be excluded, since the noise and pseudonoise from the wind is likely to swamp the energy from the noise source of interest. For measurement of ambient noise levels, measurements should only be made under calm conditions (<2.2 mph). Accurate estimates of local wind speed from a local weather station will allow noise measurements made these windy periods to be identified and excluded from subsequent analyses. Comparisons of ambient noise levels or noise output should be made only under comparable wind conditions (wind direction and wind speed) as direction and speed can affect measured levels. In order to compare measurements, wind levels for each measurement should be in the same wind class (Table 1) and, if they fall into the Upwind or Downwind classes, the wind speed should be within 2.2 mph (Caltrans & Jones and Stokes Consulting 2003).

Table 1: Wind class (adapted from Caltrans & Jones and Stokes Consulting 2003)

Wind class	Vector component of wind (mph)
Upwind	-2.2 to -11
Calm	-2.2 to 2.2
Downwind	2.2 to 11

Temperature and Humidity

Temperature and humidity can affect noise measurements, although to a lesser degree than wind. In general, for measurements to be comparable, they should be taken at temperatures within 14˚ C (25.2˚ F) of each other (Caltrans & Jones and Stokes Consulting 2003). Measurements should also be taken under similar humidity conditions, although there are no strict guidelines for equivalence. In general, measurements taken under extremely dry conditions should not be compared with those taken under humid conditions. Ground moisture and snow cover can influence the propagation of noise and should also be recorded.

Measurement of noise:

Decibels

The amplitude, or loudness, of a sound is typically measured in decibels (dB). The decibel scale is logarithmic and due to the logarithmic scale, small changes in decibel level can represent large changes in loudness. For humans, an increase of 3 dB results in a barely perceptible change in noise level, a 5 dB increase in noise level is a perceptible change and a 10 dB increase in noise level is a perceived doubling of noise level.

Frequency weighting:

Weighted decibel scales can be used to account for differences in hearing sensitivity across frequencies. If decibels are not weighted, the amplitude is averaged across all frequencies within the measurement range (for 'dBF' or 'dB flat', the frequency range is undefined; for 'dBZ' the range is defined as 10 Hz to 20 kHz). A-weighted decibels (dBA) are most commonly used for noise measurements. A-weighting (ANS S1.42-2001) is used to account for changes in level sensitivity as a function of frequency. In an effort to simulate the relative response of the human ear, A-weighting de-emphasizes the high (>6.3 kHz) and low (<1 kHz) frequencies, and emphasizes the frequencies in between. Unfortunately, there is no weighting specific to sage-grouse or other wildlife. Most birds, besides owls, have hearing capabilities similar or slightly worse than humans; therefore, some experts recommend that A-weighting may be a suitable if not ideal metric for studies of birds (Dooling and Popper 2007). Recent research on peafowl (Freeman, 2012) found that males and females were capable of detecting infrasound (<20 Hz). This suggests that the human-centric A weighting may not be appropriate for some species. Some researchers advocate for the development of new species-specific frequency weightings, but this requires detailed knowledge about the hearing ability of these species and such data do not exist for sage-grouse. Most noise regulations have limitations that are based upon a maximum A-weighted value and A-weighted measurements are the most commonly collected. C-weighting is more linear and is used to account for human perception of loud sounds (exceeding 100 dB). We recommend that measurements be collected in A-weighted decibels (dBA), and other frequency weightings (dBC and dBF) if possible. By collecting and reporting levels in at each 1/3 octave band (see below), future weightings that are more sage-grouse specific can later be applied.

Time averaging

Sound level meters can measure noise levels over a number of different time intervals: slow, fast, impulsive or peak (Table 2). These correspond to different settings on the SLM. Noise produced

by most industrial noise sources does not fluctuate rapidly, so a 'slow' time-interval setting is generally most appropriate for characterizing such noise. To describe individual noise events, such as vehicles passing by, a 'fast' time-interval setting is preferred. For explosive sounds, such as gunshots or noise from mining, the 'impulsive' setting is more appropriate.

Table 2: SLM time intervals

Averaging time	Duration of measurement
Slow	1 second
Fast	1/8 second
Impulsive	1/30 second
Peak	Instantaneous peak

Critical Metrics to characterize noise sources

- L_{50} is the median noise level—the level that is exceeded 50% of the time. This measure is collected over some time period (e.g. 1 hour, or from 6 pm to 9 am) with this period being broken down into much smaller intervals (typically 1 second); an L_{50} of 30 dBA would mean that half of the intervals measured were less than 30 dBA and half of them were greater than 30 dBA. This metric is preferable to using a measure of average noise over a longer interval, like L_{eq} or L_{avg}, since these average metrics are more heavily influenced by occasional loud events, such as those caused by a songbirds, insects, aircraft, wind gusts, etc. These intruding sounds will have no impact on the L_{50}, unless they are present more than 50% of the time.

- L_{90} is the noise level that is exceeded 90% of the time. L_{90}, also known as the residual noise level. As with the L_{50}, the L_{90} is collected over some time period with this period being broken down into much smaller intervals (typically 1 second); an L_{90} of 20 dBA would mean that 10% of the intervals measured were less than 20 dBA and 90% of them were greater than 20 dBA. Residual noise levels reflect background noise level at a site, since they exclude most intruding noise from birds, insects, wind gusts and sporadic anthropogenic noises (passing vehicles or aircraft) that raise the average (e.g. L_{eq}) and maximum values (e.g. L_{max}, L_{10}) over a measurement period. This metric is the most suited for estimating ambient values to set the baseline for management objectives. In an area with anthropogenic noise sources producing continuous noise (like most energy development infrastructure), the L_{90} measurement will not represent pre-development ambient values since the continuous noise source will contribute to the residual levels. To estimate predevelopment ambient for a disturbed site, measurements must be collected in a similar but undisturbed area, or estimated through modeling.

- L_{10} is the noise level that is exceeded 10% of the time and is a metric that characterizes the maximum noise level in an area. The L_{10} is collected over some time period with this period being broken down into much smaller intervals (typically 1 second); an L_{10} of 60

dBA would mean that 90% of the intervals measured were less than 60 dBA and 10% of them were greater than 60 dBA. As a measure of maximum noise level, the L_{10} measurement is less affected by the occurrence of a single loud noise event than the L_{max} (see below).

- *L_{eq}* is the equivalent continuous noise level and is calculated by integrating the energy in the sound over the entire measurement and dividing by the time period to determine the equivalent noise level if the noise were constant. The time period can range anywhere from one second to 24 hours. For noise sources with relatively continuous noise output, L_{eq} is commonly used as a descriptor. L_{eq} is influenced more by loud noise events, even if they are relatively brief, than by quieter noise events that are frequent. Thus, the L_{eq} metric may not be ideal for describing intermittent noise sources, such as traffic noise, where noise events are relatively quiet but frequent.

- *L_{max}* is the RMS (root-mean squared) maximum noise level integrated over a specified time interval and measured during a single noise event or specified time period. The L_{max} characterizes the maximum noise level, defined by the loudest single noise event.

- *1/3 Octave spectrums* are the sound level measurements obtained from a contiguous sequence of 1/3 octave spectral bands (typically ranging from 12.5 Hz to 20 kHz). 1/3 octave band levels can be used to construct noise spectra that show the relative power of different frequencies. 1/3 octave band measures can be used to calculate a number of other metrics, especially if they are collected continuously at short intervals. Measurements of the relative amplitude of the noise at different frequencies is important for calculating the potential of a noise source to mask sound relevant to the species of interest (e.g. Blickley and Patricelli, 2012).

Additional Useful Metrics

- *SEL* (Sound Exposure Level) is the total noise energy experienced during the whole of the noise event as if it had occurred evenly spread over a period of one second (equivalent to a one second L_{eq}). SEL relates to a single noise event and is designed to take account of both duration and loudness.

- *N-Level* (Number of events) is a count of the number of events that exceed that exceeds a maximum decibel level during a specified period of time. This metric may be particularly useful for characterizing intermittent noise sources such as roads.

- *TA* (Time above) is a measure of the percent of time that exceeds an indicated decibel level and may be useful for determining compliance with noise standards.

- *DNL* (Day-Night Average Sound level) is the average sound level measured over a 24-hour period with a 10 dB penalty for noise between 2200 and 0700. DNL is weighted to take into account the increased sensitivity to noise during nighttime hours. This is a noise level metric developed to characterize community noise and is the primary metric used by the FAA to characterize airplane noise.

Metrics to measure during noise monitoring:

Before deployment, the SLM units should be set to collect the following metrics: L_{eq}, L_{max}, L_{10}, L_{50}, L_{90}. High quality SLMs should also be able to collect additional metrics that may prove useful, including DNL, TA, SEL and N-level. If possible, the meter should log unweighted (dBF) 1/3-octave spectra of noise. Sample rates will also need to be set on logging SLMs; this is the interval over which measurements are collected and can vary from a fraction of a second to many hours. The ideal sample rate will depend on the goals of the monitoring project as well as logistical limitations. Ideally, one would collect data at 1-second intervals throughout the measurement period. This detailed time history would show how noise levels change over time in the sampling period and would be very useful in isolating the causes of change in noise levels (songbird singing versus vehicle passing by). However, collecting data every second would fill up the memory of the meter very quickly (the SLM manual will provide guidance in how to calculate how many hours can be recorded given the sample rate, the type of measurements collected and the amount of available memory). If it is difficult to regularly access the meter to download data, then it may be preferable to choose a longer sample interval and forgo some detail in the measurements. Hourly metrics are useful when focusing on a critical time window (e.g. 6 pm to 9 am). Each metric should be collected as A-weighted values (dBA), and if possible, as dBF (i.e. dB-flat or unweighted) and C-weighted (dBC) in each sample interval.

AUTHORS

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Dr. Gail L. Patricelli is an Associate Professor of Evolution and Ecology at the University of California, Davis. Dr. Patricelli studies bioacoustics, breeding behaviors and noise impacts in sage- grouse and songbirds. For the last seven years, Dr. Patricelli has been investigating the impacts of noise from natural gas development activities on greater sage-grouse lek attendance, stress levels and behaviors with graduate student Jessica Blickley and postdoctoral scholars Dr. Diane Blackwood, Dr. Stacie Hooper, and Dr. Alan Krakauer. Dr. Patricelli has published multiple peer-reviewed papers on noise impacts on wildlife and has served on Expert Panels to establish noise measurement protocols for the National Parks Service.

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