The impacts of noise on greater sage-grouse: A discussion of current management strategies in Wyoming with recommendations for further research and interim protections

Prepared for:
The Bureau of Land Management, Lander Field Office and Wyoming State Office, Cheyenne and Wyoming Game and Fish Department

Dr. Gail L. Patricelli, Associate Professor
Jessica L. Blickley, PhD Candidate in Ecology
Dr. Stacie L. Hooper, Postdoctoral Researcher

Department of Evolution and Ecology, University of California, Davis, CA 95616
email: GPatricelli@ucdavis.edu

EXECUTIVE SUMMARY

Recent research has demonstrated that noise from natural gas development negatively impacts sage-grouse abundance, stress levels and behaviors (Blickley et al. 2012; Blickley & Patricelli 2012; Blickley et al. In review). Other types of anthropogenic noise sources (e.g. infrastructure from oil, geothermal, mining and wind development, off-road vehicles, highways and urbanization) are similar to gas-development noise and thus the response by sage-grouse is likely to be similar. These results suggest that effective management of the natural soundscape is critical to the conservation and protection of sage-grouse. The goals of this report are to (I) discuss current approaches in the management of new and existing noise sources within and outside sage-grouse core areas of Wyoming, (II) recommend research priorities for establishing effective noise management strategies, and (III) provide managers and policy makers with recommendations for the interim protection of sage-grouse from known or expected impacts of increased noise levels using the best available science to date.

I. Current Management Strategies in Wyoming

In this report, we detail some concerns with current management strategies for noise. Management objectives for noise are typically established relative to ambient noise levels, stating that noise levels measured at lek edge should not exceed 10 dB over ambient. The choice of ambient value thus has large consequences, setting the upper limit of allowable noise. Outside core areas, 39 dB is typically used as a default measure of ambient; however, this value is much higher than ambient measures from undisturbed habitats. Inside core areas, Wyoming Executive Order 2011-5 stipulates measurement of ambient values at the perimeter of each lek to establish a baseline. While this will typically lead to more realistic ambient values than 39 dB, the complexity of measurement protocols and variable weather conditions make it impractical to accurately measure ambient levels at each lek. Even accurate ambient measures will include noise from existing sources, which may allow more than 10 dB of noise above an undisturbed ambient. In addition, there is little scientific basis for the "10 dB over ambient" threshold. Further research may find this threshold insufficient to protect sage-grouse—or too stringent. Further, these stipulations apply only within the lek perimeter, potentially allowing disturbance to foraging, nesting and brood-rearing habitat. Finally, this stipulation alone allows a great deal of traffic noise, which has a much more detrimental impact on sage-grouse than more continuous noise (Blickley et al. 2012). In response to these concerns, we offer the following recommendations for consideration during revision and implementation of Resource Management Plans.

II. Recommendations for research priorities

We recommend the following research priorities to inform the development of effective management strategies for noise in sage-grouse habitats. (1) We recommend an effort to map baseline pre-development ambient noise levels across the state by combining measurement of existing noise levels by trained personnel with predictive modeling. (2) Once ambient noise values are established, we recommend evaluating whether the current threshold of 10 dB above ambient is appropriate to protect sage-grouse. We recommend that the most feasible way to do so is by using habitat-selection models to analyze changes in sage-grouse population measures relative to variation in noise levels in disturbed areas. This method would also allow assessment of noise impacts outside of the breeding season. (3) Similarly, to establish more effective strategies for managing traffic noise, we recommend that researchers include noise from traffic in habitat-selection models. Doing so would help to establish whether the impacts from traffic noise are better mitigated by setting objectives for noise exposure levels or by restricting the siting and traffic volume of roads directly.

III. Recommendations for interim protections

Since the needed research will take time to complete, we provide managers and policy makers with the following recommendations for interim management strategies using the best available science to date. We emphasize that protections based on these interim recommendations may need to be revised upon completion of ongoing and future research.

1. Experimental evidence indicates that sage-grouse do not habituate to the impacts of noise over time (Blickley et al. 2012), therefore the combined impact of all anthropogenic noise sources should be considered when assessing disturbance to sage-grouse habitat. Therefore, we recommend that interim noise-management objectives should be set relative to typical ambient noise levels in sage-grouse habitat pre-development. Based on the best available measurements in undisturbed areas (discussed in detail in parts I.1. and III.1. of this report), we recommend an ambient value 20-22 dBA. This new default ambient would replace the previous default of 39 dBA or replace empirical measurements of ambient noise at lek edge.

2. We recommend continuing to allow an increase in noise levels of 10 dB above ambient. As discussed above, we do not yet know whether this level is appropriate to protect sage-grouse. However, this threshold is based on the best available science to date and is therefore reasonable when combined with realistic measures of ambient (i.e. 20-22 dBA).

   Establishing a protocol for the measurement of noise levels would facilitate accurate and repeatable assessment of compliance with noise-exposure objectives. We recommend using an A-weighted L_{50} as a measure of median noise exposure. The most relevant measurements would be those collected during times when noise exposure is most likely to affect greater sage-grouse—nights and mornings (i.e. 6 pm – 9 am). Accuracy would be improved by collection of measurements at multiple (3-4) locations between each noise source and the edge of the protected area. Measurements should be taken with a Type-1 sound level meter (ANSI S1.4-1983; or a method with similar accuracy) for ≥1 hour at each site, ideally over multiple days with suitable climactic conditions.

3. Current stipulations for sage-grouse core areas (WY Executive Order 2011-5) limit noise within the perimeter of the lek. However, in this report we review the evidence that noise will also disturb sage-grouse during off-lek activities critical to reproduction. Therefore we recommend that management strategies aim to protect the soundscape in areas critical for mating, foraging, nesting and brood-rearing activities, rather than protecting the lek alone. Thus we recommend that noise exceeding 10 dB over ambient be managed as a "disruptive activity" throughout sage-grouse nesting and brood-rearing habitat (e.g. BLM Instruction Memorandum WY-2012-019).

4. Given the difficulty of measuring intermittent traffic noise, we recommend that interim management strategies focus not on limiting traffic noise levels, but rather on the siting of roads or the limitation of traffic volumes during crucial times of the day (6 pm to 9 am) and/or season (i.e. breeding season). We estimate that noise levels will typically drop to 30 dBA at 1.3 km (0.8 mi) and to 32 dBA at 1.1 km (0.7 mi) from the road (these levels represent 10 dB over ambient using 20 or 22 dBA ambient respectively). Therefore to avoid disruptive activity in areas crucial to mating, nesting and brood-rearing activities, we recommend that roads should be sited (or traffic should be seasonally limited) within 0.7-0.8 miles from the edge of these areas. We emphasize that we are not recommending the siting of roads 0.7-0.8 miles from the edge of the lek perimeter, but rather 0.7-0.8 miles from the edge of crucial lekking, nesting and early brood-rearing areas.

BACKGROUND

Greater sage-grouse (*Centrocercus urophasianus*) populations have declined throughout their range, leading to their designation as a candidate for listing under the Endangered Species Act. Among the factors identified as a threat to sage-grouse is the expansion of energy development across much of the remaining sage-grouse habitat (e.g. Aldridge & Boyce 2007; Doherty et al. 2010; Doherty et al. 2008; Holloran et al. 2010; Holloran 2005; Kaiser 2006; Naugle et al. 2011; Walker et al. 2007). One potential means by which energy development and other human activities might impact sage-grouse populations is through the production of noise (Blickley & Patricelli 2010; Braun 1986; Braun 1998; Connelly et al. 2004; Holloran 2005; Rogers 1964).

Acoustic communication is very important in the reproductive behaviors of sage-grouse, and energy exploration and development activities generate substantial noise; it is therefore important to determine whether noise produced from energy development affects sage-grouse breeding biology. Female sage-grouse use male vocalizations to find leks within the habitat (Gibson 1989), and after their arrival at a lek, females assess male vocalizations (and other aspects of male display) when choosing a mate (Dantzker et al. 1999; Gibson 1996; Gibson & Bradbury 1985; Patricelli & Krakauer 2010; Wiley 1973). Noise from natural gas development is primarily produced by drilling rigs, compressors, generators and traffic on access roads. All of these noise sources are loudest below 2 kHz (Blickley & Patricelli 2012). Male sage-grouse produce acoustic signals between 0.2-2 kHz, so the potential exists for industrial noise to mask sage-grouse communication and thus interfere with the ability of females to find and choose mates (Blickley & Patricelli 2012). For a prey species such as sage-grouse, noise may also increase predation risk by masking the sounds of approaching predators, and/or increase stress levels by increasing the perception of predation risk (Quinn et al. 2006; Rabin et al. 2006). In other vertebrate species, noise has been found to impact individuals directly, for example, by causing startling behaviors, increased heart rate or increased annoyance; all of these factors may interfere with normal foraging, resting and breeding behaviors and contribute to higher stress levels and/or reduced fitness (reviewed in Barber et al. 2009; Kight & Swaddle 2011).

Holloran (2005) found observational evidence suggesting that noise may be at least partly responsible for impacts of natural gas development on sage-grouse populations in the Pinedale Anticline Project Area (PAPA), Wyoming. He found that juvenile males avoid recruitment to leks located near natural-gas drilling sites, even if these leks previously had high male attendance; these effects are more pronounced downwind of the drilling sites where noise levels are higher, indicating that noise may contribute substantially to these declines (Holloran 2005).

To investigate potential impacts from noise on greater sage-grouse lekking activity, we experimentally introduced noise from natural gas drilling rigs and access traffic on roads at eight leks and compared lek attendance to eight paired control leks near Hudson, Wyoming between 2006 and 2008[1]. We found immediate and sustained declines in male attendance on noise leks (29% declines on

[1] We began playback of drilling noise at two leks and traffic noise at two leks in 2006 and began monitoring their paired controls. In 2007 and 2008, we expanded the sample size to include four drilling-noise leks and four traffic-noise leks and their paired controls. Noise was played 24-hours a day beginning in mid-February to early March and continuing through the end of April of each year. Noise was recorded from drilling sites and main haul roads on the PAPA and played back using rock-shaped outdoor speakers placed in a line along one edge of the lek; this created a gradient in noise levels, decreasing with distance from the speakers. On leks with traffic noise playback, recordings of big rig trucks and pickup trucks were combined with 30- and 60-second files of silence at a ratio reflecting the average number of trucks expected to drive on a main energy field access road; these files were then played using the "random shuffle" feature on an MP3 player. On leks with drilling noise, a 14-minute recording of a drilling rig was played on continuous loop. Drilling noise recordings were broadcast on experimental leks at an L_{eq} of 71.4 ± 1.7 dBF (56.1 ± 0.5 dBA) as measured at 16 meters; on traffic noise leks, where the amplitude of the noise varied with the simulated passing of vehicles, noise was broadcast at an L_{max} (maximum RMS amplitude) of 67.6 ± 2.0 dBF (51.7 ± 0.8 dBA). These playback levels approximate the noise level at 0.25 mile (402 m) from a

drilling noise leks and 73% declines on traffic noise leks relative to paired control leks) and evidence of similar declines in female attendance; these results suggest strong noise avoidance in male and possibly female sage-grouse (Blickley et al. 2012). In addition, we found elevated stress hormone levels in fecal samples collected from noise leks compared to control leks, suggesting that even males who do not abandon noisy leks suffer a physiological impact (Blickley et al. In review). Further, our analyses of behaviors on leks with traffic noise playback suggest that males alter the timing of their vocalizations in response to noise—most males wait out noisy periods without strutting (during the sounds of trucks passing), but males who do not wait out the noise, strut at a higher rate (Blickley et al. in prep). These results are consistent with males avoiding the impacts of masking noise on their ability to attract females; other types of disturbance, such as startling or learned aversion to vehicular noise may also contribute to this response. Other types of anthropogenic noise sources (e.g. infrastructure from oil, geothermal, mining and wind development, off-road vehicles, highways and urbanization) are similar to the noise used in this experiment, and thus response by sage-grouse to other noise sources is likely to be similar. These results suggest that effective management of the natural soundscape is critical to the conservation and protection of sage-grouse.

The goals of this report are to (I) discuss current approaches in the management of new and existing noise sources within and outside sage-grouse core areas of Wyoming, (II) recommend research priorities for establishing effective noise management strategies, and (III) provide managers and policy makers with recommendations for the interim protection of sage-grouse from known or expected impacts of increased noise levels using the best available science to date.

I. CURRENT NOISE MANAGEMENT STRATEGIES IN WYOMING

Noise management strategies in greater sage-grouse habitat typically share three common components: (1) the management objective for noise is established relative to ambient levels, (2) noise is limited to 10 dB over these ambient levels, and (3), compliance with this objective is measured at lek edge. In light of the research reviewed above, here we discuss potential issues with these three components of noise management strategies, both in terms of whether they are practical to implement and in terms of their likely efficacy in reducing disturbance to sage-grouse populations. In addition, we discuss special issues related to management of noise from traffic.

1. Ambient noise levels

Management strategies on Wyoming public lands outside of the core areas (and before the core area strategy was implemented) typically allow for noise exposure on leks up to 10 dB over the ambient level; the ambient level is typically defined as 39 dBA[2], which thus sets the limit of exposure at 49 dBA (e.g. BLM 1999; BLM 2003; BLM 2008). However, there is evidence that 39 dBA is not an appropriate estimate of ambient levels in sagebrush habitat. This value originated in a 1971 EPA report; it is a measurement from a single farm in Camarillo, CA, on an afternoon. The farm is described in the report as follows:

> Rural agricultural near tomato field; 50 yards to the trees around the yard and dwelling area; 160 yds to Walnut Ave., a lightly travelled surface road; 0.6 mi to State Hwy 118, a 2-lane moderately travelled highway; 0.6 mi to LeLeror Ave. and 0.75 mi to La Vista Ave, both lightly travelled surface roads; 3.5 mi to Santa Paula Freeway; 3.6 mi to the Ventura Freeway; 4.5 mi to Camarillo. The major intruding

---

typical drilling site. To control for visual disturbance of the speaker system and researcher presence, control leks had dummy speakers placed in the same arrangement and were also visited to simulate the periodic battery changes on noise leks.

[2] All dB values presented here are measures of Sound Pressure Level (SPL) and thus relative to the threshold of human hearing (20µPa).

events were created by jet propeller aircraft flyovers and dogs barking. Other intruding events were background traffic noise. Trucks on distant freeways could be heard distinctly but did not raise the noise level above its residual value. The residual noise level during the evening hours was dominated by crickets. During the day an orchard pruner in the distance controlled the minimum noise level. (EPA 1971)(available here)

Based on this description, it is clear that this farm is very different from undisturbed sage-grouse habitat. This EPA report presented this value as an example of an afternoon noise level in an active rural area; the value was not recommended as a default level for undisturbed landscapes. Further this value is median noise level (L_{50})[3], which in a busy area such as this, will include some noise from the anthropogenic sources listed in the description above, as well as birds, insects, wind gusts, etc. A more appropriate measure is the L_{90}—the level exceeded 90% of the time. The L_{90} is accepted by the American National Standards Institute (ANSI S12.9Part1) as a measure of background or "residual noise level"[4]. Indeed, the same EPA report found residual noise levels of 30-34 dBA on rural farms and 16-22 dBA in wilderness areas—whereas 39 dBA residual values were more typical of residential areas in Los Angeles, Detroit and Boston. Further, this 39 dBA measurement was collected during an afternoon, when noise levels are typically higher[5]. Since calm nights and morning are when sound is most critical for communication in sage-grouse, as well as detection of the sounds of approaching predators, this is the most important window of time for noise measurement. Afternoons in much of the habitat of the sage-grouse are windy, making noise measurements difficult and impeding communication and predator detection by sage-grouse and other wildlife[6].

Reports and noise levels measured in disturbed and undisturbed areas in Wyoming further suggest that 39 dB is inappropriate as an ambient value for most sage-grouse habitat. KC Harvey (2009) recently measured noise exposure on leks on the PAPA and found that most leks—even those with multiple active drilling rigs nearby—had residual (L_{90}) and median (L_{50}) levels much less than the "ambient" of 39 dBA (**Table 1**), demonstrating that this value is unrealistically high. Our measurements of leks in the PAPA and Powder River Basin lead to the same conclusion[7].

---

[3] The L_{50} is the median noise level—the level that was exceeded 50% of the time (see **Figure 1**). 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.

[4] The L_{90} is the residual or background noise level. As with the L_{50}, the L_{90} 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_{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 (see **Figure 1**). 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} or L_{avg}) and peak values (e.g. L_{peak}, 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. Note that 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.

[5] L_{50} measurements at the same Camarillo farm were 32-34 dBA at night and in the early morning; the L_{90} levels at this time were < 30 dBA (US EPA 1971).

[6] This is not to say that daytime noise levels are irrelevant, rather that noise disturbance during this time is less likely to have an impact on breeding, since anthropogenic noise will often be masked by wind noise. Further, since measurements in the afternoon are more difficult and results are more variable, it is less practical to use afternoon measures for ambient or exceedance values. Ideally, however, anthropogenic contributions to noise levels throughout the day would be kept as close to nighttime/morning target levels as possible.

[7] In the Powder River Basin 2007, we measured three leks finding an average L_{eq} of 34.6 dBA, a minimum of 33.4 dBA and a maximum of 36.3 dBA. In the Pinedale Anticline between 2007 and 2009, we measured 14 leks finding an average of 39.1 dBA, a minimum of 31.4 dBA and a maximum of 47.4 dBA. Unfortunately, L_{90} and L_{50} values in dBA were not collected.

Which ambient value would be more appropriate? Based on our review of reports and empirical measurements collected in Wyoming, we estimate that true ambient values pre-development in nights and calm morning in sagebrush habitat are closer to 20-22 dBA (justification for these values is presented in part **III.1.**). If 22 dBA is the true ambient value, then a 49 dBA noise source would exceed ambient by 27 dB—this is a 22-fold increase in the noise level, which would be perceived by humans as at least 6 and a half times louder than ambient; such a sound would dominate the soundscape and cause significant disruption[8].

Indeed, results from our experiments indicate that 49 dBA is too loud to avoid significant impacts on sage-grouse. Our noise-playback leks (described above, Blickley et al. 2012) experienced levels that were in compliance these recommendations, i.e. less than 49 dBA across most of the lek area, except the area within ~20 meters of the speakers. Yet we found large declines in attendance, increases in stress levels and altered display behaviors across the lek (Blickley et al. in review, in prep). Therefore, the available scientific evidence shows that 39 dBA is inappropriate for use as a default ambient value for sage-grouse habitat, and suggests that allowing 49 dBA of noise exposure on leks and other sensitive areas will cause significant disturbance to greater sage-grouse populations.

In 2010, stipulations for sage-grouse core areas in Wyoming were created by Executive Order 2010-4. These stipulations used measured ambient values, rather than using 39 dBA as a default ambient value. A more recent executive order affirms this approach, stating:

> New noise levels, at the perimeter of a lek, should not exceed 10 dBA above ambient noise (existing activity included) from 6:00 p.m. to 8:00 am during the initiation of breeding (March 1 May 15). Ambient noise levels should be determined by measurements taken at the perimeter of a lek at sunrise. (Wyoming Executive Order 2011-5).

Since measured ambient noise levels are likely to be less than 39 dBA in most places, the core area stipulations will typically limit noise to levels lower than 49 dBA and thus offer greater protection for sage-grouse. But since existing activity is explicitly included in measurements of ambient noise, there may be some areas where the core stipulations allow more than 49 dBA, when existing sources lead to ambient measures greater than 39 dBA. Further, each new development may add 10 dB to existing noise levels, potentially causing an incremental increase in noise over time. Such increasing noise would likely cause increasing impacts, since sage-grouse do not appear to habituate to anthropogenic noise over time. The declines we observed on our noise playback leks were immediate and sustained throughout the three-year experiment (Blickley et al. 2012) and elevated stress hormones were observed through the second and third years of the experiment (Blickley et al. In review), indicating that sage-grouse do not adapt to increased noise levels over time. Therefore, the combined impact of all anthropogenic noise sources should be considered when assessing disturbance to sage-grouse habitat. To do so, management objectives would be set relative to the undisturbed soundscape, capping the total noise exposure at or near 10 dB above a "pre-development" ambient value[9].

---

[8] For reference, it is helpful to remember a rule of thumb from physics: every 6 dB increase in noise levels is a doubling in amplitude (measured as changes in air pressure). One often hears the rule of thumb that a 10 dB increase in noise is subjectively *perceived* by humans as a doubling in loudness. However, this perception depends on the frequencies (i.e. pitch) of the sounds and can vary with amplitude. Indeed, in humans a 6 dBA increase in noise level leads to an approximate doubling in the number of noise complaints (ANSI S12.9/Part 4 Table F.1), suggesting that humans are more sensitive than this 10 dB rule of thumb implies. Since we do not know if sage-grouse or other non-human animals perceive sounds similarly to humans, the non-subjective "6 dB doubling" rule of thumb is preferable. An online calculator to determine how decibel values relate to loudness ratios can be found here. OSHA examples of noise levels of common sources can be found here.

[9] Such a cap would not preclude further development at sites which already have sources that exceed ambient by nearly 10 dB. This is due to the complex way that multiple sound sources combine to determine overall noise levels (see formulas and explanation here). A new source would need to be 9 dB less than the existing source at the measurement site (edge of the protected area) to add only 0.5 dB to the total noise exposure. A new source 6 dB quieter than the existing source would lead to a 1 dB increase in total noise level.

In addition, collecting measurements of ambient noise levels in quiet areas is extremely challenging and requires expensive, specialized equipment; this makes the requirement to collect ambient values at each lek difficult to implement. Unfortunately, non-ideal weather (especially wind, even at low levels) and almost all errors by the person deploying the noise meter (e.g. poor placement of the meter for long-term deployment, rustling from clothing, crunching leaves underfoot and even breathing close to the meter when handheld) will inflate ambient measures. Even professional measurements on Type-1 sound level meters will typically overestimate ambient levels in quiet areas (<27 dBA). This is because A-weighting[10] boosts the amplitudes of the mid-frequencies, which in very quiet areas includes noise from the pre-amplifier on the sound-level meter[11]. All of these sources of measurement inaccuracy will inflate ambient values and therefore allow more noise exposure at leks.

In summary, establishing an appropriate ambient value for sage-grouse habitat is a complex task. Further research is needed to establish pre-development ambient noise values, and in the interim, using a realistic estimate of pre-development ambient would offer more protection to sage-grouse than either an unrealistic default value (39 dBA) or ambient values measured at lek edge.

2. The 10 dB threshold

Once an ambient noise value (or values) is established, most current noise management strategies limit new noise levels to 10 dB above this ambient value. This 10 dB threshold is used commonly inside and outside of Wyoming core areas and in other states; however, we do not yet know whether this threshold is sufficient to protect greater sage-grouse. This threshold is based on only a handful of studies on songbirds (Wyoming Bird Conservation Plan, 2003; Dooling & Popper 2007), and there is no scientific basis for assuming that sage-grouse will respond to noise in a manner similar to songbirds. In fact, their low-frequency vocalizations might make them more vulnerable to masking by anthropogenic noise than many songbirds (Blickley & Patricelli 2012). Recent studies of songbirds have found that species with larger body size and lower-frequency vocalizations are more prone to population declines in response to noise (Francis et al. 2009; Hu & Cardoso 2009).

Furthermore, 10 dB is a significant increase in the amount of noise. For an animal vocalizing to communicate with potential mates or offspring, a 10 dB increase in noise levels corresponds to up to a tenfold decrease in the active space of the vocalization—the "listening area" over which it can be detected by receivers (Barber et al. 2009; Brenowitz 1982)[12]. This same increase in noise will lead to

---

[10] 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).

[11] Most Type-1 (ANSI S1.4-1983) precision sound level meters (SLM) have a "noise floor" of ~17 dB, meaning that they cannot measure quieter sounds, 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, as discussed in the text. This is not a problem when measuring louder sounds (i.e. many noise sources associated with development) which overwhelm any contribution of the noise from the SLM (as well as noise from a slight breeze or other incidental sounds). Measurements of quiet sounds are thus particularly challenging. 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.

[12] Barber et al. (2009) offered simple formulas for estimating the reduction in detection distance and listening area resulting from an increase in background noise. The formula for calculating how the detection distance changes with an increase in noise is: detection distance=$10^{(-\text{ (dB change in noise)}/20)}$. This shows a halving of detection distance for each 6 dB increase in noise, therefore a more than three-fold decrease (69% decrease) in detection distance with a 10 dB increase in noise and a tenfold reduction in detection distance (90% decrease) with a 20 dB increase in noise. When one is concerned with the total area over which a sound can be detected, rather than the distance between the sound source and receiver, then the appropriate measure is listening area. The area of a circle (i.e. listening area

up to a three-fold decrease in the detection distance between two receivers (Barber et al. 2009)[12]—meaning that receiver must be three times closer to hear a vocalization in noise than in quiet conditions, and perhaps more critically, a predator would be able to approach three times closer in noise before it was detected by a sage-grouse. Indeed, the night-time capture of sage-grouse by spotlighting is greatly improved by a noise source to mask the sound of footsteps from approaching biologists (Connelly et al. 2003); predators likely gain a similar advantage in noise. Masking of vocalizations and the sounds of predator approach is only one source of impacts from noise—animals may also suffer from behavioral disruptions, elevated hearth rate, interrupted rest and increased stress levels (reviewed in Barber et al. 2009; Kight & Swaddle 2011). These impacts may have significant consequences; a recent study in humans found a 12% increase in the risk of a heart attack with every 10 dB increase in exposure to chronic traffic noise (Sørensen et al. 2012). Many of these behavioral and physiological impacts may occur at or below the 10 dB threshold. Alternatively, further study may reveal that the 10 dB threshold is sufficient or even too conservative. Therefore, research is needed to determine whether the 10 dB threshold is appropriate for sage-grouse.

3. Where measurements are collected

Inside and outside of the core areas, current management strategies that limit noise to 10 dB over ambient levels typically specify that measurements should be collected at lek edge to assess compliance (e.g. WY Executive Order 2011-5; BLM 1999, 2003, 2008). This introduces two potential problems, which are discussed in turn below.

First, the presence of sage-grouse on the lek will influence sound level measurements. On the edge of a lek with many birds vocalizing, one could find "ambient" noise measures of 50-60 dBA L_{eq}[13], which would thus allow up to 60-70 dBA of anthropogenic noise. Even after an ambient value is established, determining whether a development complies with stipulated noise levels would require measuring noise exposure again at lek edge. One can imagine a scenario where increasing development noise causes declines in lek attendance, which causes noise level 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. There are methods available to reduce this problem, such as using appropriate noise metrics (such as L_{50} and L_{90}; see part **I.1.**) and collecting measurements before birds arrive on the lek or after birds are flushed. But this issue makes the current stipulations more difficult, disruptive and ambiguous to implement.

Second, and much more importantly, if noise levels drop down to stipulated levels at the edge of the lek, then much of the area surrounding the lek will be exposed to higher noise levels (see **Figures 3** & **4**). This management strategy therefore protects only a fraction of sage-grouse activities during the breeding season—mate assessment and copulation on the lek—leaving unprotected other critical activities in areas around the lek, such as foraging, roosting, nesting and brood rearing. Our experimental design allowed us to examine only impacts of noise on the lek, since creating noise over a larger area would require noise sources much larger than battery-powered speakers (i.e. actual industrial infrastructure). Thus we cannot provide direct evidence that off-lek noise will impact sage-grouse populations. However, there is indirect evidence of such impacts.

---

around the vocalizing animal) decreases with the square of the radius (i.e. detection distance between the vocalizing animal and the receiver), so here the formula is: listening area = $10^{(-(\text{dB change in noise})/10)}$. This leads to a halving of listening area with every 3 dB increase in noise and tenfold reduction with every 10 dB. These decreases in active space and detection distance are less extreme when environmental attenuation of noise is considered, but are nonetheless very large (Blickley and Patricelli 2012).

[13] L_{eq} (also called L_{avg}) is the equivalent noise level (see Figure 1). This can be thought of as the average noise level across the sample period; more precisely, it is the level of a constant sound over a specific time period that has the same sound energy as the actual (variable) sound.

Evidence suggests that male display and copulation activities on the lek may be affected by noise occurring around the lek area, even if the lek area itself meets management objectives for noise. In order to sustain their costly display behaviors, males must forage off lek, potentially exposing them to higher noise disturbance levels (**Figures 3** & **4**). Vehrencamp et al. (1989) found that males on the lek who are in good condition and are successful in mating forage further from the lek during the day, compared to unsuccessful, poor-condition males (range 200-750 meters, or 0.12-0.46 miles, off lek). Other studies have found males travelling an average of 0.6 miles (max 1.5 miles) to forage off lek (e.g. Schoenberg 1982; Wallestad & Schladweiler 1974). If foraging in noisy areas increases male stress levels or predation risk, or decreases foraging efficiency (as has been found in other vertebrate species; Quinn et al. 2006; Rabin et al. 2006), then these noise impacts may affect subsequent male display behaviors on the lek. More importantly, there is evidence that females and juvenile males use the sounds created by males on the lek to locate leks in the landscape (Gibson 1989). Blickley and Patricelli (2012) found that industrial noise masks these sounds, which will make it more difficult for females and juvenile males in noisy areas surrounding a lek to find the lek itself. Reduced female visitation would decrease copulation activities on the lek, and reduced juvenile male recruitment would lead to male attendance declines over time. For these reasons, the protection of lekking activities may require protection of more than just the lek surface alone.

Additionally, other critical components of successful breeding occur off lek, potentially in areas with higher noise levels **(Figures 3** & **4**). Since 64% of females nest within a 5 km (3.1 mile) radius of the lek and 74-80% of females nest within a 6.4 km (4 mile) radius of the lek (Holloran & Anderson 2005; Moynahan 2004), many of these nesting females will experience noise levels exceeding management objectives for the lek. Most vocalizations used between hens and chicks are much quieter than sounds produced by males on leks (Schroeder et al. 1999), and therefore much more prone to masking (Blickley & Patricelli 2012). Additionally, predation rates can be high for chicks and females on nests in disturbed habitats (Hagen 2011), and females likely rely mainly on acoustic rather than visual cues to predator approach at night. Thus when noise masks the sounds of predator approach, females and chicks may be more at risk in noisy areas than males on the lek. Further, breeding females may suffer detrimental health impacts from elevated stress, at a time when stress levels are already elevated (Jankowski 2007). While we do not have direct evidence for an impact of noise on these off-lek activities, there is evidence that proximity to roads and infrastructure (which raises noise levels) affects nest placement, nest initiation rates, chick survival and brood-rearing activities (Aldridge & Boyce 2007; Holloran et al. 2010; Holloran & Anderson 2005; Lyon & Anderson 2003).

Other types of disruptive activities in sage-grouse habitat are managed throughout areas critical for lekking, nesting and early brood rearing (e.g. BLM Instruction Memorandum WY-2012-019; Wyoming Executive Order 2011-5); there is no scientific basis for focusing the monitoring and management of noise on the lek area alone, without including these other critical areas.

4. Traffic Noise

There is evidence that noise from traffic is has a significant impact on sage-grouse. Blickley et al. (2012) found 73% decline in male attendance on traffic-noise leks compared to their paired controls, more than twice the decline observed on drilling-noise leks (29%). Traffic noise was also found to cause an increase in stress hormone levels (Blickley et al. In review) and a disruption of strutting patterns on the lek (Blickley et al. in prep). Further evidence comes from other studies not focused on noise alone. Lyon and Anderson (2003) found that even light vehicular traffic (1–12 vehicles per day) substantially reduced nest initiation rates and increased the distance of nests from lek sites. Holloran (2005) found that traffic on roads within 0.8 miles of the lek during the early morning while males are strutting is related to declines in male attendance. These results suggest that effective management strategies should include efforts to minimize traffic near areas critical for sage-grouse reproduction.

However, management strategies that allow up to 10 dB of noise above ambient are not sufficient to protect sage-grouse from the impacts of traffic noise. Since traffic noise in sage-grouse habitat is typically intermittent and interspersed with periods of quiet, a great deal of traffic would be needed to raise overall noise levels by 10 dBA. In general, a tenfold increase in traffic is associated with a 10 dB increase in average noise levels, so an increase from 2 to 20 vehicles or from 200 to 2,000 vehicles over a given time interval. A tenfold 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. This suggests that approaches for the management of more continuous noise sources, such as noise from compressors stations, drilling rigs and other permanent or temporary infrastructure, may not be suitable for the management of traffic noise.

II. RECOMMENDATIONS FOR RESEARCH PRIORITIES

While our understanding of noise impacts on sage-grouse has improved over the last few years, there is still much to learn. Below, we outline recommendations for research that would help to develop more effective management strategies for anthropogenic noise.

1. Establishing ambient values

As discussed in part **I.1.**, management objectives for noise are typically established relative to ambient noise levels, stating that noise measured at lek edge should not exceed 10 dB over ambient. The choice of ambient value thus has large consequences, setting the upper limit of allowable noise. In order for such management strategies to protect vulnerable species, it is therefore critical to establish accurate ambient values.

Due to the previously discussed difficulty of measuring ambient values at quiet locations, we suggest that it is not feasible or practical to establish baseline noise levels by having agency personnel or consultants with little specialized training measure ambient at each lek prior to development. Further, experimental evidence indicates that ambient values should represent the pre-development ambient levels, such that new developments do not further impact already impacted soundscapes (see part **I.1.**). One approach to establish ambient noise levels is to commission the measurement of ambient levels by professionals with experience in environmental acoustics. Such professionals would need to measure ambient values for each site prior to development (or if there are already noise sources in an area, they could choose a similar but undisturbed area to estimate natural ambient levels). Alternatively these professionals could sample noise levels at representative undisturbed areas across the state, using such measurements to establish ambient values by region or habitat type. Measurements should be collected using a Type-1 precision sound level meter (ANSI S1.4-1983)[11] enclosed in environmental housing for long-term deployment at each site[14]. Alternative methods, such as carefully calibrated audio recording units that can be used to calculate appropriate metrics[14] would also be appropriate (Lynch et al. 2011; Patricelli et al. 2007).

[14] The meter should log A-weighted 1/3-octave spectra of noise at 1-sec intervals. The following metrics (at a minimum) should be collected: Leq, Lmax, Lpeak, L_{10}, L_{50}, L_{90} (see Figure 1). Each metric should be collected as A-weighted values, and if possible, as dBF (i.e. dB-flat or unweighted) and C-weighted. With a logging SLM, one can save the time history, showing how noise levels change over time in the sampling period. This can be very useful in isolating the causes of change in noise levels. One can also calculate each metric hourly or over the entire sampling period. Hourly metrics are useful when focusing on a critical time window (e.g. 6pm to 9 am). The meter (or a nearby station) should also log wind speed, so that measurements can be excluded when wind likely to contributed to noise levels.

We recommend that a better approach would be to combine such empirical sampling of noise levels with modeling, to create a map of natural ambient noise across the state. This would lead to broader coverage of the state, since collecting empirical measurements at each key site would be time consuming and interpolating levels between these sites would be inaccurate without a model. 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. 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. Output from such a model would be available to any parties interested in evaluating the natural noise levels at a current or proposed development site in the state. These measurements are not grouse specific, thus this data would be useful for multiple public and private agencies interested in tracking noise exposure.

2. Determining an appropriate threshold

Once an ambient value is determined, we must then determine whether the current threshold of 10 dB above ambient is sufficient to protect sage grouse. The ideal method to determine the appropriate threshold would be a dose-response experiment, where noise is played back at different levels to different leks, to determine the maximum noise level before an impact occurs. However, such an experiment is logistically infeasible for multiple reasons, including the necessity to impact a very large sample of leks (multiple leks at each playback level, with many playback levels) and large expense. A more feasible way to determine the threshold level at which sage-grouse are impacted by noise is by analyzing nesting success, lek attendance and other population variables relative to existing variation in noise levels in a spatially-explicit manner using habitat-selection modeling. This method examines the impact of "natural" variation in noise exposure across a disturbed landscape, while statistically controlling for other possible contributors, and allows estimation of the slope of the relationship between noise and measures of population change. This relationship can then be used to determine the threshold level at which a minimal (or acceptable) level of impact on sage-grouse occurs. We are currently collaborating with Dr. Matt Holloran to develop noise layers for use in habitat-selection models of the Pinedale Anticline during development (beginning in 1998). We encourage researchers to consider including noise layers in habitat-selection models for other regions. Such an approach would also be useful for examining noise impacts outside of the breeding season, especially in winter, where changes in habitat quality and availability can lead to significant impacts on population health (Beck 1977; Doherty et al. 2008; Swenson et al. 1987).

3. Measuring traffic noise

Evidence shows that traffic noise causes impacts on sage-grouse, as discussed in part **I.4.**; however, limiting traffic noise by setting noise-exposure objectives will be difficult. This is because 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 in setting management objectives. 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. Given that Lyon and Anderson (2003) found that nesting activities can be disturbed by only 1-12 vehicles per day, the chosen metric would need to be sensitive to infrequent sounds. 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 (see part **I.4.**). 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}, a measure of the maximum RMS amplitude during the sample period; see **Figure 1**) 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 may be useful for these exclusions. A protocol could be developed to do this, but different methods would need to be tested. Even with such a protocol in place, L_{max} values may be more informative when combined with a measure of exposure, such as L_{eq} or axle counts.

To establish more effective management strategies for traffic noise, more information is needed about which noise metrics best predict traffic impacts on sage-grouse. Such information could be gathered by including traffic noise in habitat-selection models. This approach will allow estimation of the relationships between demographic variables (e.g. lek attendance, nest location, nest success) and traffic variables (distance, traffic level and noise level). This would help to establish whether the impacts from traffic noise are better mitigated through setting noise objectives or by managing the siting and traffic levels of roads directly. If informative metrics are identified for measurement of traffic noise, then protocols should be established for accurate and repeatable measurements in the field, given the challenges discussed. The noise layers we are currently developing for the Pinedale Anticline area will include traffic noise and allow us to begin addressing this issue. We encourage researchers to consider including traffic-noise layers in habitat-selection models for other regions.

III. RECOMMENDATIONS FOR INTERIM PROTECTIONS

The research described above, however, will take time. Below, we provide managers and policy makers with recommendations for the interim protection of sage-grouse from known or expected impacts of increased noise levels using the best available science to date. We emphasize that protections based on these interim recommendations may need to be revised upon completion of ongoing and future research.

1. Setting an ambient value

Based on our review of reports and empirical measurements collected in Wyoming, we have concluded that true ambient values pre-development in nights and calm morning in sagebrush habitat are likely to be 16-22 dBA. The first source for this conclusion is the 1971 EPA report from which the original 39 dBA ambient value was drawn (US EPA 1971). This report finds residual noise levels (L_{90})[4] in wilderness areas of 16-22 dBA[15], measured during day and nighttime at a campsite on the north rim of the Grand Canyon National Park; the report concludes that “these increases in (residual) noise level, from wilderness to farm and to city, are the result of man’s activities and his use of machines”. Lynch et al. (2011) more recently measured noise exposure at 189 sites in 43 U.S. National Parks, finding an average 24-hour residual noise level of 21.6 dBA[16].

[15] 16 dBA was the daytime residual level (7am to 7pm) and ~22 dBA was the night time residual level (10pm-7am). In most places, nighttime residual levels will be lower than daytime due to environmental conditions (temperature, humidity, breeze, etc.) However, these values are reversed due to crickets which were active early in the night. Evening readings of ~28 dBA (7pm to 10 pm) were dominated by crickets and are not included here since insect noise is minimal during the sage-grouse breeding season due to low temperatures.

[16] These measures include only the 1/3 octave bands from 12.5 Hz to 800 Hz, so they are not directly comparable to the full-spectrum measures from other sources given in the text (these narrower-spectrum measures will be lower than the full-spectrum measures). However, these frequencies span most anthropogenic noise and residual noise in undisturbed areas, so this measure provides an appropriate estimate of ambient noise levels at these sites (Lynch et al. 2011).

In addition, we have analyzed the detailed data from long-term deployment of a sound level meter by KC Harvey consulting on the Pinedale Anticline Project Area (KC Harvey 2009)[17]. The median L_{90} among these 12 leks was 27.2 dBA and the minimum lek was 22.2 dBA (**Table 1**, **Figure 2**). Given that all of these leks experienced some noise from natural gas infrastructure and highways (and that this Type-2 sound level meter[11] had a noise floor of 20-22 dBA), these are conservative (i.e. slightly high) estimates of pre-development ambient. Other recent measurements in areas with low levels of disturbance have found similar residual levels[18].

Since 16 dBA is at or below the limit of measurement on most Type-1 sound level meters[11], it would be a difficult to implement protections based on this ambient value without an immediate shift in methods for measurement and/or data-processing. Further, it is clear that residual ambient values even in undisturbed areas are sometimes higher. Therefore, we recommend that an ambient value of 20-22 dBA should be used for interim protections in sage-grouse habitat. In revised management strategies, this new default ambient would replace the previous default of 39 dBA or replace empirical measurements of ambient at lek edge.

2. Setting a threshold above ambient

As discussed in part **I.2.**, we do not yet know whether limiting noise to 10 dB above ambient is appropriate for protecting sage-grouse. However, we recommend continuing to use the 10 dB threshold as an interim measure, combined with appropriate measures of ambient (i.e. 20-22 dBA). This threshold value is based on the best available science to date, but should be revised as needed when better information becomes available. Using 20 dBA as the ambient value, this would allow up to 30 dBA of noise exposure; using 22 dBA as ambient, this would allow up to 32 dBA of noise exposure.

How should compliance with this management objective be measured? Noise can be variable over time, space and frequency spectrum, so no single metric can capture this complexity. However, using multiple metrics to assess compliance may be complicated to implement, at least in the interim. Therefore, we recommend using the A-weighted L_{50} as a measure of median noise exposure[3]. This metric is useful because it is less influenced by the brief intruding sounds (e.g. birds, insects and airplanes) that can dominate other metrics. This metric may also exclude some types of noise produced by the development being monitored, including vehicles (unless traffic is very heavy). For that reason, it will typically not be effective at reflecting impact caused by traffic noise. Despite this concern, the L_{50} is recommended because otherwise birds, insects and other indicators of a healthy habitat may be counted against compliance (unless audio recordings are produced, allowing monitors to exclude time periods with such activity; this may be a preferable solution in the long run, but it will require time to develop such a protocol).

We recommend that measurements are made during times when noise exposure is most likely to affect greater sage-grouse: nights and mornings (i.e. 6 pm – 9 am). Further, we recommend using the average of L_{50} values at multiple (3-4) locations between each noise source and the edge of the protected area. Since noise values can change with topography and local ground cover, this will reduce the impact of aberrant measurements (high or low) at particular locations. Measurements should be

[17] Available here.

[18] A recent EIS (DOE EA-1849) for a geothermal development in sage-grouse habitat near Elko, NV, found an ambient noise level of 25 dBA (measured from 12-5am on 6/17/11). This area is described as follows: “Existing noise at the power plant site is dominated by ambient sources including wind, ranch vehicles, livestock, irregular mineral exploration, and recreational uses such as all-terrain vehicles, on BLM land to the west of the site”. We also collected brief ambient noise values with a handheld Type-1 noise meter on Preacher Lek near Hudson, WY. This lek is on relatively-undisturbed federal land, but noise from nearby Highway 789 was clearly audible when readings were being collected. Six males were present on the lek, but ambient measures were collected when birds were not vocalizing. The L_{90} for these measurements was 25.4 dBA. These two measures are slightly higher than the 22 dB given as the upper end of the range of pre-development ambient values, which is appropriate since both sites have anthropogenic noise sources nearby.

taken with a Type-1 sound level meter[11] (or a method with similar accuracy and a noise floor <25 dBA). We recommend making measurements of at least 1 hour at each site, ideally over multiple days and climactic conditions, since weather (temperature [especially temperature inversions], humidity and wind) can affect noise levels. We recommend collecting additional metrics whenever possible, for research and long-term monitoring[14].

It should be noted that based on the measurements presented in **Table 1**, four of the 12 monitored leks on the Pinedale Anticline are in compliance with the noise management objectives recommended here based on a 20 dBA ambient value (i.e. they do not exceed an L_{50} of 30 dBA). Two of the other leks are within 0.5 dB of compliance with recommended objectives based on an ambient of 22 dBA. Given that these leks are in a heavily developed area, which has experienced declines in sage-grouse populations (Holloran et al. 2010; Holloran 2005), this suggests (1) that these recommended protections are not as onerous as they may initially seem, even using an ambient value of 20 dBA, and (2) that even these stricter recommendations may not suffice to avoid population declines if noise levels are measured at lek edge (as in Table 1), rather than across nesting and brood-rearing habitats, as discussed below.

3. Redefining the protected area

Current noise management strategies typically recommend noise measurements at the edge of the lek to assess compliance (e.g. WY Executive Order 2011-5; BLM 1999, 2003, 2008). This approach manages noise levels the lek area itself, and not the surrounding habitat critical to support lekking activities and successful reproduction. In part **I.3.**, we review the evidence that this off-lek noise will affect on-lek activities and successful reproduction. Therefore we recommend that interim and longer-term management strategies aim to protect the soundscape in areas critical for mating, foraging, nesting and brood-rearing activities. Thus we recommend that noise exceeding 10 dB over ambient be managed as a "disruptive activity" throughout sage-grouse nesting and brood-rearing habitat (e.g. BLM Instruction Memorandum WY-2012-019). To accomplish this, we recommend measuring compliance with noise objectives at the edge of nesting/brood-rearing habitats, rather than at the ledge of the lek.

4. Limiting traffic noise

Given the difficulty of measuring intermittent traffic noise and the uncertainty about which metrics are informative (see part **II.3.**), we recommend that interim protections focus not on setting objectives for traffic noise levels, but rather on the siting of roads or the limitation of traffic during critical times of the day (6pm to 9 am) and/or year (breeding season).

To develop interim recommendations for the siting of roads, we estimated the distance from a road at which noise levels (L_{max} as a single vehicle passes) will drop down to 10 dB over ambient. Using an ambient of 20 dBA, we calculate that vehicle noise will diminish to 30 dB at ~1.3 km (0.8 miles) from the road. Using an ambient of 22 dB, we calculate that vehicle noise will diminish to 32 dBA at ~1.1 km (0.7 miles) from the road[19]. Therefore to avoid disruptive activity in areas crucial to

[19] To calculate this estimate of impact distances from roads, we used 2006 measurements of noise levels from 17 vehicles (flatbed trucks and big rigs) on the Luman Road and 8 vehicles on the North Jonah Road on the Jonah Field in Sublette County, WY. All measurements were made at ¼ mile from the road. A-weighted L_{max} values were averaged for each road and the average of the two roads was 45.47 dBA (S.E. = 1.3 dBA; range 37 - 58.7 dBA); we similarly calculated average A-weighted levels for each octave from 16-16,000 Hz. In each octave band, we calculated propagation using the assumption of spherical spreading (see formula here) and octave-specific excess attenuation values from the Pinedale Anticline Noise Analysis report prepared by the BLM with assistance from the Army Corps of Engineers and US Forest Service (BLM, 1999). Using these methods, we extrapolated noise propagation beyond our ¼-mile levels until levels reached 32, 30, 22 and 20 dBA; the distances at which those levels were reached are presented above. These estimates are based on the maximum noise levels as a single vehicle passes, however, on roads with sufficient traffic to create a steady stream of vehicles, noise

mating, nesting and brood-rearing activities, we recommend that managers consider siting roads (or seasonally limiting traffic) within 0.7-0.8 miles from the edge of these areas. We emphasize that we are recommending restrictions within 0.7-0.8 miles of the edge of sage-grouse nesting and brood-rearing habitat (e.g. BLM Instruction Memorandum WY-2012-019), not the lek edge. Further, note that noise from traffic will be audible at least until levels drop down to ambient values, which will occur 1.5-1.7 miles from the road[19]. These distances may be much farther during temperature inversions, which are common during the lekking hours in sage-grouse habitat (for an ambient of 20 dB and 22 dB respectively, traffic noise in a temperature inversion would reach 10 dB over ambient at 1.1 and 1.4 miles from the road, and this noise would reach ambient at 2.8 and 3.3 miles from the road). Therefore, adopting these recommendations will not eliminate traffic noise in critical areas, but should reduce its impact.

Given that traffic noise was found to have more than twice the impact of continuous noise on lek attendance (Blickley et al. 2012), minimizing traffic noise as a disruptive activity in all areas critical for successful reproduction should be a priority in any revised noise management strategy. In areas where implementing recommended limits on siting or traffic is not possible, other measures may reduce traffic noise impacts. One possibility would be to adjust timing of the shift change in development areas to avoid causing an increase in traffic during critical times. Avoiding shift changes between 6 pm and 9 am would be ideal, but if this is not possible, then avoiding 12 am to 9 am would likely be a significant improvement.

---

drops off more slowly and these distances would be up to *twice as far* (levels would follow predictions of cylindrical spreading, dropping only 3 dB with every doubling of distance, rather than 6 dB, as assumed here). Similarly, noise levels drop off according to predictions of cylindrical spreading during temperature inversions, which are common in sage-grouse habitat during the early morning. For these reasons, the distances presented above may be conservative estimates (i.e. underestimates) of the distance that sound will propagate from a road. The same calculations were used to estimate propagation distances around a hypothetical noise source in Figure 3 and a drilling rig in Figure 4. For Fig 4, we used an example drilling rig measured in the PAPA in 2006 at an L_{eq} of 66.7 dBA at 216 feet. This drilling rig measurement is from a single example rig and is not meant to be representative of all drilling rigs. The hypothetical source in Fig 3 uses the same octave spectrum as the drilling rig, which is typical of industrial noise sources, but is scaled to an overall dBA level of 65 dBA at 1000 feet.

AUTHORS

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.

Jessica Blickley is a graduate student completing her Ph.D. in Ecology in the Patricelli Lab at the University of California, Davis. Ms. Blickley has been studying noise impacts on sage-grouse for 6 years. Ms. Blickley 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. She recently co-edited an Ornithological Monograph on the impacts of anthropogenic noise on birds and bird studies (available here).

Dr. Stacie Hooper is a postdoctoral researcher in the Patricelli Lab in the Department of Evolution and Ecology at the University of California, Davis. Dr. Hooper has published multiple peer-reviewed papers on noise impacts on wildlife; her dissertation research addressed noise impacts on ground squirrels in Yosemite National Park. Dr. Hooper also works for the California Department of Fish and Game as the California Wildlife Habitat Relationships (CWHR) program coordinator, maintaining and updating species range data and habitat suitability models to predict species occurrence across the state. She is also part of the California contingent of the Western Governor's Association's Crucial Habitat Assessment Tool (CHAT) team.

Figure 1. Some common metrics used to measure noise levels. The gray line represents the noise level (RMS amplitude over a short sample period, typically one second) as it changes over time through the sampling period (the time history).

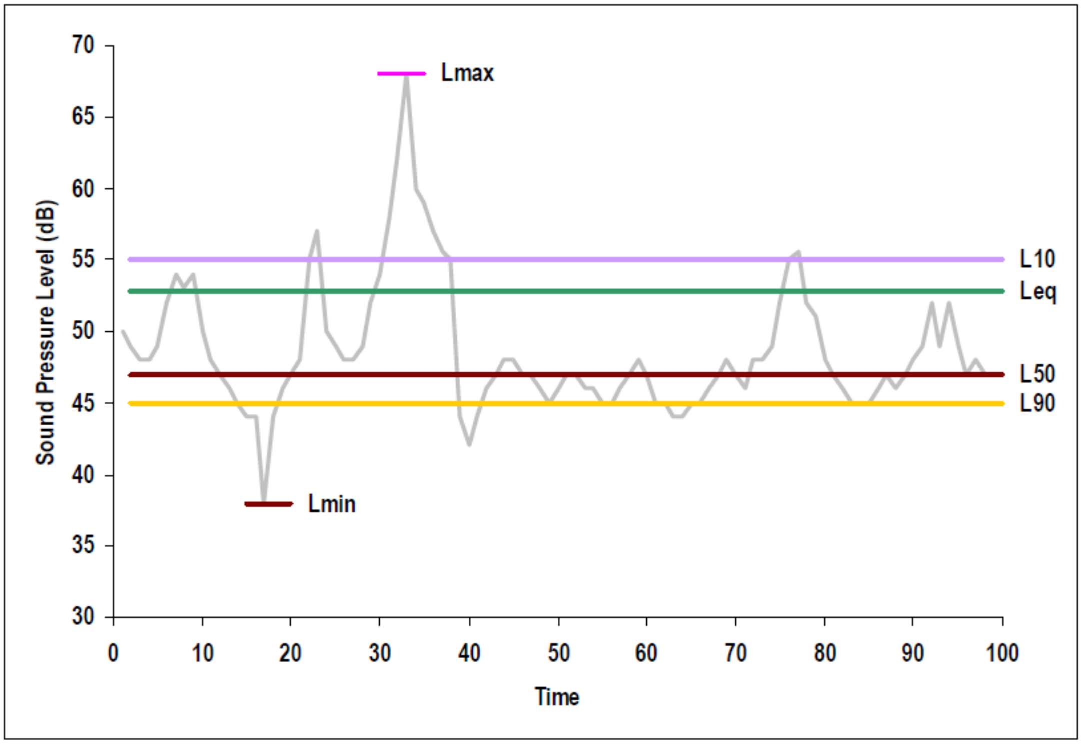


Table 1. Spring 2009 noise levels on leks in the Pinedale Anticline Project Area. Data were collected by KC Harvey Consultants (KC Harvey 2009) from multi-day deployments of four Type-2 sound level meters (Quest - SoundPRO-DL-2-1/3-10; noise floor 20-22 dB). All measures are presented in dBA. Weather data are not available and windy periods were not excluded, so these values likely include substantial energy from wind. All leks are close enough to development sites, access roads and/or highways to experience anthropogenic noise (see Figure 2); it is not clear from the report whether noise levels may also reflect sounds from males displaying on the leks (displaying males on these relatively-small leks are unlikely to significantly impact L_{50} or L_{90} measures, but may affect other metrics). Measurements are from the full 24 hrs/day, so they are not focused on the night and morning periods likely critical to greater sage-grouse (6 pm to 9 am).

Lek Name	Dates	Duration (hrs)	L_{90}	L_{50}	L_{10}	L_{avg} (L_{eq})	L_{max}	L_{min}	L_{peak}
Alkali Draw	April 2 & 6	121	23.6	28.8	41.2	44.1	92.6	19.6	114.0
Big Fred	April 12, 16 & May 12	123	27.6	33.9	44.0	42.4	80.2	22.0	100.5
Bloom Reservoir	April 22 & 27	120	22.2	29.2	44.7	41.9	83.9	19.4	103.4
Cat	May 2 & 7	120.3	22.8	28.1	44.1	44.3	86.9	19.6	106.0
Little Fred	April 12, 16 & May 7	85.5	32.7	36.7	45.5	44.2	80.8	31.8	101.9
Lovatt West	April 22, 23 & May 12	127	30.4	33.7	48.3	47.4	84.5	28.2	106.8
Lower Sand Springs Draw	May 7	111.3	25.9	29.8	41.5	39.7	73.4	23.6	88.6
Mesa Road 3	May 12	141.3	31.9	32.1	33.1	32.5	53.4	31.7	88.5
Oil Fork Road	April 17, 22 & 27	120.4	24.5	33.0	46.7	42.8	78.0	22.8	88.6
The Rocks	April 6	147.5	32.1	33.1	46.8	44.4	95.3	31.7	107.7
Shelter Cabin Reservoir	April 6, 12 & May 27	99.1	27.1	32.4	41.9	40.5	78.0	23.3	88.6
South Rocks	May 2	121	27.4	33.3	46.2	42.7	73.7	23.8	88.6
MEAN		119.8	27.4	32.0	43.7	42.2	80.1	24.8	98.6
MEDIAN		120.7	27.2	32.7	44.4	42.8	80.5	23.4	101.2
S.D.		16.4	3.7	2.5	4.0	3.7	10.8	4.8	9.4
S.E.		3.3	0.7	0.5	0.8	0.7	2.2	1.0	1.9
MAX		147.5	32.7	36.7	48.3	47.4	95.3	31.8	114.0
MIN		85.5	22.2	28.1	33.1	32.5	53.4	19.4	88.5

Figure 2. Locations of leks presented in Table 1. This is figure 1 from the report by KC Harvey showing locations where noise measurements were collected (KC Harvey 2009).

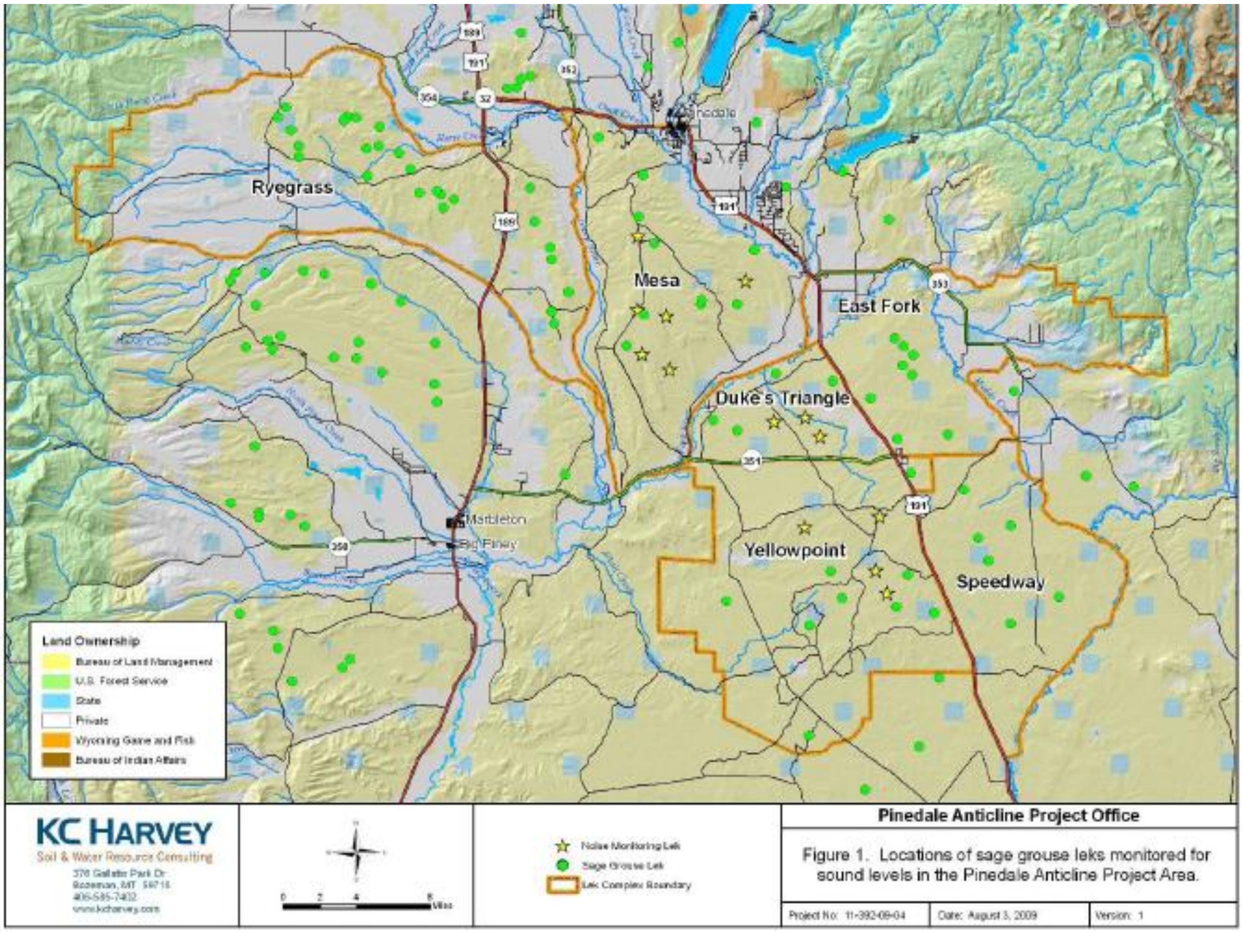


Figure 3. An illustration of noise levels surrounding a lek. This illustration shows a lek in the center, surrounded by a 0.6 mile buffer, a 1.9 mile buffer encompassing ~45% of nests, and a 4-mile buffer encompassing 74-80% of nests (Holloran & Anderson 2005; Moynahan 2004). Noise propagation is shown from a hypothetical loud noise source or combination of sources measuring 65 dBA at 1000 feet (with the same frequency spectrum as drilling noise[19]) located at the edge of the 1.9 mile buffer. Noise is predicted to exceed 10 dBA over ambient (20 dBA) for a radius of approximately 1.9 miles (darker blue), and to be audible above ambient for at least 3.4 miles (lighter blue)[19]. This figure demonstrates that even when the lek area is within recommended noise levels, much of the surrounding area critical for foraging, nesting and brood-rearing may be exposed to higher levels of noise. Distances are approximately to scale and calculations assume no temperature inversions, which nearly double sound propagation distances, and no topographical or ground effects[19].

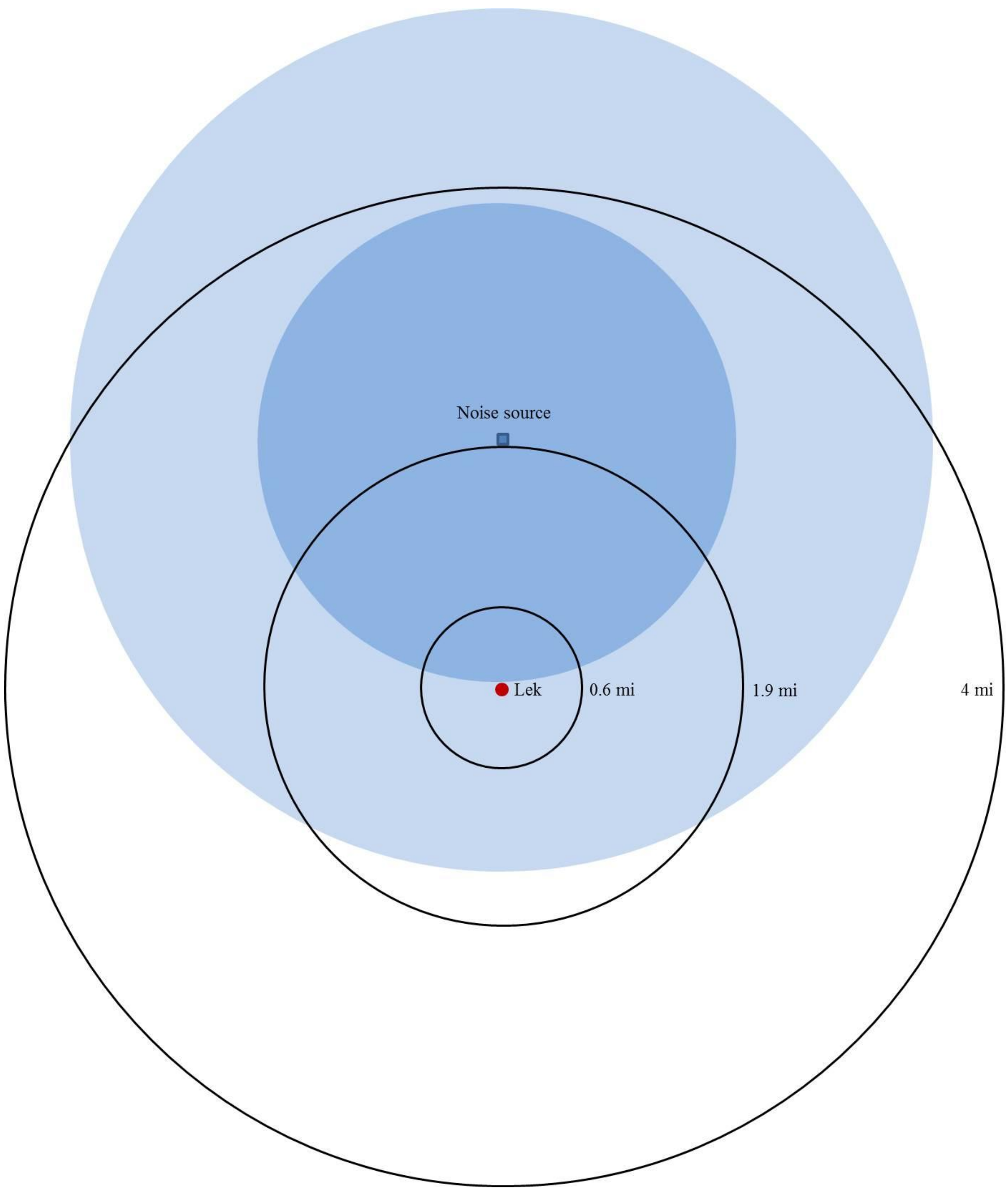
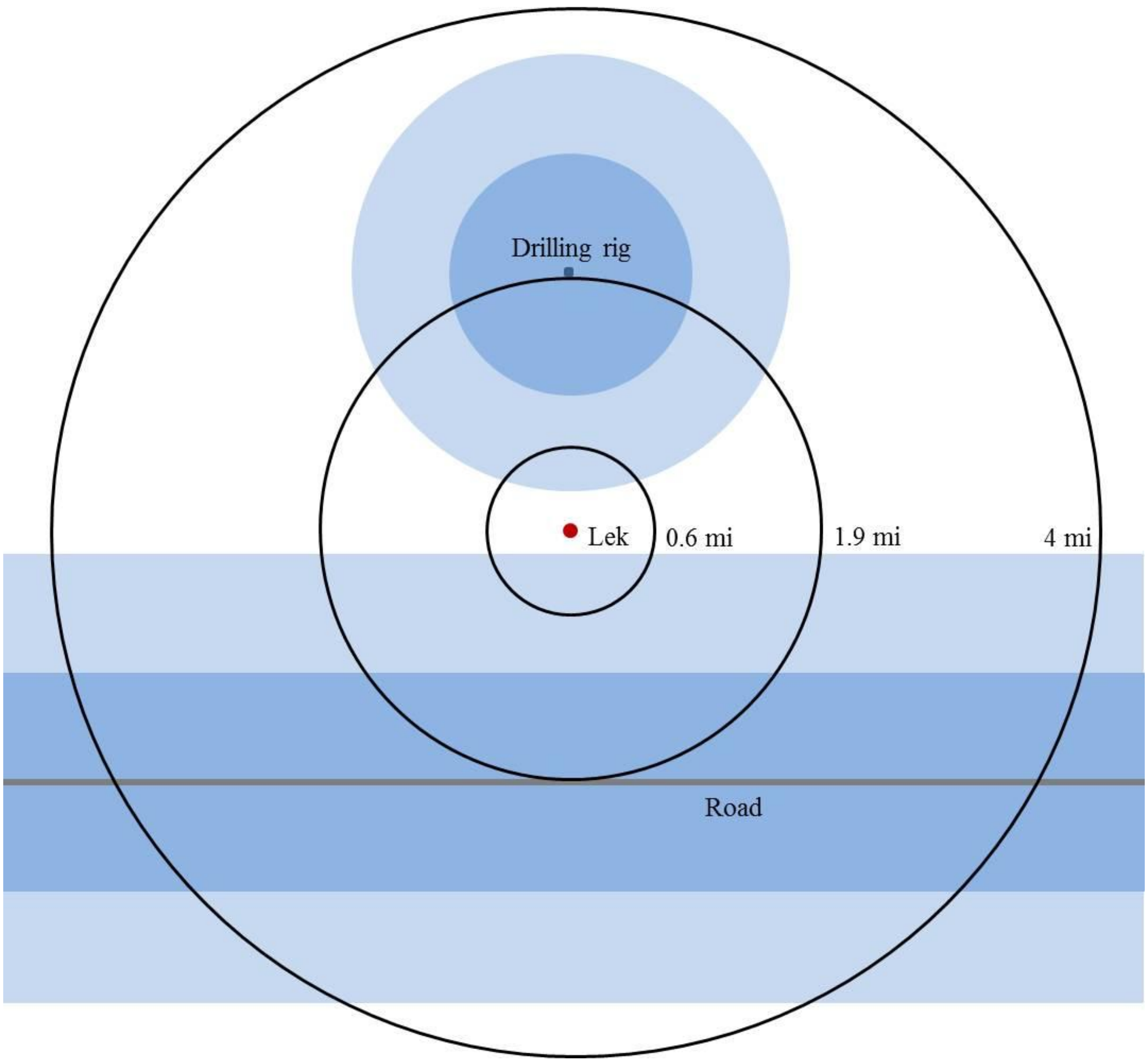


Figure 4. Traffic and drilling noise surrounding a lek. This illustration shows a lek in the center, surrounded by a 0.6 mile buffer, a 1.9 mile buffer encompassing ~45% of nests, and a 4-mile buffer encompassing 74-80% of nests (Holloran & Anderson 2005; Moynahan 2004). Noise from an example natural gas drilling rig at the edge of the 1.9 mile buffer exceeds 10 dBA over ambient (20 dBA) for a radius of approximately 0.9 miles (darker blue), and is audible above ambient for at least 1.65 miles (lighter blue)[19]. An average road at the lower edge of the 1.9 mile buffer will have noise levels (L_{max}) exceeding ambient by 10 dBA for a distance of 0.8 miles and will be audible above ambient for at least 1.7 miles with each passing vehicle[19]. With both sound sources, the lek area is within recommended noise levels, but much of the surrounding area critical for foraging, nesting and brood-rearing is exposed to higher levels of noise. Distances are approximately to scale and calculations assume no temperature inversions, which nearly double sound propagation distances, and no topographical or ground effects[19].



REFERENCES CITED

Aldridge, C. L. & Boyce, M. S. 2007 Linking occurrence and fitness to persistence: Habitat-based approach for endangered Greater Sage-Grouse. *Ecological Applications* **17**, 508-526.

Barber, J. R., Crooks, K. R. & Fristrup, K. M. 2009 The costs of chronic noise exposure for terrestrial organisms. *Trends in Ecology & Evolution* **25**, 180-189.

Beck, T. D. I. 1977 Sage Grouse Flock Characteristics and Habitat Selection in Winter. *The Journal of Wildlife Management* **41**, 18-26.

Blickley, J. L., Blackwood, D. & Patricelli, G. L. 2012 Experimental Evidence for the Effects of Chronic Anthropogenic Noise on Abundance of Greater Sage-Grouse at Leks. *Conservation Biology* **26**, 461-471.

Blickley, J. L., Blackwood, D. L., Hardy, E. L. & Patricelli, G. L. in prep Temporal flexibility in greater sage-grouse (Centrocercus urophasianus) signaling behavior in response to chronic industrial noise playback.

Blickley, J. L. & Patricelli, G. L. 2010 Impacts of Anthropogenic Noise on Wildlife: Research Priorities for the Development of Standards and Mitigation. *Journal of International Wildlife Law and Policy* **13**, 274-292.

Blickley, J. L. & Patricelli, G. L. 2012 Potential acoustic masking of greater sage-grouse display components by chronic industrial noise. *Ornithological Monographs* **74**, 23-35.

Blickley, J. L., Word, K. R., Krakauer, A. H., Phillips, J. L., Sells, S. N., Wingfield, J. C. & Patricelli, G. L. In review Experimental chronic noise exposure is related to elevated fecal corticosteroid metabolites in lekking male greater sage-grouse (*Centrocercus urophasianus*). *PloS ONE*.

BLM. 1999 Noise Analysis for the Pinedale Anticline Oil and Gas Exploration and Development Project, Sublette Co. WY: Bureau of Land Managment Pinedale Field Office.

BLM. 2003 Final Environmental Impact Statement and Proposed Plan Amendment for the Powder River Basin Oil and Gas Project, vol. 3 (ed. B. F. office).

BLM. 2008 Record of Decision for the Supplemental Environmental Impact Statement Pinedale Anticline Oil and Gas Exploration and Development Project (ed. B. P. F. O. US Department of the Interior).

Braun, C. E. 1986 Changes in Sage Grouse lek counts with advent of surface coal mining. *Proc. Issues and Tech. in the Manage. of Impacted West. Wildl.* **2**, 227-231.

Braun, C. E. 1998 Sage grouse declines in western North America: what are the problems? *Proc. West. Assoc. State Fish & Wildl. Agencies* **78**, 139-156.

Brenowitz, E. A. 1982 The active space of red-winged blackbird song. *The Journal of Comparative Physiology* **147**, 511-522.

Connelly, J. W., Knick, S. T., Schroeder, M. A. & Stiver, S. J. 2004 Conservation Assessment of Greater Sage-grouse and Sagebrush Habitats, pp. 610. Cheyenne, WY: West. Assn. Fish and Wildlife Agencies.

Connelly, J. W., Reese, K. P. & Schroeder, M. A. 2003 *Monitoring of greater sage-grouse habitats and populations*. College of Natural Resources Experiment Station Bulletin 80: University of Idaho, Moscow, ID.

Dantzker, M. S., Deane, G. B. & Bradbury, J. W. 1999 Directional acoustic radiation in the strut display of male sage grouse *Centrocercus urophasianus*. *The Journal of Experimental Biology* **202**, 2893-2909.

Doherty, K. E., Naugle, D. E. & Walker, B. L. 2010 Greater Sage-Grouse Nesting Habitat: The Importance of Managing at Multiple Scales. *Journal Of Wildlife Management* **74**, 1544-1553.

Doherty, K. E., Naugle, D. E., Walker, B. L. & Graham, J. M. 2008 Greater sage-grouse winter habitat selection and energy development. *Journal Of Wildlife Management* **72**, 187-195.

Dooling, R. J. & Popper, A. N. 2007 The Effects of Highway Noise on Birds, pp. 74. Sacramento, CA: The California Department of Transportation Division of Environmental Analysis.
EPA. 1971 Community Noise (ed. EPA).
Francis, C. D., Ortega, C. P. & Cruz, A. 2009 Noise Pollution Changes Avian Communities and Species Interactions. *Current Biology* **19**, 1415-1419.
Gibson, R. M. 1989 Field playback of male display attracts females in lek breeding sage grouse. *Behavioral Ecology and Sociobiology* **24**, 439-443.
Gibson, R. M. 1996 Female choice in sage grouse: the roles of attraction and active comparison. *Behavioral Ecology and Sociobiology* **39**, 55-59.
Gibson, R. M. & Bradbury, J. W. 1985 Sexual selection in lekking grouse: phenotypic correlates of male strutting success. *Behavioral Ecology and Sociobiology* **18**, 117-123.
Hagen, C. A. 2011 Predation on Greater Sage-Grouse: Facts, Process, and Effects. In *Greater Sage-Grouse: ecology and conservation of a landscape species and its habitats*, vol. 38 (ed. S. T. Knick & J. W. Connelly). Berkeley, CA.: University of California Press.
Harvey, K. 2009 Pinedale Anticline Project Area Sage Grouse Monitoring: Noise Monitoring Report (ed. P. A. P. Office).
Holloran, M., Kaiser, R. & Hubert, W. 2010 Yearling greater sage-grouse response to energy development in Wyoming. *Journal of Wildlife Management* **74**, 65-72.
Holloran, M. J. 2005 Greater Sage-Grouse (*Centrocercuc urophasianus*) Population Response to Natural Gas Field Development in Western Wyoming. In *Department of Zoology and Physiology*, pp. 114. Laramie: University of Wyoming.
Holloran, M. R. J. & Anderson, S. H. 2005 Spatial distribution of Greater Sage-Grouse nests in relatively contiguous sagebrush habitats. *Condor* **107**, 742-752.
Hu, Y. & Cardoso, G. C. 2009 Are bird species that vocalize at higher frequencies preadapted to inhabit noisy urban areas? *Behavioral Ecology* **20**, 1268-1273.
Jankowski, M. D. 2007 The influence of habitat disturbance and synergized resmethrin on avian immunocompetence, vol. Ph.D.: The University of Wisconsin, Madison.
Kaiser, R. 2006 Recruitment by greater sage-grouse in association with natural gas development in western Wyoming. In *Department of Zoology and Physiology*, vol. M.S. Laramie, WY: University of Wyoming.
Kight, C. R. & Swaddle, J. P. 2011 How and why environmental noise impacts animals: an integrative, mechanistic review. *Ecology Letters* **14**, 1052-1061.
Lynch, E., Joyce, D. & Fristrup, K. 2011 An assessment of noise audibility and sound levels in U.S. National Parks. *Landscape Ecology* **26**, 1297-1309.
Lyon, A. G. & Anderson, S. H. 2003 Potential gas development impacts on sage grouse nest initiation and movement. *Wildlife Society Bulletin* **31**, 486-491.
Moynahan, B. J. 2004 Landscape-scale factors affecting population dynamics of Greater Sage-Grouse (Centrocercus urophasianus) in north-central Montana, vol. Ph.D. Missoula, MT: University of Montana.
Naugle, D. E., Doherty, K. E., Walker, B. E., Holloran, M. J. & Copeland, H. J. 2011 Energy development and Greater Sage-Grouse. In *Greater Sage-Grouse: ecology and conservation of a landscape species and its habitats*, vol. 38 (ed. S. T. Knick & J. W. Connelly). Berkeley, CA.: University of California Press.
Patricelli, G. L., Dantzker, M. S. & Bradbury, J. W. 2007 Differences in acoustic directionality among vocalizations of the male red-winged blackbird (Agelaius phoeniceus) are related to function in communication. *Behavioral Ecology and Sociobiology* **61**, 1099-1110.
Patricelli, G. L. & Krakauer, A. H. 2010 Tactical allocation of effort among multiple signals in sage grouse: an experiment with a robotic female. *Behavioral Ecology* **21**, 97-106.

Quinn, L., Whittingham, J., Butler, J. & Cresswell, W. 2006 Noise, predation risk compensation and vigilance in the chaffinch Fringilla coelebs. *Journal of Avian Biology* **37**, 601-608.
Rabin, L. A., Coss, R. G. & Owings, D. H. 2006 The effects of wind turbines on antipredator behavior in California ground squirrels (Spermophilus beecheyi). *Biological Conservation* **131**, 410-420.
Rogers, G. E. 1964 Sage Grouse investigations in Colorado, vol. 16. Technical Publication No. 16, Colorado Game, Fish and Parks Department, Denver.
Schoenberg, T. J. 1982 Sage grouse movements and habitat selection in North Park, Colorado: Colorado State University, Fort Collins, CO.
Schroeder, M. A., Young, J. R. & Braun, C. E. 1999 Sage Grouse: *Centrocerus urophasianus*. *Birds of North America* **425**, 1-28.
Sørensen, M., Andersen, Z. J., Nordsborg, R. B., Jensen, S. S., Lillelund, K. G., Beelen, R., Schmidt, E. B., Tjønneland, A., Overvad, K. & Raaschou-Nielsen, O. 2012 Road Traffic Noise and Incident Myocardial Infarction: A Prospective Cohort Study. *PLoS ONE* **7**, e39283.
Swenson, J. E., Simmons, C. A. & D. Eustace, C. 1987 Decrease of sage grouse Centrocerus urophasianus after ploughing of sagebrush steppe. *Biological Conservation* **41**, 125-132.
Vehrencamp, S. L., Bradbury, J. W. & Gibson, R. M. 1989 The Energetic Cost Of Display In Male Sage Grouse. *Animal Behaviour* **38**, 885-896.
Walker, B. L., Naugle, D. E. & Doherty, K. E. 2007 Greater Sage-Grouse Population Response to Energy Development and Habitat Loss. *Journal of Wildlife Management* **71**, 2644-2654.
Wallestad, R. O. & Schladweiler, P. 1974 Breeding season movements and habitat selection of male sage grouse. *Journal of Wildlife Management* **38**, 634-637.
Wiley, R. H. 1973 Territoriality and non-random mating in sage grouse (*Centrocercus urophasianus*). *Animal Behaviour Monographs* **6**, 85-169.