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OIL AND GAS DEVELOPMENT AND GREATER SAGE GROUSE (*CENTROCERCUS UROPHASIANUS*): A REVIEW OF THREATS AND MITIGATION MEASURES

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Introduction

Concern exists over the demonstrated and potential deleterious effects of oil and natural gas development on greater sage grouse (*Centrocercus uropha-*

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sianus) populations in the intermountain region of the western United States. Numerous studies have been undertaken to assess the impacts of this development, and agencies have implemented policies and regulations that have the potential to minimize deleterious effects on sage grouse.[1] In 2010 the U.S. Fish and Wildlife Service (USFWS) found that sage grouse are warranted as a "threatened" species under the U.S. Endangered Species Act (ESA) but are currently precluded by other priorities.[2] This "warranted but precluded" ESA decision has resulted in additional regulations, mitigation measures, and conservation efforts.

To date, research on the impacts of oil and natural gas development has focused on quantifying the number of male sage grouse counted at leks (i.e., mating display areas), survivorship of juveniles and adults, and/or distribution of sage grouse relative to development.[3] The majority of this published research has focused on changes in lek attendance by male sage grouse each spring. These data have been used in predictive models to assess lek persistence (and presumably population persistence) under various development scenarios. Male lek counts are the most prevalent data on sage grouse currently available, which may explain the volume of research that utilizes them. Authors assessing lek counts typically have assumed that sage grouse avoidance of energy development leads to sage grouse population declines.[4] However, to date population-level impacts have not been demonstrated, in part due to the limitations of lek count data for inferring population number. That is, lek counts of males may not reflect the overall population numbers as they do not reflect numbers of males in non-lek habitats, females, and young.[5]

Research on the effects of oil and gas development primarily has emphasized the *patterns* of grouse response to intensive development in the immediate and surrounding area (i.e., declining lek counts, avoidance of infrastructure, and, in some cases, lower survivorship). Generalized models have been developed and used to predict outcomes of development scenarios on various time horizons.[6] Some of this body of research has been used as a basis for policy and regulations to minimize impact to sage grouse populations.[7] It also has been proposed as a basis for "conservation trade-offs," where companies forfeit their development rights in exchange for rights elsewhere, and to justify "landscape-level" management (i.e., large scale).[8]

Recent calls for prioritization of conservation efforts and trade-offs based on set-back distances from oil and gas infrastructure to sage grouse leks do not take into account the specific causes of sage grouse avoidance, mortality, or potential population-level effects.[9] Recent agency permit requirements and land management practices have been predicated on set-back distances from oil and gas infrastructure to sage grouse leks. The focus on set-back distances provides only a finite set of options for land managers and permitees alike. Because this approach does not take into account the specific causes of sage grouse avoidance, mortality, or potential population-level effects, it is of limited effectiveness to sage grouse conservation and management. A more comprehensive approach should incorporate performance standards that are based on an understanding of specific cause and effects of oil and gas infrastructure impacts on sage grouse (i.e., noise, predation, disease), as well as consideration of habitats other than leks (i.e., nesting, brood rearing, and winter habitats).

One recent author, M. Holloran, is of the opinion that stipulations to mitigate the effects of oil and gas development on sage grouse only are effective if the sage grouse exhibit zero response to the development (i.e., their response is identical to control area grouse).[10] Several others have suggested that we must assume that sage grouse avoidance of oil and gas development leads to population-level impacts, even if data are lacking.[11] These precautionary approaches imply that the threats posed by the oil and gas industry to sage grouse are not well understood and that it is difficult to achieve effective mitigation. Applying decision theory or risk analysis to this situation offers a potentially useful way to overcome this uncertainty.[12]

The purpose of this paper is to move beyond the description of sage grouse responses to energy development and review current information in an attempt to understand why these responses may occur. To achieve this objective, we review previous research that identified the general threat categories of oil and gas development to sage grouse. We selected six direct and indirect threats from oil and gas to sage grouse, based on a review of published information as well as plausible cause-and-effect mechanisms (table 1). The six threats include: noise, human activity, predation, habitat fragmentation and/or loss, strike hazards, and West Nile virus.[13] We give special attention to noise because it has not been addressed in detail elsewhere. For each of these threats we (1) identify the specific sources of each threat, (2) the likely cause-and-effect mechanisms that could lead to a behavioral and/or demographic impact, and (3) recommend specific mitigation measures that could be implemented to minimize these effects in an adaptive management framework (table 1). Next, we treat the specific sources of threats (number 1 above) as working hypotheses in terms of their congruence (or lack thereof) with existing data or, where there are currently little or no data, their plausible effect on sage grouse populations. We then propose experimental approaches that could be used to test the efficacy of potential mitigation (as suggested by D. Naugle et al.) and discuss the potential value of this and current mitigation measures.[14]

The significance of this strategy to sage grouse conservation is threefold. First, it allows for a more efficient allocation of conservation effort by focusing on threats that matter most to the conservation of local populations affected by oil and gas development. Second, it allows for the design of mitigation that is tailored to the circumstances, rather than relying on one-size-fits-all buffer zones or timing restrictions. And third, the effectiveness of mitigation measures can be evaluated using a hypothesis-testing approach, which is at the philosophical core of science-based adaptive management.[15] In other words, are there additional ways in which mitigation measures could be implemented to minimize the impact of oil and gas developments on sage grouse?

Table 1
ANALYSIS OF POTENTIAL THREATS TO SAGE GROUSE FROM OIL AND GAS DEVELOPMENT AND THEIR MITIGATION

Presumed Threat	Source of Threat	Likely Mechanism of Impact	Potential Consequence to Sage Grouse	Potential Mitigation
1) Noise	Drilling operations (noise from: site prep., drilling, pumping and processing of drill mud, fracking, power generation)	Disruption of mating vocalizations and/or ability to detect predators, annoyance	Avoidance behavior, increased risk of predation	Noise modeling and mitigation, increase efficiency, reduce density, seasonal restrictions
	Gas compressor facilities (compressor and cooling fan noise)	Disruption of mating vocalizations and/or ability to detect predators, annoyance	Avoidance behavior, increased risk of predation	Noise modeling and mitigation
	Traffic (noise from: equipment transport for site prep. and drilling, produced water disposal, crew rotation, maintenance)	Annoyance	Avoidance behavior	Noise modeling and mitigation in road design, increase efficiency to reduce road use, seasonal restrictions, lower speed
2) Human activity	Oil and gas crews/personnel (the largest number during drilling phase)	Annoyance, perceived as predators (due to hunting in area)	Avoidance behavior	Screening of activity from view, reduce amount of activity, restrict hunting in area
	Refuse	Attracts scavengers that are potential predators	Avoidance behavior, increased risk of predation	BMPs to eliminate refuse, install anti-perch devices

(continued)

Table 1 (continued)

ANALYSIS OF POTENTIAL THREATS TO SAGE GROUSE FROM OIL AND GAS DEVELOPMENT AND THEIR MITIGATION

Presumed Threat	**Source of Threat**	**Likely Mechanism of Impact**	**Potential Consequence to Sage Grouse**	**Potential Mitigation**
3) Predation	Attracting avian and terrestrial predators (e.g., ravens, foxes, coyotes)	Increase in predators commensal with humans	Avoidance behavior, increased risk of predation	Remove refuse and roadkill, install anti-perch devices, sonic deterrents, predator control
	Attracting prey species (e.g., rabbits and rodents)	Increase in prey abundance leading to an increase in predators	Avoidance behavior, increased risk of predation	Install anti-perch devices, sonic deterrents, predator control
	Powerlines	Powerpoles act as predator perches	Avoidance behavior, increased risk of predation	Install anti-perch devices, bury powerlines in critical areas
4) Habitat loss or fragmentation	Access roads	Habitat degradation and removal	Reduced carrying capacity	Conservation tradeoffs, timing and seasonal restrictions in critical areas
	Drilling and production pads	Habitat degradation and removal	Reduced carrying capacity	Conservation tradeoffs, restoration

(continued)

Table 1 (continued)

ANALYSIS OF POTENTIAL THREATS TO SAGE GROUSE FROM OIL AND GAS DEVELOPMENT AND THEIR MITIGATION

Presumed Threat	Source of Threat	Likely Mechanism of Impact	Potential Consequence to Sage Grouse	Potential Mitigation
5) Strike hazards	Traffic	Mortality	Reduced survival	Reduce speed and add signage in critical areas
	Wire fences	Mortality	Reduced survival	Install fence markers, redesign fences
	Powerlines	Mortality	Reduced survival	Increase visibility of powerlines (especially ground wires), bury powerlines,
6) West Nile virus	CBM ponds	Mosquito breeding	Reduced survival	Larvicides, reduce mosquito breeding habitat via pond design

The issue of sage grouse and oil and gas development is similar to that of caribou in the North Slope Alaska oil fields. Some local disturbance/displacement impacts initially were suspected. These were assumed to be definitive, and it was speculated that they would have population-level impacts. These perceptions persist, despite evidence that local disturbances to caribou can be effectively mitigated, and evidence that the Central Arctic caribou population has grown dramatically from an estimated 5,000 in 1978 to 66,772 in 2008, or since the oil fields were developed.[16] Population fluctuations tend to be cyclic. It is important to note that there is no hunting in the oil fields, which may contribute to habituation of caribou to human activity.[17] Comparative assessments with other species and other energy developments can provide insights that aid in the planning of sage grouse management.

Potential Threats to Sage Grouse from Oil and Gas Development

Anthropogenic Noise: C. Braun et al. and M. Holloran suggested that noise generated by oil and gas exploration and development may affect sage grouse lek attendance and rates of population increase, although they did not specify cause-and-effect mechanisms beyond potential avoidance of drilling, production facilities, and roads due to noise.[18] M. Holloran reported that lower lek attendance occurred downwind of gas production facilities and therefore was likely due to noise generated by those facilities.[19]

We believe it benefits the discussion to make the distinction between anthropogenic sound and noise. Not all sound is noise and the difference (at least among humans) can be subjective. Thus, we define noise as a subset of sound that causes consistent avoidance, interferes with a critical signal (e.g., detection of predators or selection of mates), or has a deleterious effect on the majority of individuals of a species.[20] Anthropogenic sound and noise are generated by numerous human activities, including the process of oil and gas development and production. The effects of noise range from negligible to annoying, and at the extreme, impact the health of individuals.[21] The effects of and responses to noise can vary among species and among individuals within a species. Responses to noise depend upon susceptibility to frequency, intensity, tone(s), and duration. Thus, sensitivity to noise depends upon more than how loud it is. Topography and environmental factors also play an important role in the attenuation and propagation of sound (and noise). These factors include wind speed, temperature, vegetation cover, and the medium through which the sound is propagating (e.g., air, ground, or water). For example, a strong prevailing wind will cause sound waves propagating upwind to be “bent” upwards, deflecting their energy, while sound waves propagating downwind will be “bent” downwards, thus increasing their effect at ground level over a greater distance.[22]

Sound Measurement: The variable most commonly used to measure sound pressure levels and exposure, A-weighted decibels or dB(A), is based upon a weighting that simulates the frequency range of human hearing (i.e., most sensitive in the range of 1,000 to 8,000 hertz (Hz) but audible between 20 to 20,000 Hz). Because dB(A) is measured on a logarithmic scale, a reduction of measured sound by 10 dB(A) results in sound being reduced by half. Although in widespread use (primarily in the United States), the dB(A) weighting gives a low weighting to sound below 500 Hz, and does not adequately account for acoustical energy below 20 Hz, making it a poor choice for evaluating exposure to low frequencies and infrasound (that has very long wavelengths).[23] Also, since dB(A) is based upon human hearing response, it is not universally applicable to other species, which may be more sensitive to sound. As a result of these limitations, alternative measures such as C- or Z-weighting (which have a flatter response curve over the frequency range 10 to 20,000 Hz) are increasingly used in addition to A-weightings to measure sound exposure.[24] When these sound pressure levels are graphed over the range of frequencies, at one-third octave band frequencies, an unbiased and complete picture of exposure may be obtained. Such a detailed analysis also is required to identify the type of sound that is considered to be noise (as per our definition): the presence of tones (tonal noise); the presence of low frequency noise; fluctuating, intermittent or periodic noise; and impulsive noise. In addition, time-averaged measures (L_{eq}) are used to quantify exposure.

Two acoustic properties of sound are important to understanding the change in intensity as the distance between source and observer increases. First is the inverse square law: unobstructed sound intensity will decrease by a factor of four with each doubling of distance from its source. This means that sound intensity drops off relatively quickly and with each doubling of distance the resulting intensity drops by about 6 dB.[25] This decrease continues until the sound is masked by ambient sounds of equivalent intensity and is no longer noticeable above background. For example, broadband noise produced by a heavily traveled freeway measured at 75 dB(A) may take 800 meters or more to diminish to near background levels across an open field.[26]

The second acoustic property of note—the attenuation of pure tones (sound in a narrow frequency range) through air—is directly proportional to the square of its frequency (assuming humidity and temperature are held constant). Therefore, higher frequency sound is more quickly attenuated. Conversely, low frequency sound and infrasound (that has very long wavelengths) are least subject to attenuation and can travel far greater distances though the air, water, and ground. This makes sound in these frequency ranges more difficult and expensive to control.[27] An everyday example of how low frequency sound and infrasound travel is the pounding of distant surf during a winter storm that is "felt" as much as it is heard.

Avian Hearing: In most cases, the range of hearing for many birds is thought to approximate that of humans, although there are some notable exceptions.[28] For example, M. Theuricha et al. reported that human sensitivity to sound frequencies above 3,000 Hz is greater and below 50 Hz is lower than that of guinea fowl

(*Numida meleagris*) and pigeons (*Columbia livia*).[29] These species were twice as sensitive as humans to pure tones below 10 Hz, and pigeons were almost 50 dB(A) more sensitive than humans in the region of 1 to 10 Hz.[30] Guinea fowl were sensitive down to 2 Hz and pigeons down to 0.05 Hz.[31]

How Noise Could Affect Sage Grouse: Noise from oil and gas operations may impact sage grouse in several ways. First, noise may mask display calls of male sage grouse, especially if it overlaps in frequency. Second, noise can mask the sound of approaching predators, thereby turning noisy areas into population "sinks" where sage grouse mortality is higher. Consequently, sage grouse will/or may learn to avoid it.[32] Third, broadband noise may be simply annoying above a certain threshold, causing sage grouse to avoid it or areas where there are annoying tones. And fourth, noise (and some otherwise benign anthropogenic sounds) may act as an environmental clue that an area poses a higher risk of predation (i.e., by species commensal with humans, or humans themselves in areas where sage grouse are hunted) or that individuals come to associate noise with other hazards such as the risk of being struck by vehicles.[33] Each of these potential impacts can be treated as a potentially falsifiable hypothesis and tested against experimental data to refine our understanding of acoustic threats to sage grouse. It is possible that more than one of these factors is involved in sage grouse avoidance of areas where oil and gas development exceeds a certain threshold. It is important to keep in mind that different populations may have different responses to the same types and levels of noise, depending on local factors (e.g., topography, wind, food, cover, and other habitat features).

The behavioral or physiological sensitivity of sage grouse to different frequencies of sound has not been studied to the extent it has been in other birds. It is known, however, that male sage grouse produce sounds during courtship that could be masked by anthropogenic noise. These vocalizations both attract females to leks in the spring and serve in courtship displays at leks.[34] As reported by M. Dantzker et al. and A. Krakauer et al., these vocalizations consist of mechanically generated wing "swishes," two or three low-frequency "coos" (around 40 to 70 Hz), several broadband "pops" with a low frequency component (down to around 10 Hz), and two higher frequency whistles (600 to 3,200 Hz) that appear to function only over short ranges.[35]

The fact that sage grouse are a ground-nesting and ground-feeding species makes them more vulnerable to mammalian predators. Consequently, they may be more sensitive to low frequency sounds and infrasound transmitted through the ground than arboreal bird species. Regardless of the specific mechanism, noise has the potential to decrease available habitat if sage grouse avoid it, and thus potentially lowers the carrying capacity of the population.

Anthropogenic Sound and Noise from Oil and Gas Development: To date, published information on the effects of oil and gas operations on sage grouse has not specifically addressed the potential effects of sound produced by various sources, their frequency signatures, or intensities. In considering the effects of noise on sage grouse and its potential mitigation, it is important to separate it into its sources, frequencies, sound levels, and spatial arrangement. We therefore start by dividing potential major sources of noise in oil and gas operations into the following three categories: (1) drilling, casing, and hydraulic fracturing operations that are powered by large diesel engines, generators, and pumps; (2) compressor stations used to boost natural gas pressure obtained from wells for through transport pipelines; and (3) heavy equipment, trucks, and other traffic that are used to construct roads, pads, and facility sites, to transport materials, equipment, and staff, and to remove produced water and liquid hydrocarbons (condensate) from well sites.

We also acknowledge that gas flaring, pipelines that are above ground, and injection wells are potential sources of noise to sage grouse but consider them to be of secondary importance compared to the three primary and more prevalent sources listed above. Gas-processing facilities are another noise source but, because of their larger footprints (20 acres or more) and complexity, such facilities are typically located in areas outside sage grouse habitat, so noise from gas plants are of secondary importance.

All three of the major sources of noise produce broadband sound across a wide range of frequencies as well as low frequency sound (less than 1000 Hz) and infrasound (less than 20 Hz, which is felt as a low rumble or vibration, rather than heard). The latter of these can propagate long distances (i.e., several kilometers). Some diesel engines, compressors, or other machinery also may produce specific tones, which alone may be annoying and/or may interfere with acoustic communication among sage grouse.

Anthropogenic Sound and Noise from Drilling Operations: Prior to drilling a well(s), an access road and drilling pad are constructed and reserve pits are excavated. The duration of site and road construction ranges from a few weeks to several months due to topography, weather and permit conditions, and length of access roads. The drilling rig is then raised and infrastructure to power and support the drilling operation is installed. This involves numerous heavy trucks, dozens of staff, and up to two weeks to complete. Following this stage is around-the-clock operation of the drilling rig, during which time surface casing is set and cemented, and intermediate and bottomhole sections of wellbores are drilled and casing installed. Actual drilling may be limited to several weeks (for shallow or single bore holes) but can span more than 20 months if multiple wells are drilled from a pad. The advent of deviated (less than 20 degrees from vertical) and horizontal drilling (greater than 75 degrees from vertical) has meant greater efficiency (more wells can be drilled from one pad) and is an innovation that reduces the overall footprint—and impact—of gas field development.

The primary sources of sound and noise associated with oil and gas drilling operations are the large diesel motors and diesel-powered generators. These motors power drill bits, drive mud pumps that circulate mud to lubricate the well bore, and remove rock chips, as well as power winches to pull and replace drill strings, pump casing cement, operate shaker tables (to remove rock chips from drilling mud), and provide lighting and power.

It is well known that large diesel engines produce high levels of broadband sound as well as low frequency sound and infrasound. The latter two are produced by diesel impulsiveness (knocking), cylinder-to-cylinder and individual cylinder firing variation, and mechanical vibration. The transmission of low frequency and infrasound is particularly acute if the source is not isolated from the ground.[36]

An additional source of low frequency sound in drilling operations is the shaker tables that are attached rigidly to circulation tanks, which in turn serve as low frequency sound transducers. In other words, vibrations are transferred to the tank and the ground in much the same way that sound transducers operate in the audio industry. This source of low frequency sound can travel long distances (greater than 1 km).

Anthropogenic Sound and Noise from Natural Gas Compressors: Compressors are installed near wellheads, along gas lines, and at compressor stations to provide pressure for efficient transport in pipelines. Compressors and compressor stations vary widely in type (i.e., reciprocating, rotary screw, centrifugal, or axial), in size from tens to thousands of horsepower, and from single compressors near one or more wellheads to large mainline compressor stations in the distribution network. Therefore, they differ widely in frequency signatures and sound pressure levels. Some produce virtually no discernable sound.

Compressors are one of the more permanent and ubiquitous potential noise producers because of their continuous operation. However, compressors are not necessarily permanent fixtures: well pressures decline over time and line-pressure changes occur when other wells are taken off the distribution system or new production is added to the system. These variables may alter the type, size, or number of compressors at a location over time and the amount of noise generated. Compressors in natural gas production fields, such as those in sage grouse habitat, are primarily powered by natural gas-fired engines and are one source of continuous sound and potential noise that could affect sage grouse. Other sources include large cooling fans that are necessary to dissipate the substantial amount of heat generated by gas compressors. Very large cooling fans used on compressors of greater than 1,500 horsepower (hp) also can produce infrasound (perceived as a low beat). Moreover, compressors, cooling fans, and the power units that drive them produce pure tones and modulating frequencies, which are more likely to be annoying to humans than sound in the broadband spectrum. Electric motors are being used to drive compressors in some areas. Although the use of electric motors in these instances is driven by a need to reduce air emissions, electric motors may be effective for noise mitigation in fields that have electric power.

The fact that there is substantial variation in noise levels and frequency signatures produced by compressor stations means that the effects on sage grouse could vary widely among sites as well as near a single compressor site over time. Evaluating the impact of compressor stations on sage grouse leks or other sage grouse habitat based solely on their proximity yields an incomplete picture.[37] Thus, an experimental approach that quantifies sage grouse responses to different anthropogenic sound signatures (frequencies, intensity, and tones) is therefore needed, along with a spatial and temporal analysis of sage grouse responses to compressor noise. If sage grouse are fitted with satellite global positioning system (GPS) transmitters (rather than traditional very high frequency (VHF) transmitters), higher resolution data could be obtained.

To date, four studies have measured local effects of sound (and noise) generated by natural gas compressor stations on passerines: one along a proposed pipeline route in the Canadian arctic, another in Canada's boreal forest, and two in pinyon-juniper woodlands in northwestern New Mexico. The first study used artificial compressor noise to simulate 60 to 83 dB(C) noise and its effects on Lapland longspurs (*Calcarius lapponicus*).[38] Observers found no significant effects of this sound source on clutch size or the density of breeding birds. The second study reported a one-third reduction in overall passerine bird density close to compressor stations.[39] A related study by the same research group on ovenbirds (*Seiurus aurocapilla*) reported reduced pairing success and significantly more first-time breeders near compressor stations (75 to 90 dB(A) at the source).[40] The authors conjectured that reduced avian diversity could have been due to some species being susceptible to masking of territorial defense calls or predator detection from noise generated by compressor stations. The third study found approximately the same number of species and total number of birds observed at control and compressor sites, although species varied in their response.[41] Some species were negatively impacted, such as the spotted towhee, while others, such as house finch and juniper titmouse, were more abundant at compressor sites. The fourth study also found different responses of species to compressor noise, but reported decreased nest predation by scrub jays and nest parasitism by brown-headed cowbirds near compressors.[42] These studies underscore the variation in response among species to sound (and noise) generated by compressor stations. They further underscore the lack of accounting for variation in compressor noise output, the spatial arrangement of compressors, or the mitigating effects of sound abatement measures (if they were installed). None of the studies were designed to address population level effects.

Anthropogenic Sound and Noise from Traffic on Access Roads: Sound and noise generated by field-related vehicle use is an inescapable but mitagateable consequence of oil and gas development and operations. The typical noise from heavy-laden diesel powered trucks on highways is further amplified/exacerbated by the uneven, rough surface of gravel roads that results in excitation and deformation of tires and frames and subjects the vehicle to vertical oscillations that cause dynamic axle loads or "axle hop." This source of noise increases with speed and load and, in turn, generates low frequency acoustic waves that propagate through the ground.[43] This is in addition to noticeable diesel engine noise that is ubiquitous with truck traffic. Similarly, passenger vehicles that are used to shuttle personnel are another source of noise and, like heavy trucks, these generate more noise per vehicle on gravel roads than on pavement.

Frequent truck traffic is associated with roads, well pads, rig mobilization (and demobilization), and equipment assembly. In preparation for drilling, heavy trucks deliver drill rigs, drillpipe, well casing, cement, drilling and well completion fluids, diesel fuel, and other equipment and materials, most of which are removed from the site (outside of casing pipe and cement) after completion of the well. After production starts, wells frequently produce naturally occurring salt water along with the oil or gas. The produced water is stored above ground in tanks until it is moved by truck or pipeline to injection wells and it is pumped deep underground. Liquid hydrocarbons from gas wells and crude oil from oil wells also may be trucked or piped off site.

M. Holloran reported declining male sage grouse lek attendance with increased proximity of roads to leks (e.g., main haul roads within three kilometers of leks, and a length of more than five kilometers of main haul road within three kilometers of leks) and increasing truck traffic (as determined from axle counters).[44] Furthermore, nesting yearling females showed avoidance of road-related disturbances when compared to adult females. A. Lyon and S. Anderson reported that females tended to nest farther from roads and that the primary impact of energy development was traffic-related; however, some female sage grouse nested near roads and producing gas wells, suggesting that avoidance of these features was not absolute.[45] Avoidance appeared to be related to traffic levels and well density.

To quantify the effects on sage grouse, studies to date have utilized straight-line distances, length of road segment in proximity to sage grouse leks and nests, and whether or not a road was in sight. This is an area of study where sound modeling could greatly increase our understanding of the effects of traffic noise by taking into account topography, vehicle speed and load, variability (and periodicity) of traffic density and road configuration in the mapping of sound levels and sage grouse distribution in response to them.

Testing the "Noise Hypothesis": We concur with the view of C. Braun et al. that "The effects of oil and gas developments on sage-grouse and other sagebrush-grassland avifauna are poorly understood because of the lack of replicated, well designed studies."[46] This need not be the case. That sage grouse may avoid oil and gas infrastructure because of noise from drilling, compressors, and/or traffic on access roads is a plausible hypothesis that could be tested against data obtained from laboratory and field studies as well as results from adaptive management experiments. Recognizing that there is variation in the type, size, age, and duration of each of these types of infrastructure along with variation in topography and environmental conditions is a necessary part of any experimental design. In and around urban areas, where humans are impacted by oil and gas infrastructure, noise monitoring, modeling, and mitigation are well-established practices. These practices could be applied when testing the above hypothesis on sage grouse.

Laboratory Studies: As with other species of birds, the sensitivity of sage grouse to a range of frequencies—from infrasound to high frequency broadband sound—could be determined by measuring auditory-evoked potentials and quantifying behavioral responses to sound of differing frequencies and intensity in a controlled laboratory setting.[47] The fact that sage grouse spend the majority of their time on the ground and are a ground-nesting species (as compared to passerine species that are primarily arboreal), laboratory experiments should include low frequency and infrasonic sound propagated through the ground (i.e., similar to that produced by some oil and gas infrastructure).

Field Experiments: Variation in the types of oil and gas infrastructure and observed variation in the responses of sage grouse to that infrastructure means that a one-size-fits-all approach to quantifying impacts to sage grouse is inappropriate.[48] Noise monitoring and spatial noise modeling of infrastructure at multiple sites is therefore essential when quantifying the characteristics of noise and sage grouse response(s) to it.

To ascertain how sound generated from oil and natural gas development affects sage grouse behavior, we recommend that field experiments to compare sage grouse responses to noise-mitigated and unmitigated operations be conducted during both pre- and post-development periods. The information thus gathered could then be utilized in noise-modeling calculations to map the spatial and temporal intensity and dispersion of sound across the landscape. This could then be compared with data on sage grouse distribution (i.e., using high-resolution GPS transmitter data) and lek counts, to test how sage grouse distribution or abundance is affected. Alternatively, noise mitigation could be fitted to existing infrastructure (e.g., gas compressors) or to infrastructure in the process of installation (e.g., drilling rigs), and sage grouse responses measured to mitigated versus unmitigated infrastructure. This would require a departure from the current approach of monitoring for compliance of the installation. Presently, there is no central, publicly accessible database on mitigation measures employed by the oil and gas industry for sage grouse.

A combined laboratory and field approach is necessary for quantifying sage grouse responses to noise because of obvious confounding variables associated with oil and gas development: tall structures, human activity, lights, power lines, and potential attraction of predators to the area surrounding them. Similarly, the effectiveness of conditions of permit approval employed by state and federal agency managers could be tested.

Noise Mitigation in the Oil and Gas Industry Could be Applied to Drilling and Production in Sage Grouse Habitat: Noise mitigation approaches employed by the oil and gas industry have evolved due to industry's experience in recent years with natural gas development in and near urban areas such as the Barnett Shale that underlies Fort Worth, Texas, and its environs. In such locations, mitigation efforts begin with base-line 24-hour ambient sound surveys to establish pre-development background levels. The results of these base-line surveys are used in combination with information on equipment used, the directionality of machine-generated noise, topography, prevailing wind, and temperature to provide input data for noise modeling to evaluate mitigated vs. unmitigated noise impacts and to develop a noise abatement plan. Noise mitigation measures carried out under a noise mitigation plan may include enhanced mufflers on diesel engines and gas compressor engines, acoustically engineered sound barrier blankets and sound walls to surround drilling and fracking operations, isolation of vibrating equipment from the ground (e.g., large diesel motors), isolation of shaker tables from holding tanks to prevent the latter from acting as a low frequency transducer, installing mufflers on compressors and surrounding them in sound walls or in soundproof buildings, adding silencers to compressor cooling fans, and scheduling truck traffic to reduce noise conflicts.

Directional and horizontal drilling techniques allow development of resources that might otherwise be foregone.[49] Development utilizing multiple wells (up to 20 wellbores) on one wellpad and use of year round drilling are major innovations that eliminate the need for rig mobilizations and demobilizations and associated truck hauling (about 80 to 100 truckloads per rig move). The viability of drilling techniques is contingent on local geological conditions, drill depths, and reservoir characteristics. Overall footprint and impact of drilling in an area have been reduced significantly through enhanced drilling techniques, advanced well completion designs that allow greater recovery of resources from fewer wellbores, and comprehensive project planning that reduces surface disturbance and human presence (e.g., fewer drilling pads, access roads, centralized gas treatment plants, co-location of facilities, placement of pipelines in one right-of-way, buried power lines, transportation planning, and remote well monitoring and control). Additionally, newer generation drilling rigs and gas compressors tend to be more efficient and quieter than older models.[50] Although the noise from compressors is continuous, the fact that compressors are semi-permanent means they may be one of the more easily mitigated sources of noise. Loud compressors can be muffled with soundproofing.

If thresholds for sage grouse tolerance to noise can be determined, then performance standards could be established. This would be similar to limits for broadband and low frequency noise that have been set for drill rigs and gas compressors in residential areas.[51] The City of Fort Worth regulates noise generated by oil and gas operations as low as the 16 Hz octave band frequency (Ordinance No. 18399-12-2008).

Human Activity: What constitutes a human activity that causes disturbance? We narrowly define human activity associated with oil and gas development as the presence of humans working outside and on foot or on equipment (such as on a drill rig, site and pad construction, performing maintenance, or loading produced water at a site). This distinguishes it from human activities covered under other threats (e.g., traffic).

Most of the published literature that addresses human disturbance to sage grouse or other species assumes that if individuals avoid human activity or take flight in response to humans, then the activity will eventually lead to a deleterious effect on their populations.[52] However, human disturbance is of importance to populations only if it has a demographic consequence, ultimately manifested as a lowering of carrying capacity. This occurs when the total area of available habitat is reduced (due to the species avoiding areas of human activity) or the density of animals that the habitat can support is reduced (due to a decline in habitat quality caused by the disturbance). In the case of sage grouse, reduction in male lek counts has been assumed to equate with population losses. To our knowledge, this hypothesis has not been tested with probability-based population counts.

If human activities are geographically predictable and non-threatening, then wildlife may habituate to them.[53] Conversely, they may learn to associate humans with danger. One aspect of sage grouse management that has the potential to aversely condition them to human activity is sport hunting: a reported 207,433 sage grouse were harvested in the United States during 2001-2007.[54] If sage grouse perceive humans as predators and associate them with danger (thus avoiding areas of human activity as a result), then the effects of human activity associated with oil and gas development will be amplified. Firearms are not allowed in oil and gas development areas for obvious safety reasons, but hunted sage grouse populations frequently overlap these areas and, therefore, can be expected to be conditioned aversely to human activity.[55]

It is possible that un-hunted sage grouse populations would habituate to human activity and noise associated with oil and gas development more readily than hunted populations. This hypothesis is testable by comparing flight initiation distances (and habitat use near energy development) in hunted vs. un-hunted populations.

If greater avoidance of human activities is found in populations that are hunted, then mitigation for energy development is straightforward: either do not hunt grouse in these populations (similar to caribou hunting restrictions near Prudhoe Bay, Alaska) or screen human activities to the extent possible from sage grouse.

Predation: The extent to which oil and gas development may result in increased predation on sage grouse has not been quantified, but plausible cause-and-effect mechanisms exist because species such as ravens, foxes, and coyotes are commensal with, and frequently subsidized by, humans. A recent review of published and unpublished research about predation on sage grouse concluded that all of the predators on sage grouse are generalists, meaning that they prey on other species as well.[56] Sage grouse eggs have been preyed upon by red foxes (*Vulpes vulpes*), coyotes (*Canis latrans*), badgers (*Taxidea taxis*), common ravens (*Corvus corax*), and black-billed magpies (*Pica hudsonia*). Common predators of juvenile and adult sage grouse include golden eagles (*Aquila chrysaetos*), prairie falcons (*Falco mexicanus*) as well as other raptors, coyotes, badgers, and bobcats (*Lynx rufus*). Younger birds are likely preyed on by common ravens, red fox, northern harrier (*Circus cyaneus*), ground squirrels, snakes, and weasels. More recent data used continuous video monitoring of sage grouse nests to quantify predation rates and microhabitat parameters that favored predation.[57] These authors documented predation on nests by common ravens and American badgers and reported that an increase in one raven per 10-kilometer transect survey was associated with a 7.4 percent increase in the odds of nest failure from raven predation. The probability of predation by ravens and badgers also increased with reduced shrub canopy cover, suggesting a negative synergism for sage grouse between increasing predator density and decreasing cover.

To address predation, several strategies have been proposed. C. Hagen suggested an untested, indirect approach: "The most effective long-term predator management for sage-grouse populations may be through maintaining connectivity of suitable habitats."[58] The author does not explain the mechanism by which this could reduce predation on sage grouse. In contrast, P. Coates and D. Delehanthy proposed a more specific approach, one that addresses the two primary mechanisms they identified as contributing to sage grouse predation: (1) reduce interactions between ravens and nesting sage grouse by managing raven populations (i.e., reduce abundance of this predator that is commensal with humans) and (2) restore and maintain shrub canopy cover in sage grouse nesting areas to reduce the effectiveness of ravens and other predators on nesting sage grouse.[59] The approach of P. Coates and D. Delehanthy represents a more integrated and science-based predator management strategy that addresses specific cause-and-effect mechanisms, and could be tailored to specific circumstances involving other predators on sage grouse in areas affected by oil and gas development.[60]

Other mitigation measures that address specific cause-and-effect mechanisms of predation include: (1) installation of anti-perch devices on power poles, fence posts, structures, and equipment to discourage raptors and (especially) ravens from perching in sage grouse habitat; (2) burial of power lines, thus completely eliminating perches for raptors and ravens in critical nesting areas; (3) trash control measures to eliminate food subsidies and attractants to ravens, magpies, red foxes, and coyotes (i.e., use of covered dumpsters with self-closing lids that cannot be left open and clean worksite procedures); (4) discourage the use of oil and gas infrastructure as den sites for mammalian prey (e.g., rabbits and rodents) that then provide a subsidy to predators such as foxes and coyotes; and (5) removal of road killed animals that attract and provide a food subsidy to ravens, foxes, and coyotes.

Although the USFWS devoted an extensive discussion of this hazard in their 2008 Interim Status Update, current stipulations by the Bureau of Land Management and the State of Wyoming and best management practices (see http://www.oilandgasbmps.org/) address these issues in a limited way.[61] That mitigation measures such as those listed above could result in sage grouse being more tolerant of oil and gas infrastructure (due to a lower perceived risk of predation) is a testable hypothesis.

Habitat Loss and Fragmentation: Sage grouse habitat loss and fragmentation is of serious concern to federal land managers. Significant direct losses result from natural events such as lightning-caused fires and noxious weed infestations, among others. Federal land managers make concerted efforts to minimize habitat loss and fragmentation through activity siting and mitigation of potential impacts. Direct losses from oil and gas development include construction of roads, drilling pads, and facility sites for compressor stations and related infrastructure to support production operations. Indirect losses result from: habitat degradation, inadvertent creation of population "sinks" due to increased predation, and sage grouse avoidance of oil and gas infrastructure (described elsewhere in this paper).[62] Clearly, the direct loss of habitat is more permanent because it involves substantial earthworks and is therefore the most challenging to mitigate.

Spatial/Temporal Management: Modeling of hypothetical oil and gas build-out scenarios and avoidance of sage grouse core areas (defined from lek location and count data) have been proposed as a means to prioritize the conservation of sage grouse habitat and thereby reduce direct and indirect impacts of habitat loss and fragmentation.[63] This may include forgoing development in core areas until either the functional relationship between actual sage grouse population numbers and core habitat is better understood or more effective mitigation measures are developed. While these are important contributions in *spatial* analysis, a common limitation is the absence of *temporal* analysis. The latter is needed because the rate of development of oil and gas is highly variable and can be determined by conditions such as commodity prices, market conditions, new information about reservoir and production characteristics, and development of new drilling and well completion technologies. Further, the duration of oil and gas production is finite (generally assumed to be 30 years) and their impacts are not necessarily permanent to sage grouse. After development and resource extraction has passed, sage grouse populations have the potential to recover, especially if reasonable and prudent restoration efforts are undertaken.[64]

An additional and significant limitation to these modeling efforts has been their failure to keep pace with technological advances. These advances have increased the efficiency of oil and gas drilling (fewer dry holes, fewer drill days, and multiple-wellbores from one pad) and production (greater recovery using fewer wellbores), resulting in reduced surface footprints, less infrastructure, and reduced noise impacts. These advances have the potential to render obsolete those modeling efforts that were based on impact studies from a previous generation of oil and gas extraction technologies (*circa* 1970s and 1980s). Briefly, these technological advances include the following.

1. Directional drilling can reduce surface disturbance by drilling multiple wells from one drilling pad. This allows for a more efficient tapping of underground reservoirs of oil and gas (a 3.2 to 1 average production ratio compared to vertical drilling) and can reduce both well pad density on the surface and the volumes of drilling waste generated by the activity.[65]
2. Steerable downhole motors and horizontal wellbores, that is, drilling multiple deviated wellbores (as many as 20 wellbores) from one pad, are feasible in some areas, such as the Piceance Creek Basin. Horizontal wells are used in many areas. Such applications greatly increase the effective radius of production from one wellpad.
3. Materials technology advances in drill bits have made them more efficient. This reduces drilling time and rates of equipment failure. For example, the latest-generation polycrystalline diamond compact bits drill at a rate that is 150 to 200 percent faster than similar bits just a few years ago. Small, mechanically assisted high-pressure water jet drills are in development.
4. Lightweight modular drilling rigs are deployed more easily and require a smaller footprint.
5. Technology that allows measurement while drilling provides precise, real-time down-hole drilling data to allow more efficient and accurate drilling.
6. Slim-hole drilling, micro-holes, and coiled tubing are more efficient than conventional drilling operations for extracting additional oil and gas from mature fields or tapping into complex reservoirs. This is accomplished by drilling smaller diameter holes (compared to a conventional 8-3/4 inch diameter hole) and using a more flexible, steerable, down-hole drilling apparatus. Drilling waste volumes are lower, surface footprints are up to 75 percent smaller, and noise impacts are reduced, e.g., at 1,300 feet a conventional well is around 55 dB(A), while a coiled tubing unit's noise level at the same distance is about 40 dB(A).

The pace of technological improvements taking place in oil and gas development and their implementation in the field require that efforts to model potential impacts to sage grouse keep pace as well. To remain relevant, modeling efforts also need to acknowledge and incorporate information on new technology and more effective mitigation measures for sage grouse, rather than rely on simplifying assumptions regarding spatial scale of impacts (i.e., a one-size-fits-all approach to quantifying impacts).[66]

Conservation Trade-Offs: One approach to mitigating direct loss of habitat is the use of conservation trade-offs. These include land trades, mitigation banks, conservation easements, lease buybacks, and other ways to set aside sage grouse habitat with a high-priority for conservation and management.[67] While this does not alleviate direct and indirect impacts at specific sites or ensure that the level of off-site mitigation is equivalent to the level of on-site impact, it does provide a mechanism for land preservation that can benefit sage grouse populations elsewhere. The U.S. Fish and Wildlife Service, in its "Policy for Evaluation of Conservation Efforts," has collected information for a database (PECE); however, these data and analyses derived from them have not yet been made public.

Another approach to conservation trade-offs, but more specifically aimed at reducing threats on private lands, is Candidate Conservation Agreements with Assurances (CCAAs). This program is administered by the USFWS and designed to incentivize conservation efforts on private lands that will benefit a "candidate" species while providing assurances that no additional requirements will be imposed should a species subsequently be ESA-listed. (The 2010 "warranted but precluded" decision on sage grouse means this species is now officially a candidate for ESA-listing.) A similar program exists for public lands but does not provide assurances. Although these programs hold promise, we are unaware of any agreements having been implemented, owing to lack of alignment among parties and state and federal agencies.

Habitat Restoration: Where habitat disturbance has occurred as a result of oil and gas development, it can be offset by reclamation efforts, and more effective restoration approaches are under development.[68] Although full reclamation is required after well fields have been abandoned, it also can be implemented on an interim basis in areas where development is still occurring. While sage grouse have repopulated areas previously abandoned, there has been a delay in the methods to: (1) encourage natural re-colonization, (2) enhance the success of translocations and augmentations, and (3) subsequently foster population growth.[69] One aspect of restoration research that has been overlooked in recent years is the development of methods to attract sage grouse to (artificial) lek sites.[70] This is an area of research that could benefit sage grouse conservation both in and near energy development. Suggestions that there is no evidence populations will attain their previous size and reestablishment may take 20 to 30 years appear to us as problems to be solved rather than inevitabilities to be accepted.[71]

Strike Hazards: Wire strand and woven wire fences, road traffic, and distribution power lines are ubiquitous throughout the range of sage grouse and may be strike hazards for sage grouse.[72] These hazards are sometimes associated with oil and gas development. Fencing around oil and gas facilities is required by some municipalities for public safety (Evanston, Wyoming) and may be erected along access roads to contain livestock. Power lines may be strung to provide electrical power to infrastructure. Wire fencing and traffic are considered to be strike hazards because sage grouse typically fly low and fast to avoid predators. Power lines could pose a hazard to migrating sage grouse; however, the empirical evidence supporting power lines as a strike hazard is lacking. The mortality that each of these strike hazards inflicts upon sage grouse is difficult to quantify, and most accounts are based on scattered, unpublished incidents that researchers happened upon opportunistically.[73] Once a carcass is scavenged, it is also difficult to distinguish between mortality from a strike versus other causes.

The level of mortality from each of these three hazards could be quantified through the labor-intensive process of walking fence lines and power lines and driving roads in search of dead sage grouse (at least daily). Such data are needed in areas where sound population data are available to quantify the proportion of the population annually lost to these hazards and the habitat parameters associated with those losses. Only then would it be possible to rank the degree of threat posed by these hazards and prioritize mitigation.

Mitigation for each of these hazards already exists. Inexpensive fence markers to increase visibility to sage grouse have been developed for wire strand fencing. Although the amount of fencing that could be marked is staggering, areas of highest risk could receive higher priority.[74] Power lines in areas deemed of high strike risk to sage grouse could be buried or restrung on taller poles. This is a potentially expensive proposition, underscoring the need for quantifying the risk before prioritizing areas to be mitigated. And finally, in similar areas of high risk, vehicle traffic could be slowed and drivers alerted with training and signage.

West Nile Virus: In December 2009 the Bureau of Land Management (BLM) issued stipulations requiring comprehensive mosquito control at produced water ponds associated with energy development in areas where West Nile virus poses a threat to sage grouse.

> This may include but is not limited to: a) the use of larvicides and adulticides to treat reservoirs; b) overbuilding ponds to create non-vegetated and muddy shorelines; c) building steep shorelines to reduce shallow water and aquatic vegetation; d) maintaining the water level below rooted vegetation; e) avoiding flooding terrestrial vegetation in flat terrain or low lying areas; f) constructing dams or impoundments that restrict seepage or overflow; g) lining the channel where discharge water flows into the pond with crushed rock, or use a horizontal pipe to discharge inflow directly into existing open water; h) lining the overflow spillway with crushed rock and construct the spillway with steep sides to preclude the accumulation of shallow water and vegetation; and i) restricting access of ponds to livestock and wildlife.[75]

Subsequent to those policies, new recombinant larvicides have improved the efficacy of *Bacillus thuringiensis* subsp. *Israelensis* (Bti) to control mosquito larvae. Newly developed bacterial strains that are 10-fold more toxic to mosquito larvae than wild-type species of Bti and *Bacillus sphaericus* (Bs) are used in current commercial formulations.[76]

Despite these advances in mitigating potential effects of West Nile virus on sage grouse (or eliminating them entirely), recent papers have made no mention of these advances and have continued to associate energy development with increased risk of West Nile virus.[77]

Discussion

In this paper our first step was to distill the general threat of oil and gas development into specific threats to sage grouse, and then evaluate each threat based on its cause-and-effect mechanisms. This process establishes the credibility of each threat, and then addresses the question of *why* sage grouse could be affected by it. In some cases, additional research has been proposed to quantify aspects of the threat. Next, we identified specific mitigation measures that could be implemented in an adaptive management framework. This approach ensures that precautionary measures are reasonable, appropriately related to mitigation of a perceived threat, the level of risk (or reward) is quantified, and an experimental approach is used to fill in knowledge gaps.

Recent Regulations: Current stipulations and regulations for oil and gas development in sage grouse habitat are largely based on studies from the Jonah Gas Field and Pinedale anticline. These and other intensive developments were permitted decades ago, using older, more invasive technologies and methods. The density of wells is high, largely due to the previous practice of drilling many vertical wells to tap the resource (before the use of directional and horizontal drilling of multiple wells from a single surface location became widespread), and prior to concerns over sage grouse conservation. This type of intensive development set people's perceptions of what future oil and gas development would look like and what its impact to sage grouse would be. These fields, and their effect on sage grouse, are not necessarily representative of sage grouse responses to less-intensive energy development.[78] Recent environmental regulations and newer technologies have lessened the threats to sage grouse.

Two instructional memoranda issued by the BLM and an Executive Order issued by the Governor of Wyoming have sought to address potential impacts of surface-disturbing activities and disruptive activities to sage grouse both inside and outside identified sage grouse "Core Areas."[79] These documents lay out regulations that include timing, setback distance, and density restrictions to protect sage grouse leks as well as winter and brood-rearing habitat. For example, both BLM and Wyoming regulations limit development to one well pad or compressor station ("energy production and/or transmission structures") per 640 acres, with a 5-percent limit on the amount of sagebrush habitat disturbance within those 640 acres.

Of these regulatory documents, only the Wyoming Executive Order includes actual performance standards, and only two of those performance standards partially address the potential threats raised in this review: (1) power lines must be raptor-proof, either by burying them or by installing anti-perching devices (although no mention is made of limiting raven perches or discouraging mammalian predators, even though these cause the bulk of sage grouse nest mortality) and (2) the levels of new sources of noise are limited to 10 dB(A) above ambient at the perimeter of leks, with the acknowledgement that actual thresholds may be adjusted pending results of ongoing research (although for reasons cited above dB(A) is a scale inappropriate for quantifying low frequency noise). While these new regulations have potential to benefit sage grouse, they fall short in addressing the likely mechanisms behind the threats to sage grouse (discussed in this paper) and rely on adaptive management in a limited way. The Executive Order assesses success or failure of mitigation (and adaptive response) on a case-by-case basis using only monitoring data from the mitigated site (rather than utilizing data from multiple mitigation projects or pooling data for a meta analysis). Similarly, "adaptive management" is only mentioned once in the BLM Instructive Memoranda.[80] The effect of this piecemeal approach is twofold. First, it provides a disincentive for cooperative efforts (i.e., multi-company, multi-agency, multi-partner) to coordinate, and report on, monitoring of mitigation measures for their effectiveness. And second, the limited (local) scope of this "adaptive management" strategy can stifle innovation.[81]

Presently, there is no central repository of information on mitigation measures implemented on behalf of sage grouse, nor their outcomes.[82] In our view, this is a critical data gap that hampers sage grouse conservation and the effective mitigation of oil and gas development in sage grouse habitat. It is difficult to learn from the experiences of others if those experiences are not shared.

To facilitate testing the effectiveness of mitigation measures, a more systematic approach is needed. Currently, when mitigation is required by governmental agencies, monitoring for compliance is customary. If greater effort were channeled towards monitoring the *effectiveness* of mitigation measures (i.e., sage grouse responses), it would allow for a more rapid development of conservation measures.

A Need for Spatial and Temporal Management: Several authors have stated that federal and state governments and industries need to implement solutions on a large scale (i.e., "landscape-level" management).[83] They suggest that one approach is to forgo development in priority landscapes until new "best management practices" are implemented. This is reasonable, but implementation requires sharing of information and trust. However, J. Connelly et al. note that, although mining and oil and gas development can have negative impacts on sage grouse, populations can recover after the development has ceased.[84] The critical point is that both temporal and spatial management is needed. Development with subsequent restoration of areas with oil and gas resources can occur over time to maintain populations over the range of the species. Coupled with development of more effective mitigation and recent, less-invasive technologies, this approach would allow multiple objectives to be achieved without permanently excluding oil and gas extraction from large areas.

Conclusion

If sage grouse and energy development are to coexist successfully in the long term and effective management be developed in a timely manner, it is imperative that both threats and management actions be treated as potentially falsifiable hypotheses, rather than as certain knowledge.[85] In other words, even hypothetical threats can be prioritized and subsequently investigated in a scientific manner. In cases where quantitative data are lacking, threats may be initially ranked based on their plausible cause-and-effect mechanisms and revised as additional data become available. In this process, mitigation measures that have been designed to address a specific threat may be treated as alternative hypotheses and their effectiveness tested against quantitative thresholds. These can be laid out in a series of "if - then" statements in adaptive management plans. This same strategy can be used to set "triggers" for additional or alternative management actions. Such a scientific approach to adaptive management increases the likelihood that conservation effort will be allocated in a way to provide the greatest benefit.

NOTES

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