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Research Paper

Modeling anthropogenic noise impacts on animals in natural areas

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ABSTRACT

Noise is a globally pervasive pollutant that can be detrimental to a range of animal species, with cascading effects on ecosystem functioning. As a result, concern about the impacts and expanding footprint of anthropogenic noise is increasing along with interest in approaches for how to mitigate its negative effects. A variety of modeling tools have been developed to quantify the spatial distribution and intensity of noise across landscapes, but these tools are under-utilized in landscape planning and noise mitigation. Here, we apply the Sound Mapping Tools toolbox to evaluate mitigation approaches to reduce the anthropogenic noise footprint of gas development, summer all-terrain vehicle recreation, and winter snowmobile use. Sound Mapping Tools uses models of the physics of noise propagation to convert measured source levels to landscape predictions of relevant sound levels. We found that relatively minor changes to the location of noise-producing activities could dramatically reduce the extent and intensity of noise in focal areas, indicating that site planning can be a cost-effective approach to noise mitigation. In addition, our snowmobile results, which focus on a specific frequency band important to the focal species, are consistent with previous research demonstrating that source noise level reductions are an effective means to reduce noise footprints. We recommend the use of quantitative, spatially-explicit maps of expected noise levels that include alternative options for noise source placement. These maps can be used to guide management decisions, allow for species-specific insights, and to reduce noise impacts on animals and ecosystems.

1. Introduction

Anthropogenic noise affects species' occupancy (Francis, Paritsis, Ortega, & Cruz, 2011), behavior (Shannon et al., 2015), distribution (Ware, McClure, Carlisle, & Barber, 2015), reproduction (Francis et al., 2011), physiology (Kight & Swaddle, 2011), and ultimately fitness (Schroeder, Nakagawa, Cleasby, & Burke, 2012). Noise can be an invisible source of habitat degradation (Ware et al. 2015), influence trophic interactions (e.g., predator-prey dynamics, Francis, Ortega, & Cruz, 2009), and change the provision of ecosystem services (Francis, Kleist, Ortega, & Cruz, 2012). Although most noise studies have focused on birds, terrestrial noise has been shown to affect a wide variety of taxa, including mammals, reptiles, amphibians, and invertebrates (Bowles et al., 1999; Bunkley, McClure, Kawahara, Francis, & Barber, 2017; Morley, Jones, & Radford, 2014; Shannon et al., 2015). Consequently, there is increasing interest in describing and mitigating the impacts of noise pollution on biodiversity (e.g., Mullet, Gage, Morton, & Huettmann, 2016).

With increased awareness of the threats posed to ecological systems by noise, several approaches to model noise propagation across landscapes have been developed (e.g., Ikelheimer & Plotkin, 2005; Kragh et al., 2002; Reed, Boggs, & Mann, 2012). Sound propagation models provide a means of assessing current and predicted noise levels and evaluating noise propagation under alternative management options (Harrison, Clark, & Stankey, 1980; Reed et al., 2012) or future scenarios (Dumyahn & Pijanowski, 2011). As such, the application of propagation modeling can provide rapid and cost-effective insights for planning or management decisions to mitigate potential noise impacts (e.g., management of snowmobile noise in Yellowstone National Park, Jacobson, 2013).

Energy development and motorized recreation are noise sources of particular concern, as they are widespread and can substantially

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increase sound levels in natural areas (e.g., Harrison et al., 1980; Ramirez and Mosley, 2015). Noise from natural gas extraction has been shown to reduce species' abundance in large areas of habitat (Bayne, Habib, & Boutin, 2008), change patterns of habitat selection (Kleist, Guralnick, Cruz, & Francis, 2017), interfere with species' hunting behavior (Mason, McClure, & Barber, 2016), alter species' physiology (Blickley et al., 2012), and influence trophic interactions (Francis et al., 2011).

Recreational noise, too, has been shown to directly, negatively affect species' behavior (Brattstrom & Bondello, 1983; Karp & Root, 2009). A recent review of recreational impacts found that ~45% of studies of summer-season motorized recreation and ~80% of snow-based, winter motorized recreation had negative effects on species (Larson, Reed, Merenlender, & Crooks, 2016). Noise is hypothesized to be an important factor driving the negative effect of motorized recreation on species (Harrison et al., 1980; but see Reimers, Eftestøl, & Colman, 2003). Among other effects, species may avoid noise sources (Bradshaw, Boutin, & Hebert, 1997), and the resulting displacements may be energetically costly (Bradshaw, Boutin, & Hebert, 1998). Noise may also mask species' communication (Lohr, Wright, & Dooling, 2003), which may cause species to compensate using a variety of potentially costly strategies (Brumm & Slabbekoorn, 2005).

Our study aims to develop approaches that allow a spatially-explicit evaluation of the benefits of different mitigation approaches to reduce the amount of area exposed to noise. We applied noise propagation models to assess noise-related impacts of gas development, off-highway vehicle use, and snowmobile use and examined the potential to reduce noise impacts through relocating noise-producing activities or, in the case of snowmobiles, by reducing noise levels at the source. A variety of acoustic metrics are available, including sound pressure levels, thresholds, audibility, and potential for masking. We demonstrate the utility of summarizing noise propagation data in these various manners, highlighting the applicability of these different metrics to different types of questions. We predicted that small changes at the planning stage could greatly reduce noise levels, especially in sensitive areas. We used threshold-, audibility-, and masking-based metrics (see Methods) as different indices of noise impacts for different ecological situations. Finally, we discuss modeling decisions to consider when developing and applying sound propagation model outputs to management questions.

2. Methods

2.1. Study area

We examined noise impacts from energy development or motorized recreation in three study locations: gas extraction in Shale Ridges Management Area, CO (39.3 N 108.3 W; BLM, 2015), all-terrain vehicle recreation in Bangs Canyon, CO (38.93 N 108.5 W), and snowmobile use in the Stanislaus National Forest, CA (38.514 N, 119.92 W). These sites were selected to represent a variety of anthropogenic noise sources relevant to land managers, and to illustrate sources with different spatial arrangements (point-, line-, and area-based noise sources). We used site-specific approaches to incorporate specific situation of each location in the noise propagation models.

The Shale Ridges Management Area has recently been the subject of a Master Leasing Plan (BLM, 2015), which included the potential for new natural gas extraction in the area. This management area also contained lands designated as Areas of Critical Environmental Concern (ACEC) for wildlife. The study landscape was comprised of ridges and valleys, with a mean elevation of 1906 m (1382–2723 m min-max, USGS, 2013), and was comprised of a variety of vegetation types, with pinyon-juniper (*Pinus edulis* and/or *Juniperus osteosperma*) woodland (30%) and big sagebrush (*Artemisia tridentata*) scrubland (21%) accounting for over half the land cover. No other land cover type accounted for more than 10% of the total land area (LANDFIRE, 2012). One of the most iconic species in the region is the mule deer (*Odocoileus hemionus*), and previous research has suggested that mule deer are sensitive to natural gas development (Johnson et al., 2016; Northrup, Anderson, & Wittemyer, 2015; Sawyer, Kauffman, & Nielson, 2009; Sawyer, Nielson, Lindzey, & McDonald, 2006). Consequently, we examined the potential for drilling and operating new wells to affect mule deer.

Bangs Canyon, adjacent to Colorado National Monument and located near Grand Junction, CO, is managed by the BLM for motorized recreation, non-motorized recreation, and wildlife. Bangs Canyon is also topographically diverse (mean: 1902 m, min-max: 1362–2955 m USGS, 2013), with a similar vegetation composition to the Shale Ridge Management Area: 30% Pinyon-Juniper Woodland, 11% Big Sagebrush Shrubland, and no other land cover > 10% of the landscape (LANDFIRE, 2012). Motorized recreation can be disruptive to non-motorized recreationists and wildlife (e.g., Rapoza, Sudderth, & Lewis, 2015; Seip, Johnson, & Watts, 2007); consequently, we tested the degree to which motorized recreation would be audible along non-motorized trails. We chose to use a single all-terrain vehicle (ATV) as our motorized source (although model results could be scaled to represent any number of ATVs), and evaluated human audibility (ISO 389-7). In addition to evaluating effects on other recreational visitors, humans are a useful proxy for many species because human hearing is similar to or better than that of many wild animals (e.g. see audiograms in Fay, 1988; Buxton et al., 2017).

Finally, we considered snowmobile use in a recreation area within Stanislaus National Forest proposed by the USDA Forest Service (hereafter 'snowmobile area'). In contrast to the other two study regions, Stanislaus National Forest was higher in elevation (mean: 2459 m, min-max: 1675–3328 USGS, 2013), but predominantly wooded (49% Red Fir Forest, no other landcove > 10% of the landscape, LANDFIRE, 2012). The potential for avian communication to be masked by anthropogenic noise has been a topic of considerable research (e.g., Brumm & Slabbekoorn, 2005; Hu & Cardoso, 2010; Lohr et al., 2003), and winter may be a time when masking of alarm and other social calls of birds place these animals in particular risk due to weather extremes and limited food (e.g., Jansson, Ekman, & von Brömssen, 1981; Robel & Kemp, 1997). Therefore, we chose to evaluate the potential for snowmobiles to mask species-specific vocalizations in a recreation area. We focused on vocalizations by White-breasted Nuthatches (*Sitta carolinensis*), as this species is present in the Stanislaus National Forest year round, vocalizes in winter, and quality recordings of the species' vocalizations are available (Nelson, 2015a, 2015b).

2.2. Modeling approach

2.2.1. Modeling approach overview

We used Sound Mapping Tools V4.4 (SMT, Keyel, Reed, McKenna, & Wittemyer, 2017 http://purl.oclc.org/soundmappingtools) with ArcGIS (10.3, 10.4, ESRI, Redlands, CA) to evaluate potential acoustic impacts using publicly-available data sets (see Table 1, code used to run the analyses given in Appendix 1). SMT provides an easy-to-use ArcGIS interface for several existing sound models: SPreAD-GIS (Harrison et al., 1980; Reed et al., 2012), NMSIMGIS (Ikelheimer & Plotkin, 2005), and a GIS implementation of ISO 9613-2 (ISO 9613-2). These sound models make spatially-explicit quantitative predictions of sound levels based on distance from a sound source, land cover, topography, and environmental conditions, and they have been used previously to address natural resource-related questions (e.g., Barber et al., 2011; Sunder, 2003).

We represented line and polygon noise sources as arrays of points to meet the point input requirement of the models. Each point source had the same starting sound level. All decibel values reported here are A-weighted sound pressure levels re: 20 μPa (dBA) unless otherwise noted. One-third octave band ranges used in the weightings are given in Table 1. We used weather data from a nearby weather station using seasonally appropriate weather conditions. Our goal was not a precise

Table 1
Data used for the study sites.

Variable	Shale Ridge	Bangs Canyon	Stanislaus National Forest
Nearest weather station	Grand Junction	Grand Junction	South Lake Tahoe[8]
Weather station WBAN	23066[2]	23066[2]	93230[2]
Year used for weather conditions	2014	2014	2014
Months used for weather conditions[1]	September	July	January
Mean temperature (°C)	19.8	26.4	2.5
Mean relative humidity (%)	44.3[3]	29.7[3]	50.0[3]
Mean wind speed (kph)	12.0	13.6	5.5
Modal wind direction (°)	120	45	30
Land Cover	LANDFIRE[4,5]	LANDFIRE[4,5]	SNOW
Elevation	NED[5,6]	NED[5,6]	NED[5,6]
Source data	Drill rig[7], gas compressor[7]	All-terrain vehicle[7]	Snowmobiles[7]
1/3 octave band range	125-2000 Hz	125-2000 Hz	2500 Hz

[1] Months were chosen to be representative of the activity under consideration, with exception of drilling, which could potentially happen at any time. The exact time is not critical, as the research objective is focused on identifying large, relative, differences.
[2] Weather data acquired from QCLCD files (NOAA, 2015).
[3] Relative humidity was calculated using the August-Roche-Magnus approximation (Alduchov & Eskridge, 1996; McNoldy, 2017), and a single average value was computed for the focal month.
[4] (LANDFIRE, 2012).
[5] Resampled to 30 × 30 m cell size and converted to the appropriate UTM zone.
[6] National Elevation Data, 1 arc-second resolution, (USGS, 2013).
[7] Drill rig measurements provided by E. Brown, National Park Service, gas compressor measurements made by XXX, (masked for blind review), all-terrain vehicle source data from Harrison et al. (1980), snowmobile data provided by D. Joyce, National Park Service Natural Sounds and Night Skies Division.
[8] The closest weather station was Bridgeport Sonora Junction (WBAN 433) but this had no data for the year and month of interest.

instantaneous sound level for one given point in time, but a relative assessment of the different options under equivalent conditions (see Appendix 2 for a broader discussion of weather-related model considerations). To facilitate the modeling process, sound sources were assumed to be omni-directional (but note this assumption may be inappropriate for some sources; e.g., helicopters, Conner & Page, 2002).

2.2.2. Modeling energy development using thresholds

We selected SPreAD-GIS (Reed et al., 2012) to model the noise impact from proposed wells on mule deer within the ACEC. While several models could have been chosen, the SPreAD-GIS model executes more quickly, and our goal was to compare alternative management scenarios using a consistent model. We made spatially-explicit predictions of noise from active drilling of a well and from a hypothetical on-site gas compressor station at four proposed well sites. We modeled drilling and compressor stations at each site, as these represent two substantial noise sources associated with wells. We assessed where mule deer might be displaced within the ACEC by gas exploration activities using a threshold-based approach to provide a discrete value that could be used for interpreting relative area impacts among well locations. A weakness of thresholds is that they can be somewhat arbitrary (e.g., a mule deer could respond similarly to values immediately below and above the selected threshold), however, the threshold approach provided a clear basis for comparing the relative footprints of the different well locations. We used a 45 dBA 1 s L_{eq} threshold as the level at which mule deer would be displaced. As hearing among ungulates is similar (Heffner & Heffner, 2010), the threshold was empirically estimated for a proxy species, caribou (*Rangifer tarandus caribou*; see Appendix 3 for derivation; [Bradshaw et al., 1997]). Finally, we repeated the procedure with a systematic grid of points spaced 500 m apart to evaluate the potential impact of alternative well placement locations. Potential impacts were quantified by the area that would be raised above a 45 dBA 1 s L_{eq} by drilling or placement of a compressor station at that location. Well locations were compared on the basis of their predicted noise footprints.

2.2.3. Modeling summer recreation and audibility

In Bangs Canyon, we examined where motorized recreation (represented by an all-terrain vehicle, ATV) could be audible above natural background sound levels. Audibility may serve as an estimate of the minimum potential impact, as inaudible decibel levels are not expected to have negative effects (but see studies on infrasonic effects, e.g., Landstrøm, 1987). Audibility only assesses *potential* impact, as a sound may be audible without necessarily causing any negative effects (Rapoza et al., 2015). While audibility will depend on species, individual, and even the degree of attention paid by an individual animal to the noise source (Fay, 1988; Rapoza et al., 2015), an international standard has been developed for calculating human audibility (ISO 389-7). We used this standard, as humans often have better hearing than many mammals and birds (Fay, 1988) in the low-frequency bands that travel the furthest. Audibility was calculated using the audibility statistic d’, calculated by comparing background sound levels taken from Harrison et al. (1980) to ATV sound levels for each 1/3 octave frequency band, accounting for human hearing (ISO 389-7). Values of $10 * \log_{10}(d')$ greater than 7.3 were considered audible, based on empirical results (Fidell et al., 1994). We excluded trails within 200 m of highways from the analysis based on the assumption that the highway would be the dominant source of noise in these areas.

To characterize the noise along the motorized route, the route was broken into a series of points to simulate a single ATV traveling at $\sim 6\,\mathrm{m\,s^{-1}}$ sampled every 20 s, which resulted in an approximately 120 m point spacing along the line. We chose a spacing that gave sufficient coverage to examine relative impacts of different sections of the motorized trail and assumed a single ATV traveling the route. This spacing may not adequately represent sound propagation from line sources, as sound levels drop by 6 dB per doubling of distance for point sources compared to 3 dB per doubling of distance for line sources (Bies & Hansen, 2009). To model line sources, one must check that when sound levels are summed across points, the spacing is adequate to show the 3 dB reduction per doubling of distance. The SPreAD-GIS model was run for each point using source levels reported by Harrison et al. (1980).

We considered the audibility impact in two ways. First, we looked at where on the non-motorized trails an ATV would be audible by calculating audibility based on a single ATV for each point along the motorized trail. Second, we examined which locations along the motorized trail were most responsible for this impact on the non-motorized trail, to prioritize any mitigation measures or development of alternative routes. To accomplish this, the length of non-motorized trail where each motorized point was audible was computed (length was approximated by examining the area affected for a 1 m wide trail). Points with more than 1 m of affected non-motorized trail were classified as points having a greater impact; the remaining points were classified as lower impact.

2.2.4. Modeling winter recreation and masking

In Stanislaus National Forest, we chose to examine the potential for masking the peak frequency of White-breasted Nuthatch calls and songs. Peak frequency of nuthatch vocalizations was extracted using Raven Pro (Bioacoustics Research Program, 2014) and was found to be in the 2.5 kHz 1/3 octave band. Potential noise levels within a snowmobile area (polygon) were assessed using a systematic grid of points spaced 30 m apart (to match the land cover and elevation cell sizes). We modeled standard and next-generation four-stroke snowmobiles, running at a speed of 13.4 m s^{-1} (48.3 km h^{-1}, source data provided by D. Joyce, National Park Service). Model predictions were first made for a single snowmobile of each type at every grid point. Then, the maximum sound level from any grid point was used to evaluate the potential impact of the snowmobile area. Finally, the maximum sound level results for a single snowmobile were compared to the results from a group of snowmobiles by scaling the single snowmobile results by a factor corresponding to the number of snowmobiles in the group (on an energy basis, not a decibel basis). We used a group count of eight snowmobiles; this corresponds to the low number of snowmobiles per group in a study of snowmobile impacts (Eckstein, O'Brien, Rongstad, & Bollinger, 1979). The results are intended to demonstrate the relative increase in noise level with an increase in the number of snowmobiles, and could be rescaled to accommodate additional scenarios. We used the NMSIMGIS model (Ikelheimer & Plotkin, 2005) from Sound Mapping Tools due to its ability to model snow-covered ground and its greater frequency range than SPreAD-GIS. Number and type of snowmobiles were compared on the basis of predicted sound levels where a 90% or more reduction in listening area might occur for White-breasted Nuthatches.

Listening area is defined as an area where a receiver could detect a signal. For example, the area where one White-breasted Nuthatch could hear another White-breasted Nuthatch calling. Barber, Crooks, and Fristrup (2010) showed that a 3 dB increase above ambient leads to a 50% reduction in listening area, and by the same logic a 10 dB increase corresponds to a 90% reduction in listening area. Harrison et al. (1980) estimate the maximum ambient sound levels in conifers for the 2 kHz band (the closest spectrum to 2.5 kHz with data) to be 27 dB (minimum 9 dB). Therefore, we considered areas in excess of 37 dB to represent 90% or greater reduction in listening area to provide a minimum estimate, to account for the uncertainty in the ambient dB levels. We measured the minimum and maximum distance outside the snowmobile area where a 90% or more reduction in listening distance would occur using the measure tool in ArcGIS.

3. Results

For natural gas development in the Shale Ridges Management Area, the four proposed wells were predicted to raise sound levels above 45 dBA for 0, 11.6, 69.1, 76.3 ha during drilling and 0, 6.9, 39.0, 43.0 ha during operation of a compressor station (Fig. 1, for wells 1, 2, 3, 4, respectively). When alternative locations were considered, potential acoustic impacts varied across the landscape. Most areas outside the ACEC would raise the dBA level within the ACEC above 45 dBA for less than 1 ha. Wells 3 and 4 were among the locations with the greatest potential acoustic footprint. For these wells, alternative locations within 1 km would substantially reduce the area expected to exceed 45 dBA (Fig. 2). Moving well 3 by less than 1 km could reduce the area above 45 dBA by 27.7% during drilling and 17.7% during operation of a compressor station. For well 4, the potential reduction in affected area for a move of 1 km or less was even greater: 64.9% for drilling and 34.8% for a compressor station. These differences within the ACEC were primarily due to terrain effects.

For summer motorized recreation in Bangs Canyon, ATVs were predicted to be audible to humans on over 16% of the non-motorized trails (Fig. 3a). For most locations along the non-motorized trails, a single ATV would be inaudible due primarily to the barrier effects of intervening terrain and distance from the motorized trail (Fig. 3a). Similar to reported results for the Shale Ridges site, not all points along the motorized trail were equal in their acoustic impacts, with seven point locations having a much larger acoustic impact on the non-motorized trail than the others (i.e., affecting at least 1 m of the non-motorized trail, Fig. 3b) due to a combination of proximity and topography.

For winter motorized recreation in Stanislaus National Forest, snowmobiles differed in their potential to mask White-breasted Nuthatch vocalizations (Fig. 4). The next-generation snowmobiles produced lower sound levels in the 2.5 kHz one-third octave band used by White-breasted Nuthatches than did the standard snowmobiles, as well as having reduced noise footprints. In all cases, the presence of a snowmobile was expected to reduce the listening area (for a conspecific cue) for White-breasted Nuthatches by more than 90% within the snowmobile-exposed area. The exact distance at which a 90% or greater reduction was no longer expected varied spatially. For a single next-generation snowmobile, this distance ranged from 13 to 86 m outside the snowmobile area while for eight next-generation snowmobiles, it ranged from 83 to 210 m. For one and eight standard snowmobiles, these distances were 64–137 m and 158–286 m respectively.

4. Discussion

As noise pollution expands and threatens natural systems, approaches to plan for and mitigate negative effects of noise sources are increasingly needed. We demonstrated the application of noise propagation models in three systems with differently structured noise sources and areas of concern. We applied sound propagation models to these systems to identify critical locations where noise sources had disproportionate impacts on landscapes and where alternative locations of noise sources could reduce the area of the landscape exposed to noise. This information can provide targeted guidance for noise mitigation efforts of existing activities or for proactive planning to reduce undesirable noise impacts. As has been previously noted (e.g., Embleton, 1996), our results demonstrated the key role topography can play in sound propagation. Properly planning around topographical barriers can help to mitigate noise impacts. As has been shown previously (Bies & Hansen, 2009), reduction of noise levels at the source also reduced noise impacts. While our approaches were varied to match the characteristics of our three systems, they demonstrated the capacity of sound propagation models to produce spatially-explicit maps identifying areas of concern (e.g., threshold exceedance) and comparative noise footprints (e.g., between two types of noise sources) to inform noise management. The resulting maps demonstrate the capacity to greatly reduce noise impacts in ecologically sensitive areas through fine-scaled (i.e., within 1 km) site selection.

Topography was identified as a major factor because spherical spreading loss (a reduction in sound pressure levels as sound waves spread out over an increasing area) and atmospheric absorption are not expected to differ for equidistant points, while acoustic losses due to land cover are relatively small (Embleton, 1996). Consequently, the large differences observed for equidistant locations were due to topographical features acting as natural barriers. This was evident across all three examples: in Shale Ridges, nearby alternate locations were expected to have large reductions in noise footprints, in Bangs Canyon, proximity to the motorized trail was important, but the points with the greatest effect were those that were not shielded by topographical barriers. Similarly, in Stanislaus National Forest, the distance from the snowmobile area where a 90% or greater reduction in listening area was expected to vary by more than 100 m, despite relatively

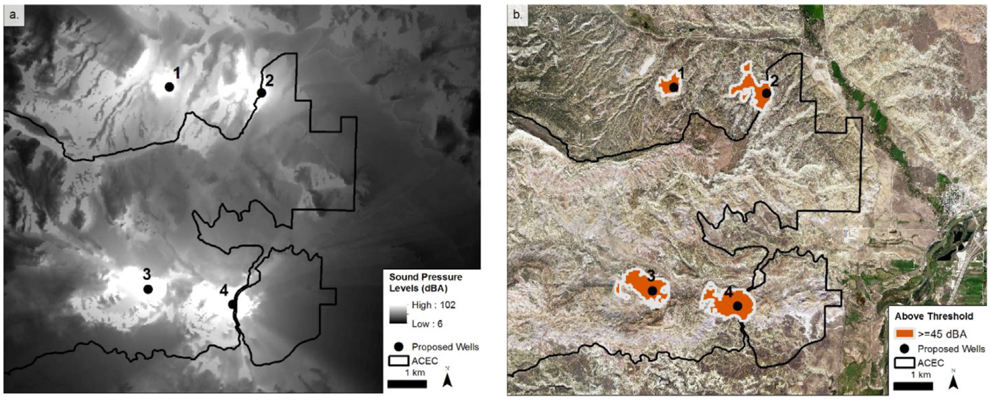

Fig. 1. The predicted acoustic impact of drilling four new wells (1–4). (a) The predicted sound pressure levels of drilling the well sites are displayed, while in (b) only the areas where sound pressure levels would meet or exceed a 45 dBA threshold (derived for mule deer, *Odocoileus hemionus*) are shown. The Area of Critical Environmental Concern (ACEC) is outlined in black.

homogeneous vegetation cover.

4.1. Using sound propagation to explore mitigation impacts

In the Shale Ridges Management Area, we demonstrated the strong differences between well locations in their potential noise impacts (Fig. 1), and the potential for a reduction in noise impacts with changes to well placement (Fig. 2). Use of a systematic grid greatly increased the rigor of the consideration of alternative locations, and was computationally feasible for our study area. Similarly, we found that consideration of the spatially explicit audibility of noise may help guide route planning decisions. Some locations on the motorized trail in Bangs Canyon contributed substantially more noise to the non-motorized trail than other locations (Fig. 3). The predicted noise levels in Bangs Canyon were anticipated to be inaudible over most of the non-motorized recreation trail, suggesting that noise management at this location may be of limited value. Were noise management to occur, the maps identify the points where the greatest reductions could be achieved. These maps could also be used to identify areas that would need to be closed in order to protect particularly sensitive areas.

General model predictions may be used to identify locations on the landscape more susceptible to noise intrusions. These locations are expected to remain the same, even if source type and source number are varied. For example, the locations most affected by drilling were the same locations as those identified in the compressor station analysis. In some cases, the source with the lowest overall sound level may not be the quietest with respect to a particular frequency band. By modeling just the noise expected to interfere with White-breasted Nuthatch vocalizations, we demonstrated how models could be used to focus on noise that is expected to be most disruptive to specific species' detection of conspecific cues.

With recognition of the problems created by noise exposure, emphasis on developing quieter technologies has created options for noise mitigation efforts. We only assessed the change in impact using quieter snowmobile technology in the Stanislaus National Forest site. As expected, quieter snowmobiles led to lower noise impacts (Fig. 4), but even noise from these next-generation snowmobiles greatly reduced White-breasted Nuthatch listening area. The potential to use quieter technology for gas extraction (e.g., noise-dampening walls) has been addressed and can provide substantial reduction in noise levels (Bayne et al., 2008; Francis et al., 2011), consequently, we did not examine it explicitly here. Additionally, management based on total noise levels may be more desirable than by focusing on particular mixtures of noise sources. Total noise level management was done in the winter travel management plan for Yellowstone National Park (Jacobson, 2013). This travel management plan used the NMSim model to determine restrictions on the number and types of snowmobiles allowed in an area based on total anticipated noise levels.

4.2. Modeling decisions and limitations

The analyses required several modeling decisions, and the appropriate decision depended on the specific question being asked in each case study. These included the choice of acoustic metric, sound propagation model, source level data and number of sources, resolution and extent of the analysis, weather data and season, and alternatives for evaluation of planning and mitigation options. The choice of sound propagation model can be guided by empirical data (e.g., see Appendix 4), consideration of the model capabilities (e.g. frequency range, land cover), and applicable standards (e.g., Sunder, 2003). When reporting acoustic results, it is critical to report details, such as the timeframe of the acoustic measure, which weightings were used, and what frequency range was considered (reviewed by McKenna, Shannon, & Fristrup, 2016). An important next step would be to use field measurements to evaluate and refine the sound propagation models. The analyses presented here could be further refined in the future, especially in cases where absolute sound levels are more important than relative differences between locations. When absolute levels are required, identifying the sensitivity of the analysis to model choice and selection of input conditions may be useful. When multiple models make the same prediction, more confidence can be placed in the model results. Where the models make differing predictions, careful consideration of the model assumptions or field measurements may be necessary.

4.3. Potential applications

Available modeling tools, including the ones employed here, can facilitate studies of animal behavior and fitness. These tools make it easier to include sound levels as ecological covariates. While all of the approaches employed here used a single sound level per noise source, many noise sources vary in decibel level over time. More sophisticated examples could be developed to use more than one source level (e.g. for multiple speeds or for sources that vary in sound level over time). In the case of Bangs Canyon, while a single ATV was not audible over the majority of the trail, multiple ATVs or different models might be audible. Additional summary information could be extracted such as maximum sound level, duration of the noise source, time audible, and whether the noise source is impulsive (such as a gunshot) or continuous. These different noise attributes can have different degrees of influence on animals' behavior and fitness (Shannon et al., 2015), and additional studies examining these noise components could be valuable.

Further model applications could include characterization of other sound sources in the areas. In the Shale Ridges analysis we considered only the noise impacts of the well site itself, and not those of any associated infrastructure (e.g., roads, well pad construction). A quiet well location that would require a noisy access road through sensitive areas may be worse than an alternative well location with quieter access. As such, it is critical to consider the potential noise impacts of all noise sources to inform well site selection. Further research quantifying these

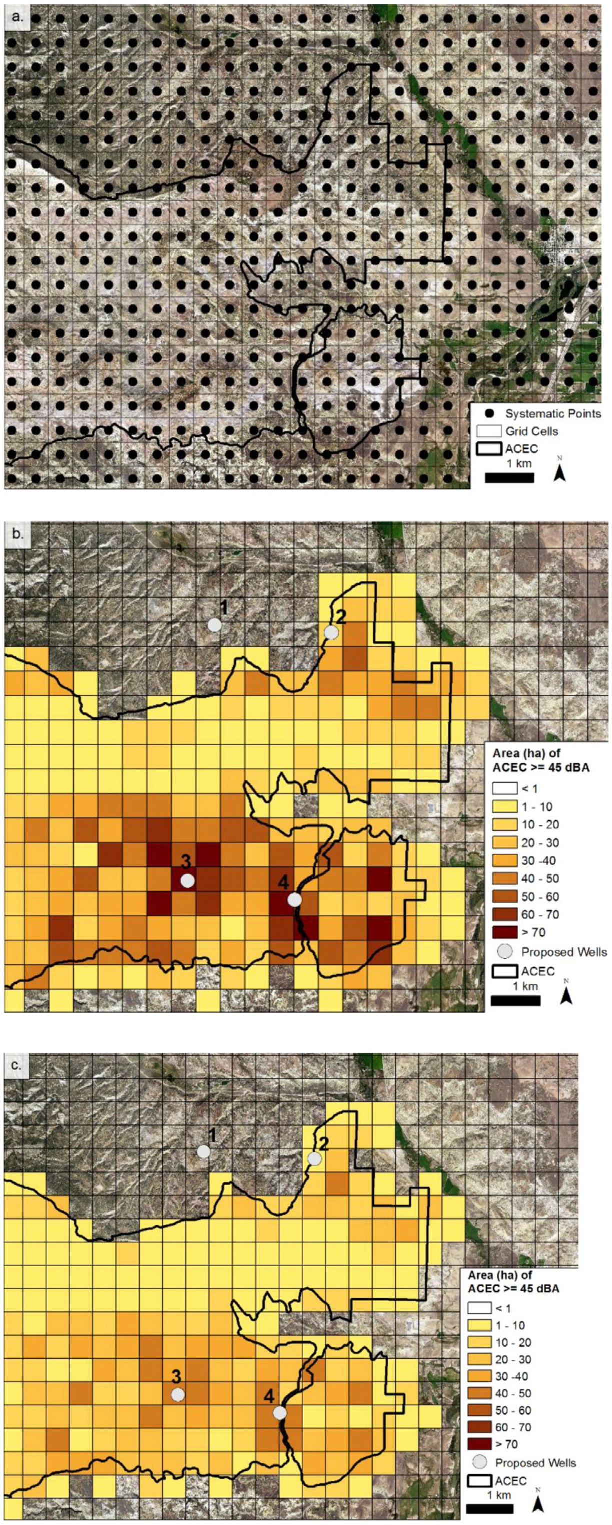

Fig. 2. The potential impact on mule deer within the Area of Critical Environmental Concern (ACEC) was evaluated for (a) systematic points across the landscape. The impact of each systematic point was extrapolated to the entire grid cell, and each cell was color-coded according to the area of the ACEC that would be elevated above 45 dBA during (b) drilling and (c) by operation of a hypothetical on-site compressor station at that point. Note that the actual spatial extent above a 45 dBA threshold of each systematic point (as was shown in Fig. 1b) is not shown, rather the color coding provides an index to the spatial extent that would be affected by drilling or compressor operation at that point (the darker the shading the greater the area affected). The locations (but not the sound levels) of the four proposed well sites (1–4) are included for context.

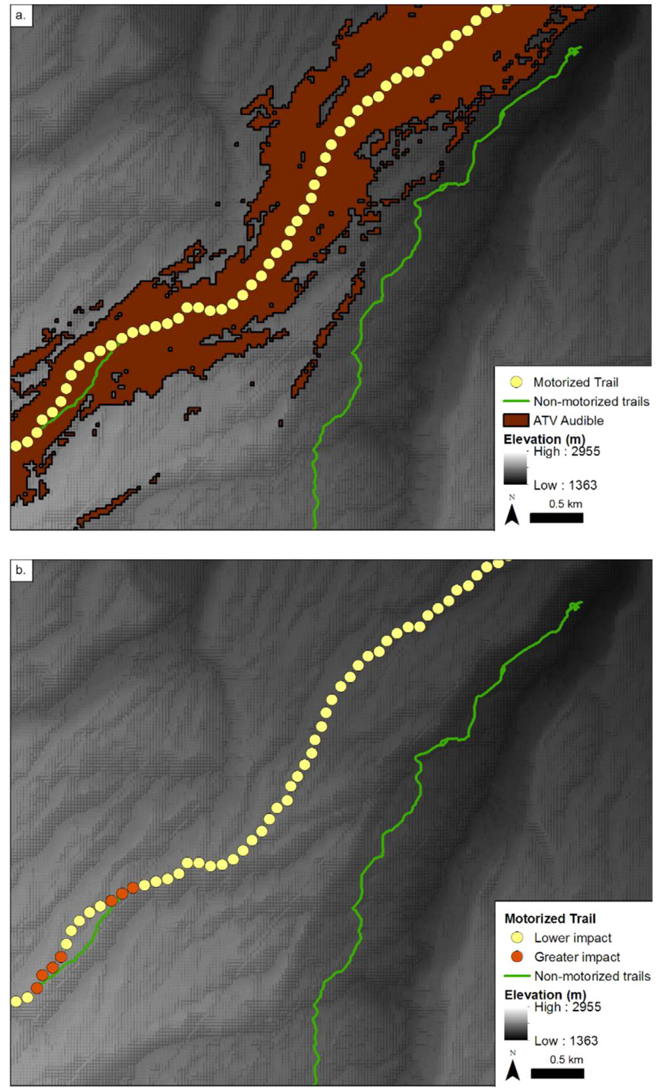

Fig. 3. (a) Audibility of a single ATV traveling a motorized vehicle trail in Bangs Canyon, CO. Audibility was defined based on human hearing abilities (ISO 389-7), and was defined as a cumulative d' statistic at or above 7.3. (b) The relative impact of individual sections of the motorized trail on the non-motorized trail highlight potential targets for management action. Lower impact points affected < 1 m of the non-motorized trail, while greater impact points affected ≥ 1 m. Elevation is from a hillshaded 1 arc-second digital elevation model (USGS, 2013).

potential noise sources is an important next step. Similarly, the Bangs Canyon analysis did not include other nearby anthropogenic noise sources, such as a nearby highway. Importantly, management decisions would need to consider information beyond just noise (e.g., presence of sensitive species, wilderness characteristics, access to the resource of interest, sensitivity of the habitat to disturbance, etc.).

A focus on the percentage reduction in listening area, while including simplifying assumptions, bypasses many of the limitations associated with studying masking. Masking depends on signal sound level (i.e. how loud a nuthatch vocalizes), noise level, how well an animal can hear during noise events (e.g., critical ratios, Lohr, et al., 2003), and how the animal behaviorally adjusts for the noise (e.g., by shifting vocalization amplitude, frequency or timing, Brumm & Slabbekoorn, 2005; Slabbekoorn, 2013). While critical ratio data exist for some animals, the data are lacking for the majority of species (Dooling, Lohr, & Dent, 2000; Fay, 1988). However, the percent reduction in listening area, in contrast to the size of the listening area, is determined by the

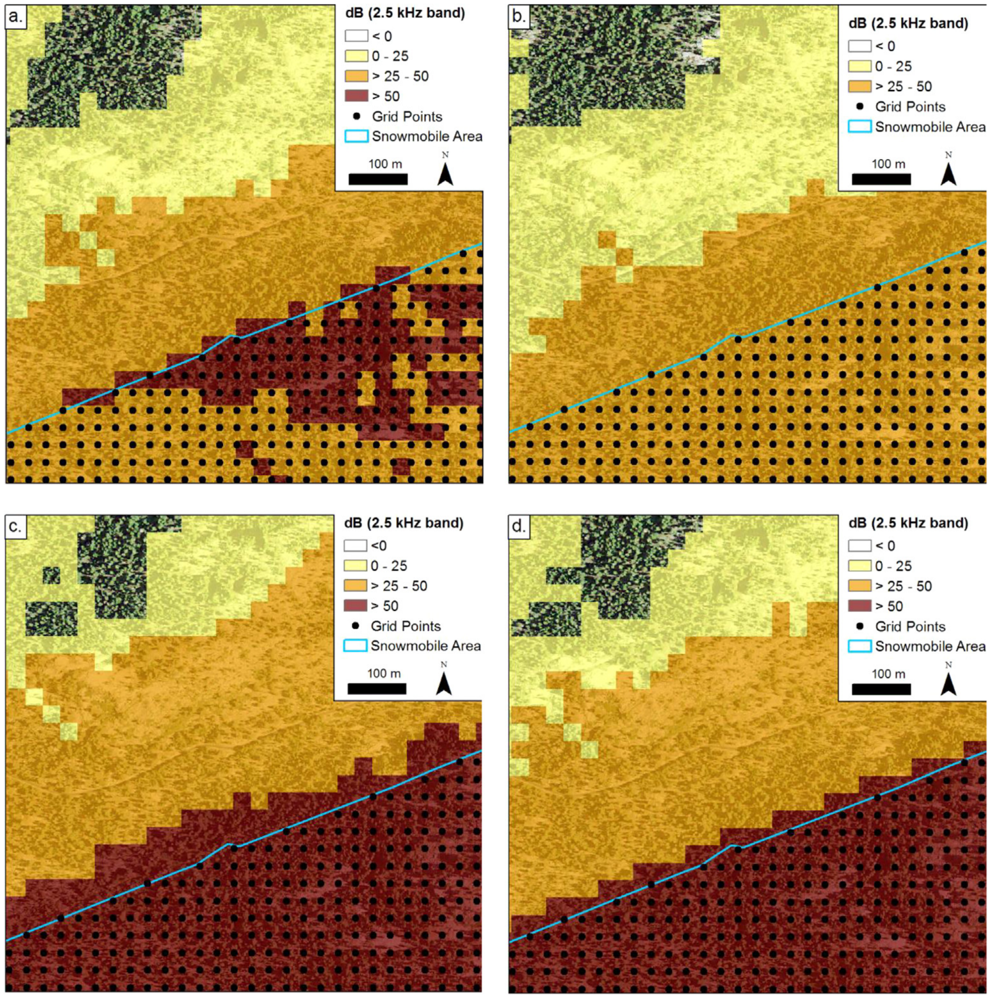

Fig. 4. The potential for snowmobiles to mask White-breasted Nuthatch vocalizations in the 2.5 kHz band differed by snowmobile type and number. Standard four-stroke snowmobiles (a, c) produce more acoustic energy in the 2.5 kHz one-third octave frequency band than snowmobiles utilizing next-generation technology (b, c). Increasing the number of snowmobiles from one (a, b) to eight (c, d) raises the maximum sound level within the snowmobile area to above 50 dB for both snowmobile types (aerial photo from USDA-FSA-APFO, 2016).

sound level relative to ambient, and not by species-specific hearing abilities. Thus, while it may be possible to model species-specific listening areas (e.g., US8223980B2, 2009), an approach based reduction in listening area may be sufficient and more feasible for many management questions.

5. Conclusions

In three empirical examples, we demonstrated a modeling approach for evaluating the potential noise exposure to animals. This approach can be used to evaluate alternative management scenarios with respect to noise source locations, such as designation of quiet areas, where noise intrusion would likely be harmful to ecological systems. Similarly, areas could be identified where noise impacts should be mitigated (e.g., through use of quieter technology, Bayne et al., 2008), and those where additional noise sources are unlikely to contribute an appreciable increase above background levels or negatively impact critical resources. We recommend the use of quantitative, spatially-explicit maps of expected noise levels that include evaluation of alternative options. These maps can be used to guide management decisions, allow for species-specific insights, and to reduce noise impacts on animals and ecosystems.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.landurbplan.2018.08.011.

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